Università degli Studi di Padova

Dipartimento
di Ingegneria Industriale

HEATING VENTILATION AIR CONDITIONING SYSTEMS

Thermal Comfort

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Thermal Comfort: what?

OK, OK, but what is "good" for an Engineer?

Summary

- Thermal environment and energy balance of the human body
- Fanger’s model: the comfort equation and evaluation parameters
- Localized thermal discomfort
- Testing and instrumentation
- Recent developments: adaptive thermal comfort

Comfort

- **psycho-physiological state** involving all the senses;
- need to study the effect of environmental inputs (thermal, acoustic, visual) on the psyche or organism;
- **thermal**, **acoustic**, **visual** comfort.
- for a correct definition of well-being it is necessary to delimit and define the area to which well-being refers;
- the simultaneous presence of various types of comfort increases the complexity of the problem (greater number of input to take into account)
- in order to appreciate any form of comfort, the satisfaction of other forms of comfort must be verified.

... you can be in a perfect environment for listening to music, or rather, to a particular type of music, have the best orchestra in the world, but if unfortunately you are hit by a current of cold air on the neck, you will lose much of the pleasure of music, the same thing will happen if dazzled by a poorly positioned headlight or even just if plagued by a nagging toothache.

Comfort

It is a condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. (ASHRAE 55, 2017)

Standard UNI EN ISO 7730
“Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indexes and local thermal comfort criteria”

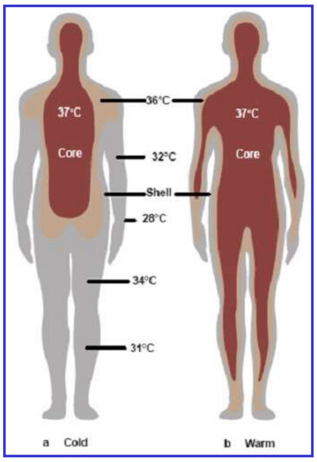
provides this definition:

Mental condition of satisfaction related to the thermal environment.

Comfort

- the problem of comfort is MAN (complexity and absolute lack of determinism);
- Insufficient engineering skills to study the comfort problem;
- Interdisciplinarity, i.e., involvement of other disciplines, such as medicine, physics, statistics, and psychology;
- evolution towards ever higher standards of comfort;
- control of an increasing number of parameters;
- use of increasingly sophisticated measuring instruments;
- complex measurement techniques and procedures;
- attempt to define global indices, or a scale of overall well-being.

Temperature of the human body



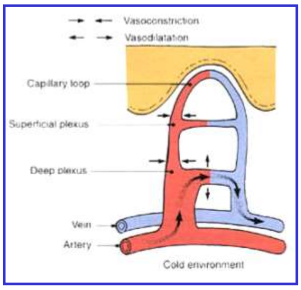
The function of keeping the core of the body nearly isothermal is delegated to the thermoregulatory system:

- vasomotor thermoregulation - peripheral capillaries equipped with sphincters (valves), which by opening or closing, allow or restrict blood flow;
- behavioral thermoregulation.

Thermal sensation is related to thermo-receptors, nerve endings located under the skin that are very sensitive to temperature.

There are about ten times as many thermo-receptors for cold as for heat. This explains why people are much more sensitive to cold than to heat.

Vasomotor Thermoregulation



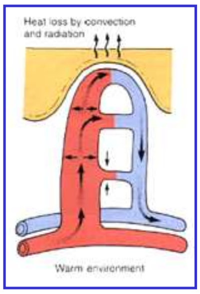
Cold environments:

valve closure (vasoconstriction);

decrease in blood flow to the periphery;

decrease in surface temperature;

decrease in heat exchange with the outside.



Hot environments:

opening of valves (vasodilation);

increased blood flow to the periphery;

increase in skin temperature;

increased heat exchange with the outside world.

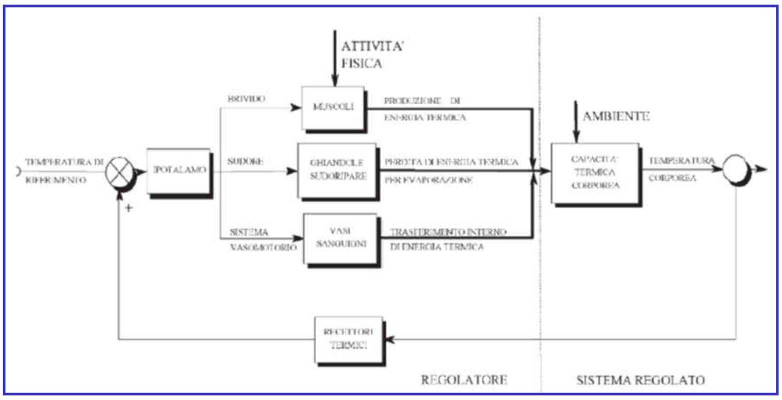
Behavioral Thermoregulation

Behavioral thermoregulation occurs if vasomotor thermoregulation is not sufficient:

- ☞ against the cold consists of shivering (activation of almost all muscle groups and increased energy generation within the body);

- ☞ against the heat consists of sweating.

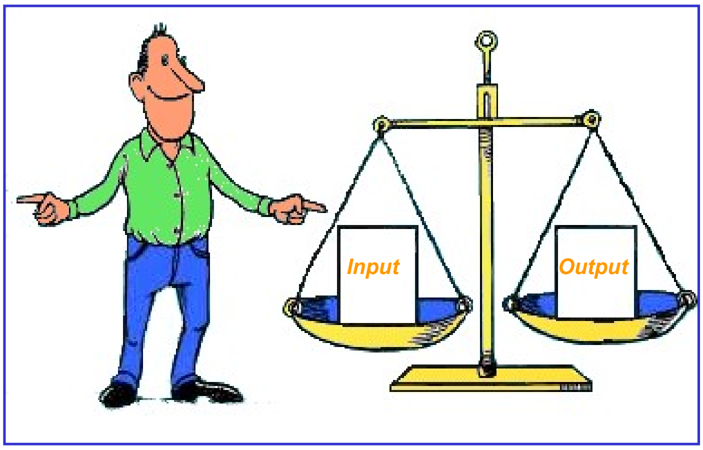
The Control System



If the behavioral thermoregulation is not sufficient to ensure homeothermia, it can occur:

- ☞ Hypothermia (to the point of death from cardiac fibrillation);
- ☞ Hyperthermia (to the point of death due to irreversible damage to nerve tissue proteins).

Energy Balance



A necessary condition for the maintenance of thermal comfort (steady-state conditions) is that the energy inputs (predominantly metabolism) equal the losses through the body surface.

Energy Balance of Human Body

$$S = M - (W + E_{res} + C_{res} + C + R + E + K)$$

where:

S = energy storage

M = metabolic rate

W = external mechanical power

E_{res} = latent respiration heat loss

C_{res} = dry respiration heat loss

C = heat loss by convection

R = heat loss by radiation

E = heat loss by evaporation of sweat from the surface of the skin

K = heat loss by conduction

Metabolic rate

Metabolism is the complex of chemical and physical processes that take place in the cells and tissues of the human body

- processing of food;
- transformation of oxygen into carbon dioxide;
- modification, growth and regeneration of the cells of the organism;
- physiological functions (nerve activity, blood circulation, respiration);
- motor functions and activities.

Metabolic rate

- is the average difference in the unit of time between energy administered (food, drink and oxygen) and energy expelled (feces, urine, carbon dioxide)
- assimilated to a generation term for man control volume;

is not constant over time; it depends on:

- quality and quantity of foods ingested;
- the time of their ingestion;
- external environmental conditions;
- the activity the person performs (it increases from quiet to intense and tiring activities).

Metabolic rate

The mechanical power given up for motor activities is always less than the generation term.

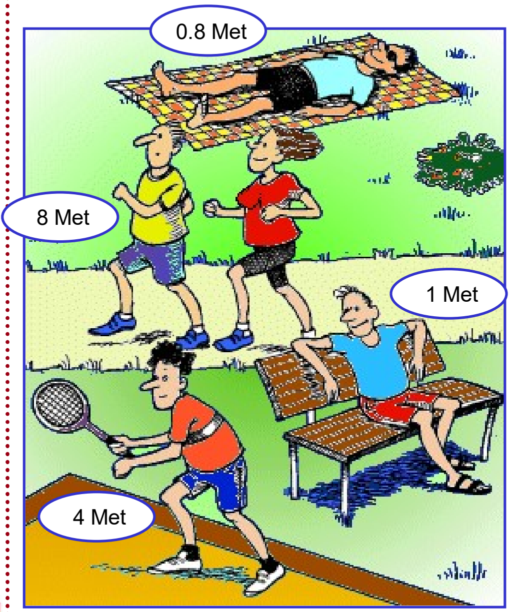
The human body, so that its internal energy and temperature do not vary, gives up energy to its surroundings:

- by convection with air;
- by radiation with surrounding surfaces;
- by evaporation of water (from skin and lungs);

If the energy released is greater (*less*) than the metabolic rate, the average body temperature decreases (*increases*) until it reaches a new steady state condition (or even collapse).

The organism reacts to possible imbalances by triggering complex thermoregulation mechanisms (well-being is the condition in which the activity of the thermoregulation mechanisms is low).

Metabolic rate and met



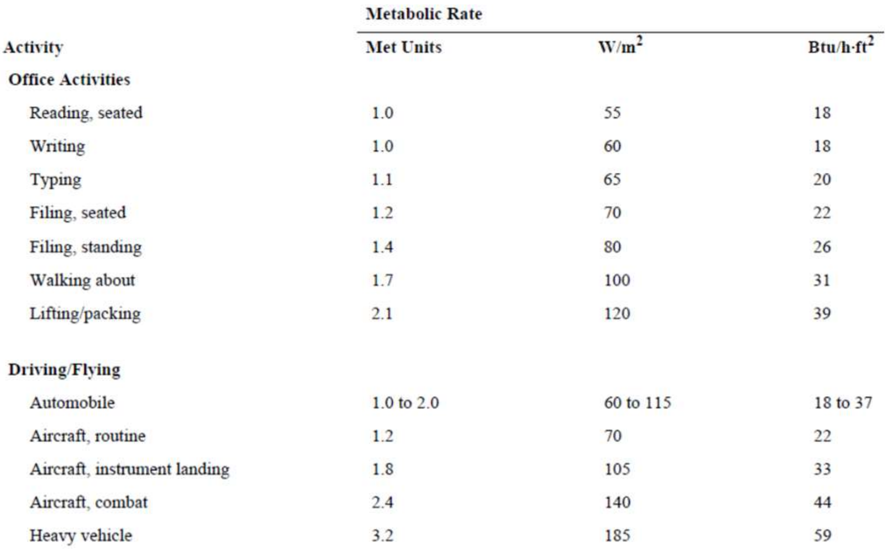
1 met = 58 W/m^2

The body area of an individual of average build is 1.80 m^2

(m = 70 kg, h = 1.70 m).

A seated person, in a state of comfort, has a heat loss of about 100 W.

Metabolic rate and met



Activity	Metabolic Rate Met Units	 W/m^2	 Btu/h·ft^2
Office Activities			
Reading, seated	1.0	55	18
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 to 2.0	60 to 115	18 to 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

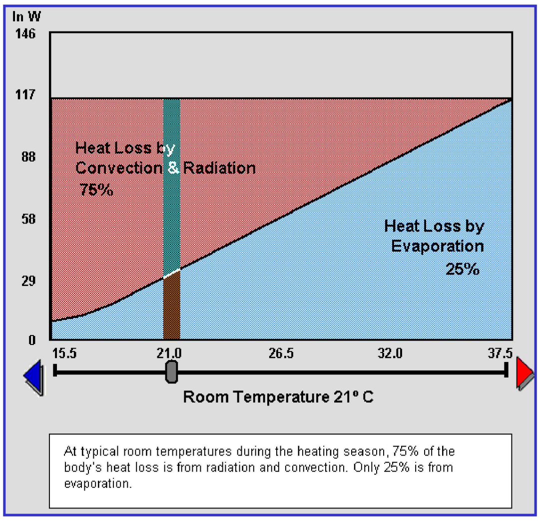
Heat transfer processes

E_{res} is a function of M, temperature and humidity of air (order of magnitude: tens of W);
C_{res} is a function of M, temperature and humidity of air (order of magnitude: tens of W);
C is function of clothing, temperature and velocity of air (order of magnitude: tens of W);
R is a function of the type of clothing and the temperature of the surfaces of the environment (order of magnitude: tens of W);
E is a function of the type of clothing and the temperature, humidity and ambient air speed (order of magnitude: tens of W - for sports activities or intense efforts even hundreds of W).

The influence of clothing is expressed through its thermal resistance, I_{cl}, usually expressed in clo (1 clo = 0,155 m^{2}K/W).

Typical values expressed in clo are: 0,5-1-1,5 respectively for summer, winter and heavy winter clothing respectively.

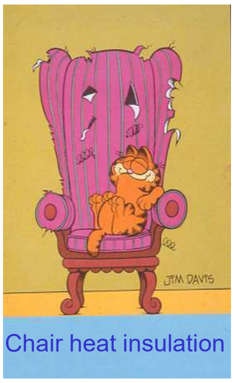
Heat transfer processes

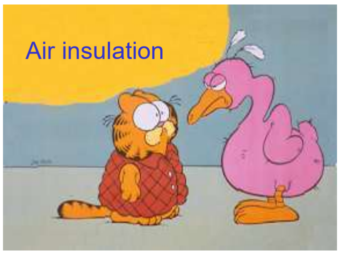


At typical room temperatures during the heating season, 75% of the body's heat loss is from radiation and convection. Only 25% is from evaporation.

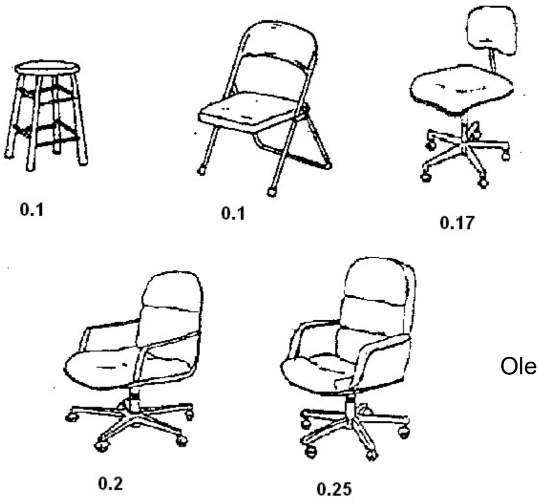
The example at the left is for people who are seated at rest, in a space with modest relative humidity of about 45% to 50%.

Thermal resistance of Clothing



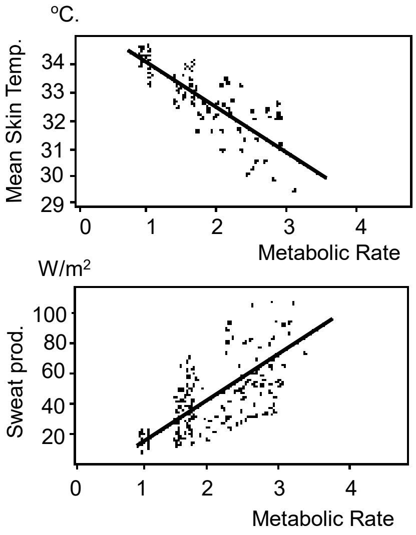


The Influence of the Chair on Thermal Comfort



Olesen, 1996

Thermal comfort conditions



The two conditions for Thermal Comfort:

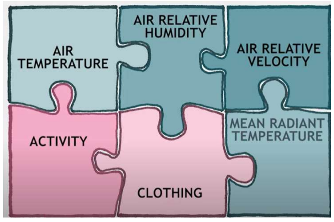
- The incoming thermal power must equal the outgoing thermal power;
- Skin temperature and sweating, for people in a comfort condition, depend only on metabolic rate.

Variables

In conclusion, the determination of the thermal state of the human body contribute:

four physical parameters of the environment:

- Air temperature (t_a)
- Air velocity (v_a)
- Mean radiant temperature (t_{mr})
- Relative humidity (HR)



two parameters related to the subject:

- activity performed, i.e. energy metabolism (M)
- clothing thermal resistance (I_{cl})

All six variables constitute the thermal environment.

Moderate thermal environments

Indoor environments for which the objective of thermal design is to achieve conditions of well-being are called moderate thermal environments.

On the other hand, severe thermal environments are defined as those in which there are very significant deviations from the conditions of well-being, so that the objective of the design becomes that of avoiding the onset of pathologies (such as thermal stress, heat stroke, etc.) in exposed persons.

Global thermal comfort

- Function of the six variables in heat balance .
- They are evaluated as a function of the spatial average values of the four environmental variables.
- Evaluation of possible conditions of local discomfort.

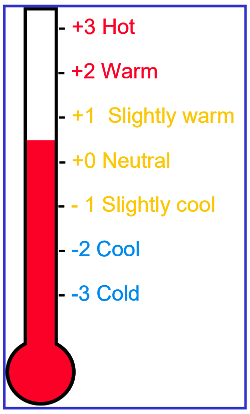
The indices express the average response of a large number of subjects, which means that, for values of the indices corresponding to conditions of well-being, there may still be individuals who feel hot or cold.

Global thermal comfort: PMV - PPD

PMV (Predicted Mean Vote)
by Fanger (1970), Standard UNI EN ISO 7730
Thermal neutrality is characterized by PMV=0.
Average comfortable environments $-0{,}50 < PMV < 0{,}50$

The Standard UNI EN ISO 7730 shows three categories of thermal comfort :
(A) with $-0{,}2<PMV<0{,}2$
(B) with $-0{,}5<PMV<0{,}5$
(C) with $-0{,}7<PMV<0{,}7$

Thermal sensation scale



- +3 Hot
- +2 Warm
- +1 Slightly warm
- +0 Neutral
- - 1 Slightly cool
- -2 Cool
- -3 Cold

The PMV is a function of the six independent heat balance variables and is defined on the thermal sensation scale

Fanger's Equation

The thermal sensation is a function of the thermal load of the body (difference between the internal heat production and the heat losses to the actual environment for a body kept at the comfort values of the mean skin temperature and sweat secretion at the actual activity level)

$$PMV = (0{,}303e^{0{,}036*M} + 0{,}028)*[\,(M\text{-}W) - (C^{*} + R^{*} + E^{*}_{sw} + E^{*}_{d} + C_{res} + E_{res})\,]$$

$$\begin{aligned} PMV = {} & (0{,}303e^{0{,}036*M} + 0{,}028)* \\ & \{\, [(M\text{-}W) - 3{,}05*10^{-3}*[\,5733 - 6.99*(M\text{-}W) - p_a\,] - 0{,}42*[(M\text{-}W) - 58{,}15] \\ & -1{,}7*10^{-5}*M*(5867 - p_a) - 0{,}0014*M*(34 - t_a) \\ & -3{,}96*10^{-8}*f_{cl}*[\,(t_{cl}+273)^4 - (t_{mr}+273)^4\,] - f_{cl}*h_c*(t_{cl}-t_a)\,\} \end{aligned}$$

$h_c = 2{,}38*(t_{cl} - t_a)^{0{,}25}$ if $2{,}38*(t_{cl}-t_a)^{0{,}25} > 12{,}1(v_a)^{0.5}$

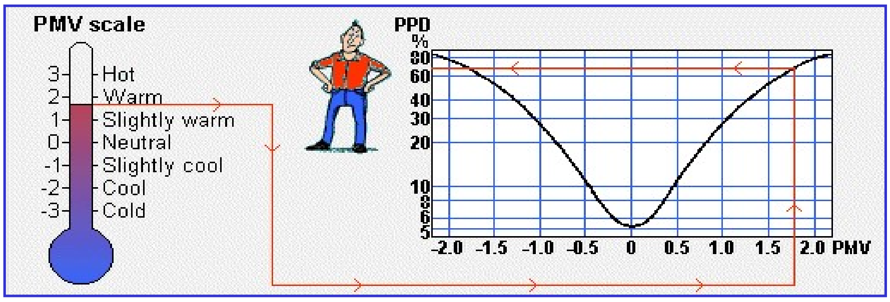
$h_c = 12{,}1(v_a)^{0.5}$ if $2{,}38*(t_{cl}-t_a)^{0{,}25} < 12{,}1(v_a)^{0.5}$

$f_{cl} = 1{,}00+0{,}2*I_{cl}$ if $I_{cl} < 0{,}5$ clo

$f_{cl} = 1{,}05+0{,}1*I_{cl}$ if $I_{cl} > 0{,}5$ clo

M [met] I_{cl} [clo]

PMV and PPD



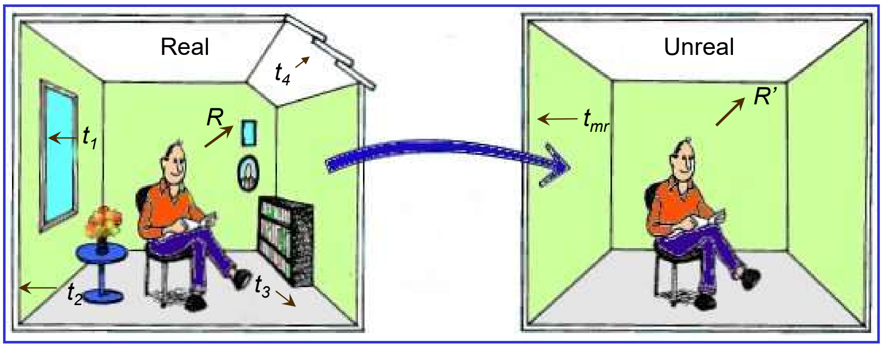
A graphical representation of the experimentally obtained relationship between the PMV and PPD indices is provided in the ISO Standard.

A PMV = 0 corresponds to a PPD = 5% and this is because experimental research has shown that it is impossible to achieve a single environmental condition that satisfies all the people who stay there.

The PMV and PPD indices are used to predict the subjective evaluation of the thermal environment by a group of people.

Mean radiant temperature

- "Imaginary" temperature of a cavity, black and isothermal, in which the person would exchange the same thermal power by radiation as he exchanges in the real (non-uniform) environment
- Varies strongly with position!

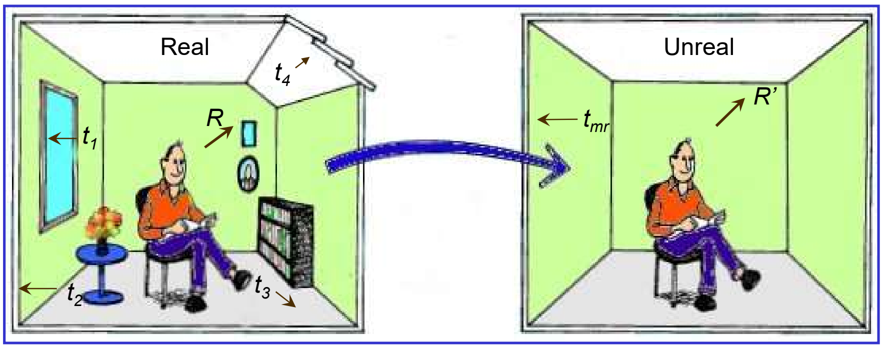


Equal thermal power exchanged by radiation R = R'

Mean radiant temperature

- The average radiant temperature can be calculated from the temperatures, areas, and view factors of the surfaces bordering the room using the relationship:

$$\overline{t_{mr}} = \sum_i t_i F_{p-i}$$



Equal thermal power exchanged by radiation R = R'

Mean radiant temperature

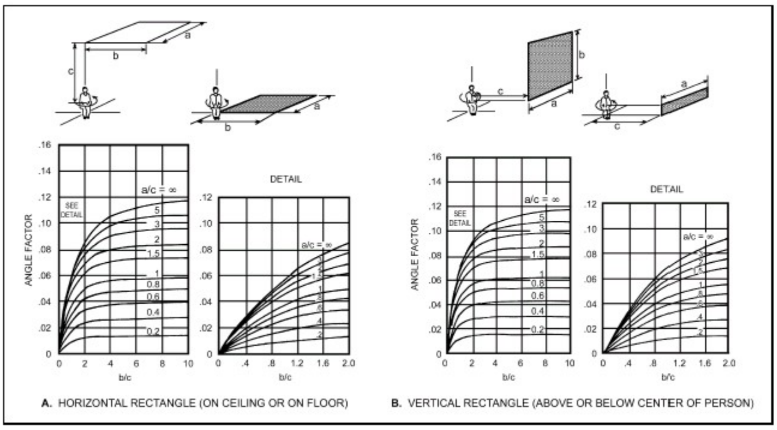
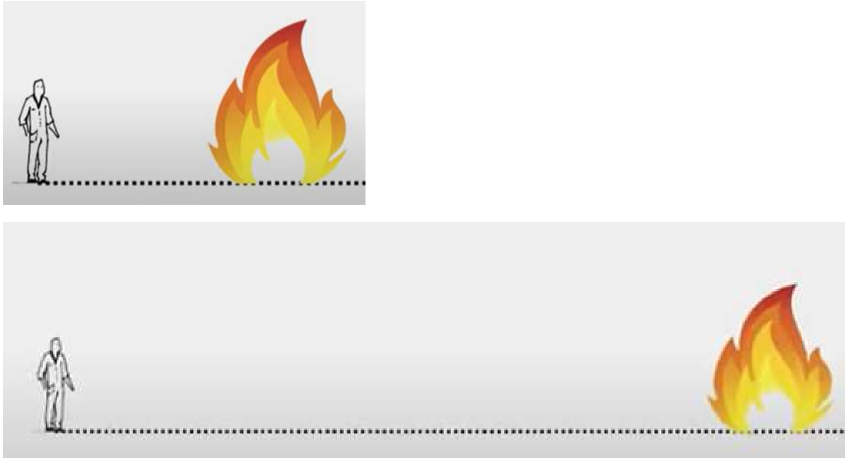


Fig. 3 Mean Value of Angle Factor Between Seated Person and Horizontal or Vertical Rectangle when Person is Rotated Around Vertical Axis
(Fanger 1982)

Mean radiant temperature



Operative temperature

Combination of air temperature and mean radiant temperature

$$\boxed{t_o = \frac{h_r \overline{t_r} + h_c t_a}{h_r + h_c}} \longrightarrow \boxed{t_o' = \frac{\overline{t_r} + t_a}{2}}$$

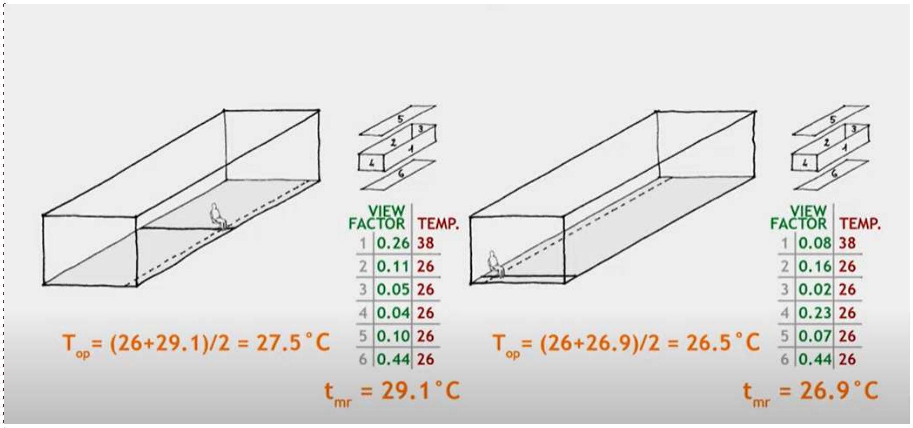
Operative temperature: ASHRAE 55 (2017)

Combination of air temperature and mean radiant temperature

$$t_o = (1 - A) \cdot \overline{t_r} + A \cdot t_a$$

v_r	< 0.2 m/s	da 0.2 a 0.6 m/s	da 0.6 a 1.0 m/s
A	**0.5**	**0.6**	**0.7**

Example



	VIEW FACTOR	TEMP.
1	0.26	38
2	0.11	26
3	0.05	26
4	0.04	26
5	0.10	26
6	0.44	26

$T_{op} = (26+29.1)/2 = 27.5\,^\circ C$

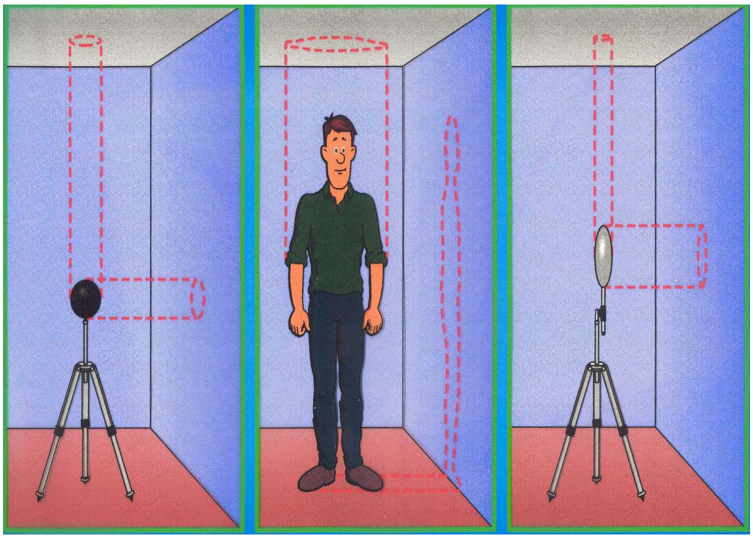
$t_{mr} = 29.1\,^\circ C$

	VIEW FACTOR	TEMP.
1	0.08	38
2	0.16	26
3	0.02	26
4	0.23	26
5	0.07	26
6	0.44	26

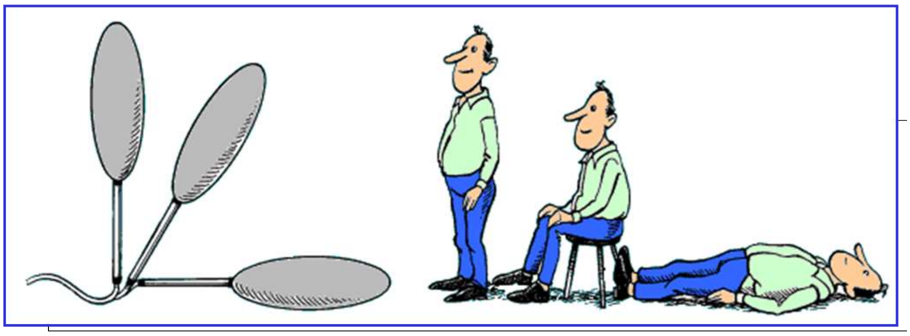
$T_{op} = (26+26.9)/2 = 26.5\,^\circ C$

$t_{mr} = 26.9\,^\circ C$

Operative temperature: measurements



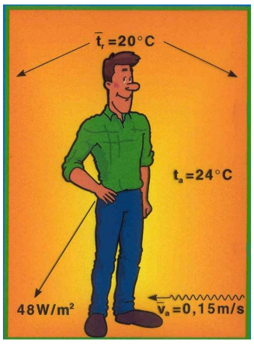
Operative temperature: measurements



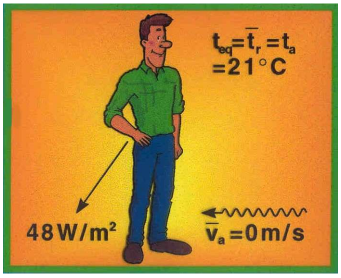
Operational temperature to integrate the effect of t_a and t_{mr}

A sensor (active, heated) for measuring the operating temperature should have the same exchange characteristics as the person in different positions (standing, sitting, lying).

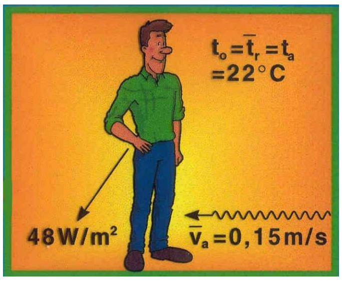
Operative temperature and Equivalent temperature



Equivalent Temperature



Operative Temperature



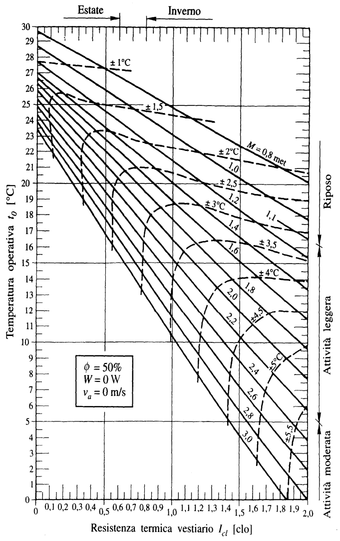
Temperature and Comfort

1,7 CLO
2,5 MET
RH=50%
t_o=6ºC.

0,8 CLO
2,2 MET
RH=50%
t_o=18ºC.

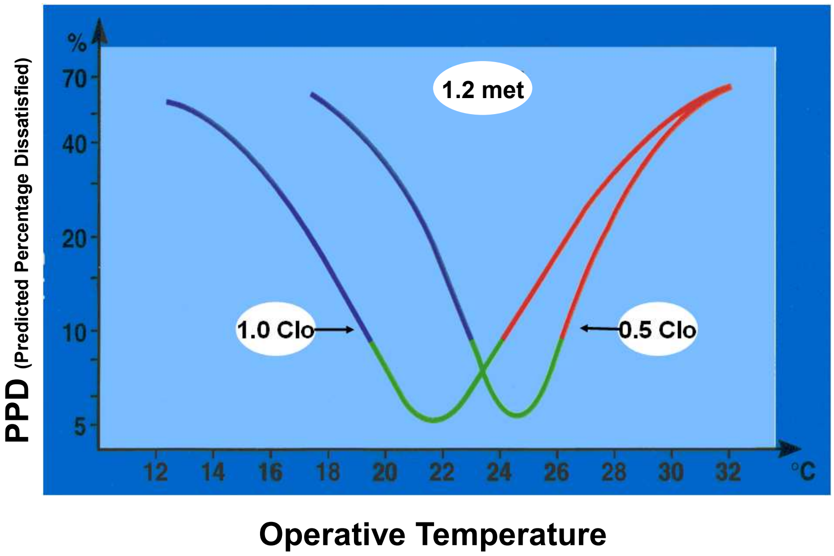
0,5 CLO
1,2 MET
RH=50%
t_o=24,5ºC.

Diagrams

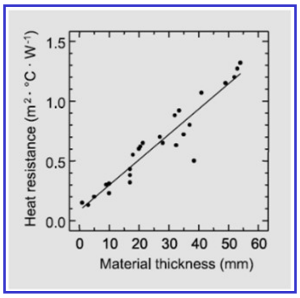


1. The continuous curves represent the conditions of thermal neutrality (PMV=0)
2. Dashed curves represent the acceptable deviation of the operative T (PMV remains in the range -0.50<PMV<0.50)

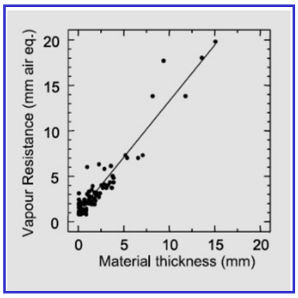
Diagrams: effect of clothing



Clothing

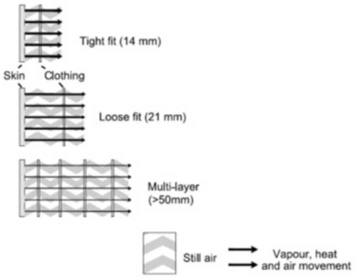


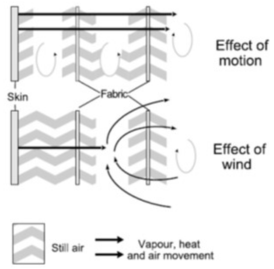
- ✓ Relationship between thermal resistance and thickness of garment material (Havenith and Wammes, in Lotens, 1993).



- ✓ Relationship between vapor resistance and clothing material thickness (Havenith 1999, Lotens 1993).

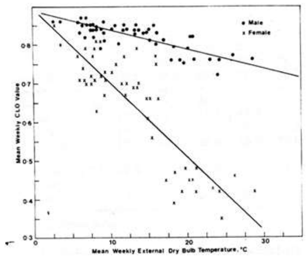
Clothing



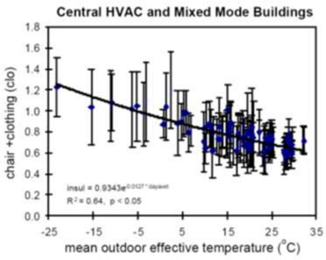


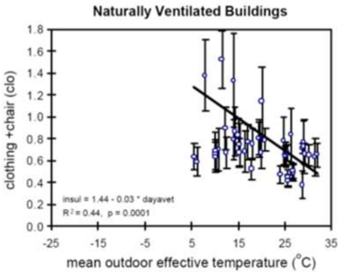
- ✓ Generally, clothing is made up of several garments and, therefore, of several layers of different fabrics between which layers of air are interposed; when people move, this air, together with that which enters through the openings of the garments, such as cuffs and collars, enters into movement determining an effect, known as the "pumping effect" (Havenith et al, 1990), which can also be determined by high air velocity values, due for example to the presence of wind, which can determine a compression of the fabric layers, reducing their thickness with a consequent variation of both thermal insulation and evaporative resistance.

Clothing and Weather

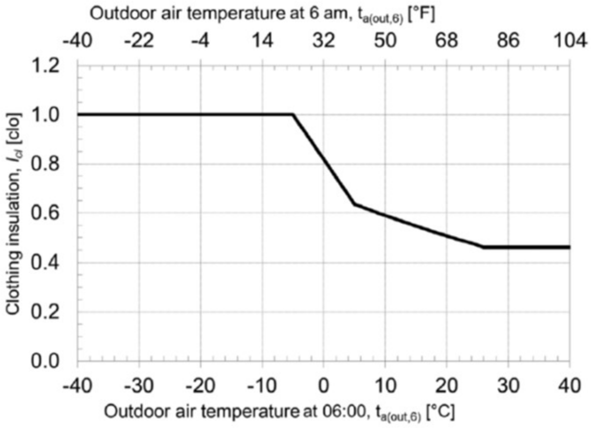


← Clothing resistance as a function of weekly average outdoor temperature [Fishman D.S., Pimbert S.L. 1982].





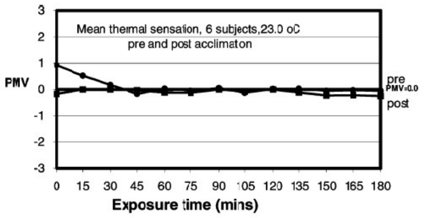
Clothing and Weather



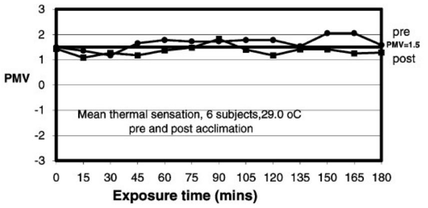
ASHRAE 55 (2017)

Representative clothing insulation I_{cl} as a function of outdoor air temperature at 06:00 a.m.

Acclimation

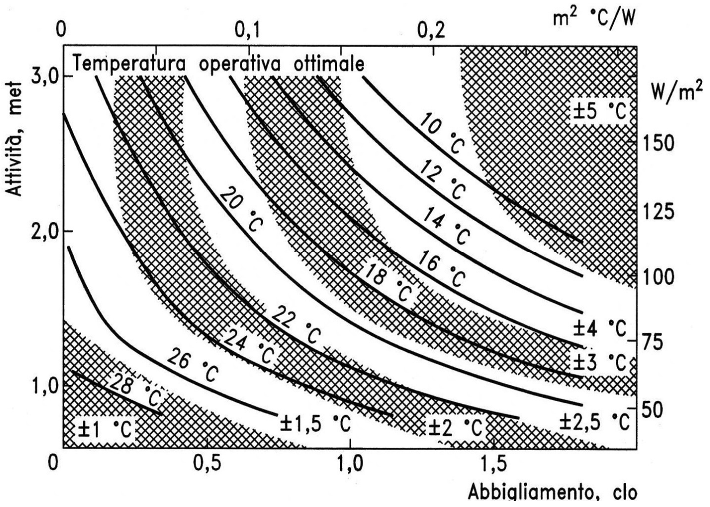


✓ PMV before and after acclimation in climatic chamber (PMV=0) [Parsons K.C. 2002].



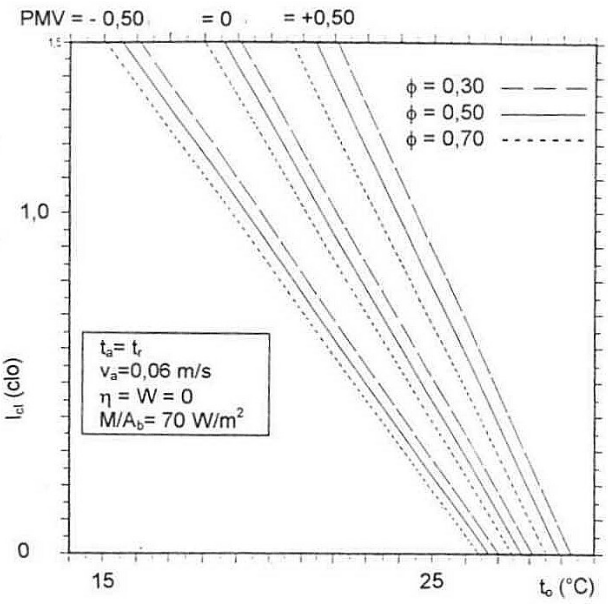
✓ PMV before and after acclimation in climatic chamber (PMV=1.5) [Parsons K.C. 2002].

Diagram: M vs I_{cl}



Operative temperature curves of constant thermal neutrality as a function of M and I_{cl} for HR = 0.50, W = 0 e v_a = 0.

Diagram: effect of I_{cl} and HR



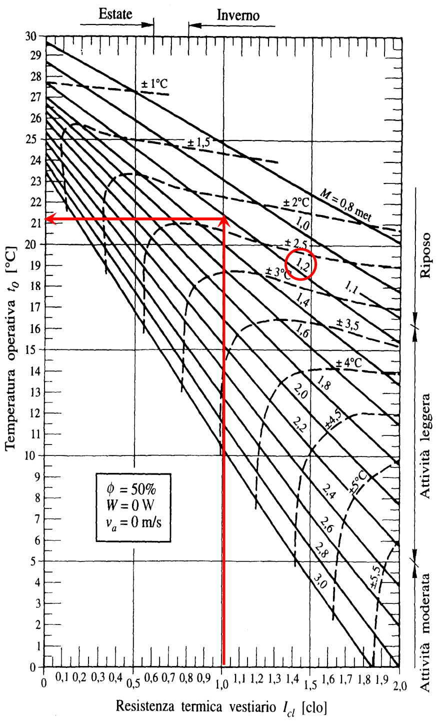
Examples – Winter

Determining the operative temperature of an office in the winter season

Subject parameters:
M = 1,2 met and I_{CL} = 1 clo

Environmental parameters:
HR = 50 % and v_a = 0 m/s

t_o = 21,5 °C ± 2 °C
(PMV = 0 ± 0,5)

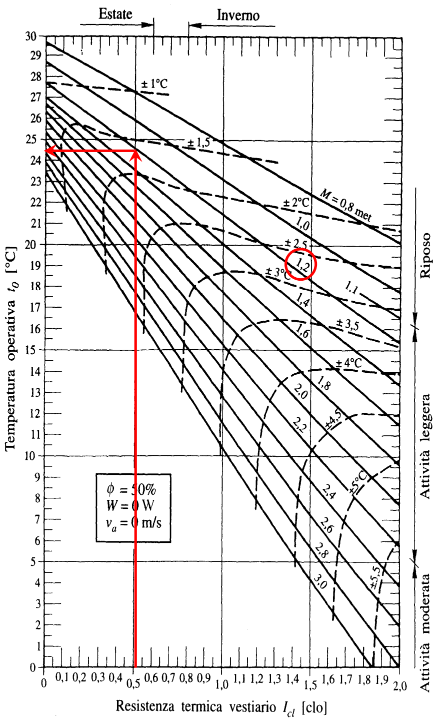


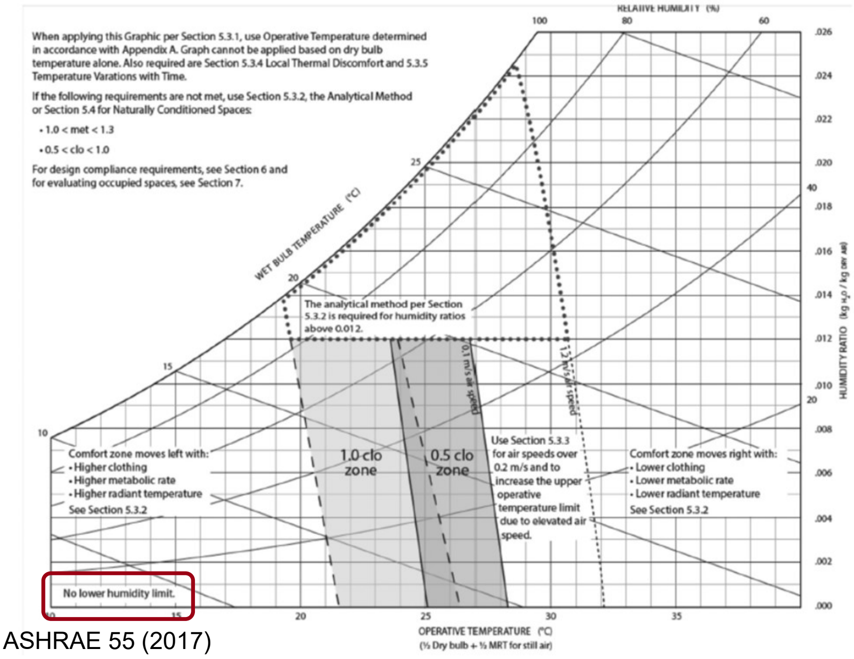
Examples – Summer

Determining the operative temperature of an office in the cooling season

Subject parameters:
M = 1.2 met e I_{CL} = 0.5 clo

Environmental parameters:
t_o = 24.5 °C ± 1,5 °C





When applying this Graphic per Section 5.3.1, use Operative Temperature determined in accordance with Appendix A. Graph cannot be applied based on dry bulb temperature alone. Also required are Section 5.3.4 Local Thermal Discomfort and 5.3.5 Temperature Varations with Time.

If the following requirements are not met, use Section 5.3.2, the Analytical Method or Section 5.4 for Naturally Conditioned Spaces:

- 1.0 < met < 1.3
- 0.5 < clo < 1.0

For design compliance requirements, see Section 6 and for evaluating occupied spaces, see Section 7.

The analytical method per Section 5.3.2 is required for humidity ratios above 0.012.

Comfort zone moves left with:
- Higher clothing
- Higher metabolic rate
- Higher radiant temperature

See Section 5.3.2

Use Section 5.3.3 for air speeds over 0.2 m/s and to increase the upper operative temperature limit due to elevated air speed.

Comfort zone moves right with:
- Lower clothing
- Lower metabolic rate
- Lower radiant temperature

See Section 5.3.2

No lower humidity limit.

ASHRAE 55 (2017)

Local Discomfort

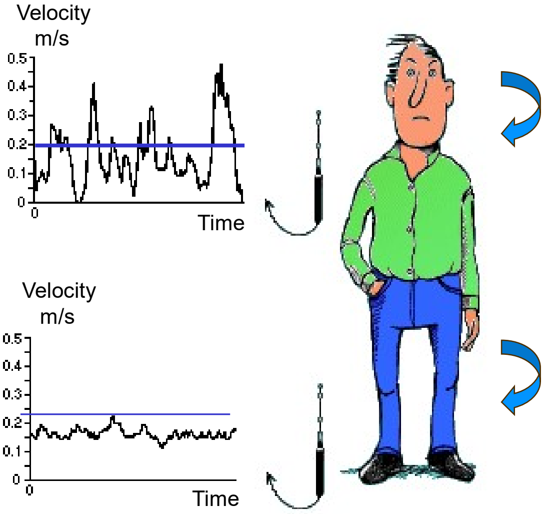
Draft

Asymmetric radiant fields.

Vertical temperature difference

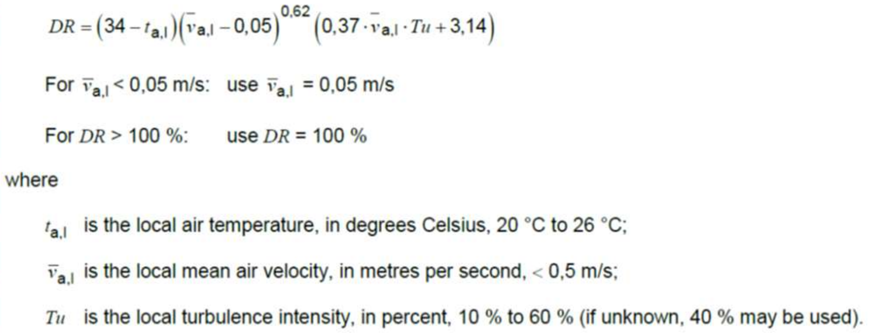
Floor temperature.

Draft



- ✓ It is the most common cause of complaint in the indoor environment.
- ✓ The feeling is of excessive heat loss.
- ✓ Dispersion from average air velocity, temperature, and turbulence.
- ✓ High turbulence causes marked discomfort.

Draft



$$DR = (34 - t_{a,l})(\bar{v}_{a,l} - 0{,}05)^{0{,}62}(0{,}37 \cdot \bar{v}_{a,l} \cdot Tu + 3{,}14)$$

For $\bar{v}_{a,l} < 0{,}05$ m/s: use $\bar{v}_{a,l} = 0{,}05$ m/s

For $DR > 100$ %: use $DR = 100$ %

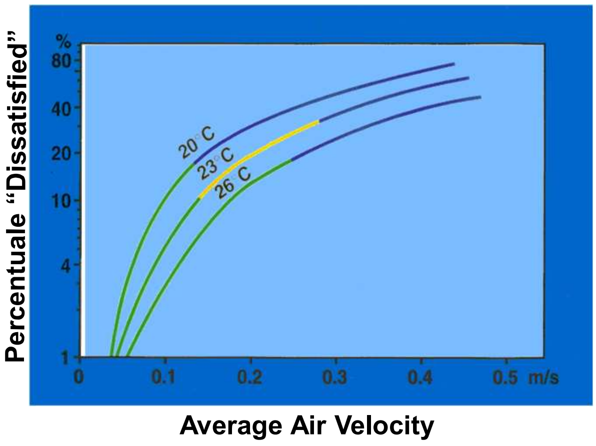
where

$t_{a,l}$ is the local air temperature, in degrees Celsius, 20 °C to 26 °C;

$\bar{v}_{a,l}$ is the local mean air velocity, in metres per second, $<$ 0,5 m/s;

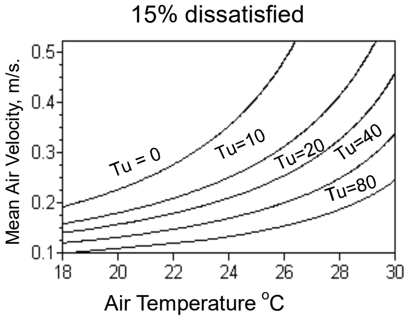
Tu is the local turbulence intensity, in percent, 10 % to 60 % (if unknown, 40 % may be used).

Draft

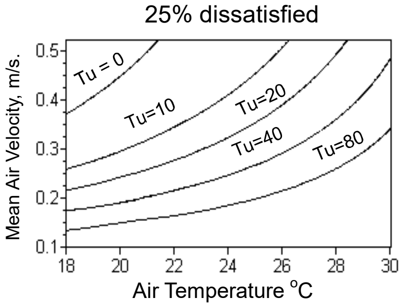


- The sensation of draft depends on air temperature.
- The percentage of dissatisfied increases as the temperature decreases.

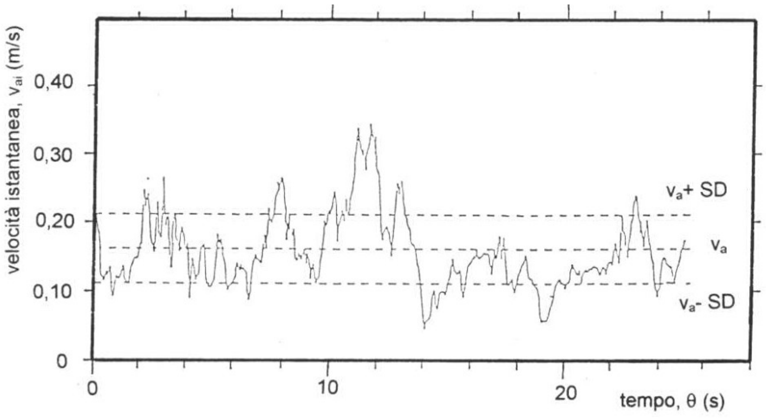
Draft



- Velocity fluctuations are described by the Turbulence Intensity Index (Tu).
- Index considered in the UNI EN ISO 7730.



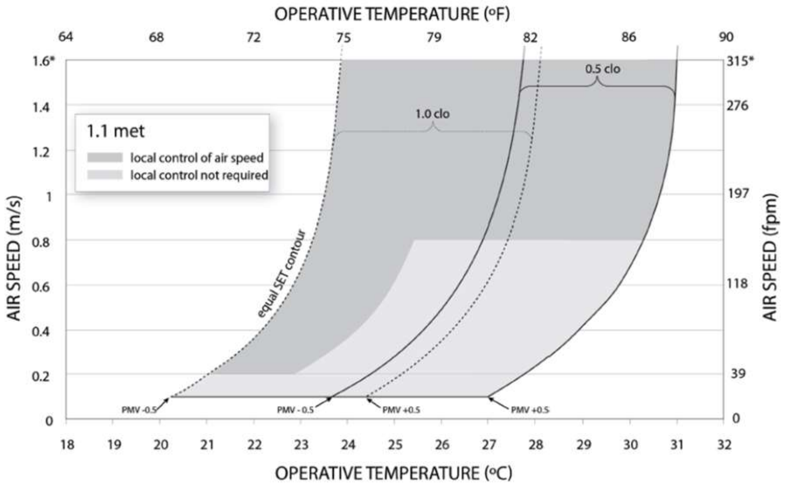
Turbulence



Tu = 100 * SD / v_a

SD is the standard deviation

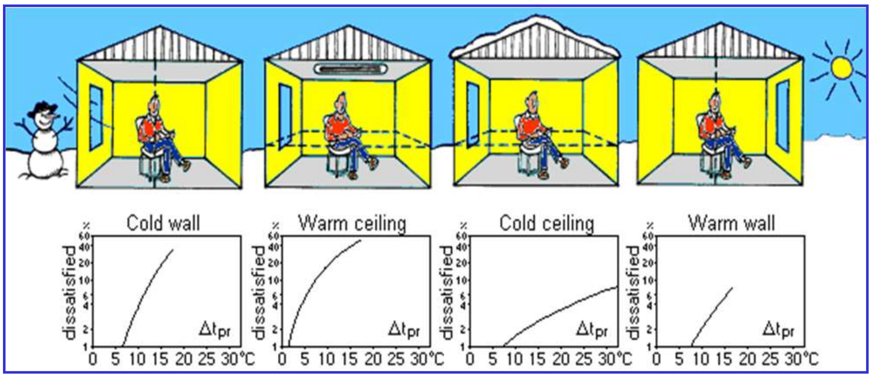
Air velocity



* There is no upper limit to air speed when occupants have local control.

ASHRAE 55 (2017)

Radiant temperature asymmetry



- Radiant temperature asymmetry is considered uncomfortable.
- The most pronounced comfort is the one related to warm ceilings and cold walls.

Radiant temperature asymmetry

a) Warm ceiling

$$PD = \frac{100}{1 + \exp(2{,}84 - 0{,}174 \cdot \Delta t_{pr})} - 5{,}5$$

$\Delta t_{pr} < 23$ °C

b) Cool wall

$$PD = \frac{100}{1 + \exp(6{,}61 - 0{,}345 \cdot \Delta t_{pr})}$$

$\Delta t_{pr} < 15$ °C

c) Cool ceiling

$$PD = \frac{100}{1 + \exp(9{,}93 - 0{,}50 \cdot \Delta t_{pr})}$$

$\Delta t_{pr} < 15$ °C

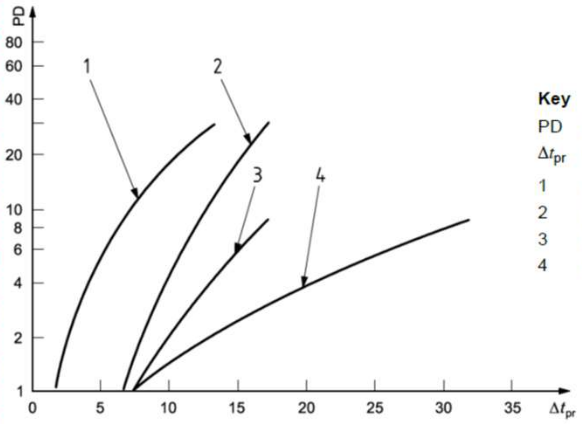
d) Warm wall

$$PD = \frac{100}{1 + \exp(3{,}72 - 0{,}052 \cdot \Delta t_{pr})} - 3{,}5$$

$\Delta t_{pr} < 35$ °C

Radiant asymmetry (Δt_{pr}) can also cause discomfort.

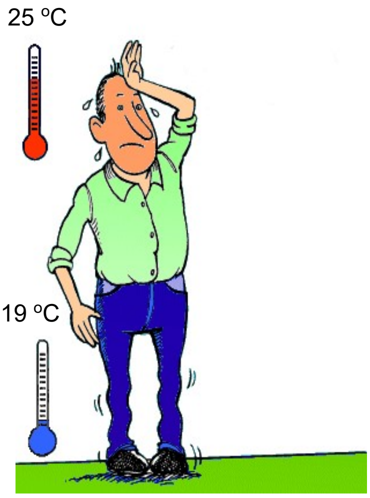
Radiant temperature asymmetry

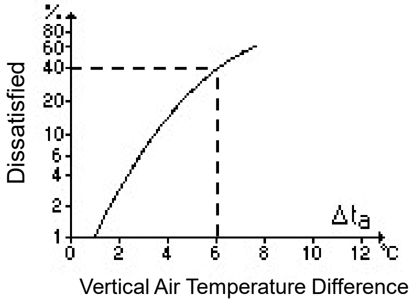


Key

PD	percentage dissatisfied, %
Δt_{pr}	radiant temperature asymmetry, °C
1	Warm ceiling.
2	Cool wall.
3	Cool ceiling.
4	Warm wall.

Vertical air temperature difference



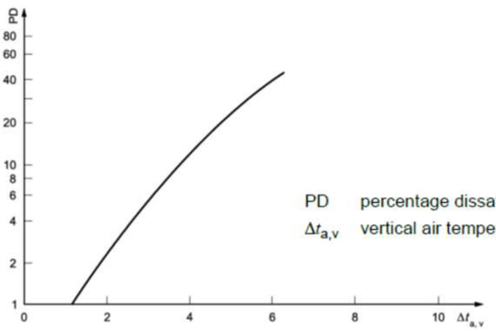


- Vertical air temperature difference is "the difference between values at head and feet level".

Vertical air temperature difference

$$PD = \frac{100}{1 + \exp(5,76 - 0,856 \cdot \Delta t_{a,v})} \qquad (7)$$

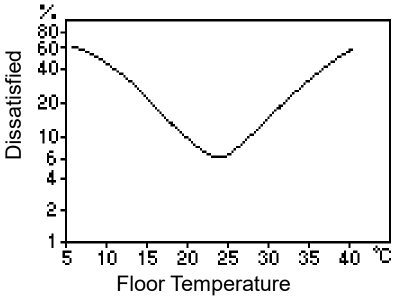
Equation (7), derived from the original data using logistic regression analysis, should only be used at $\Delta t_{a,v} < 8$ °C.



PD percentage dissatisfied, %

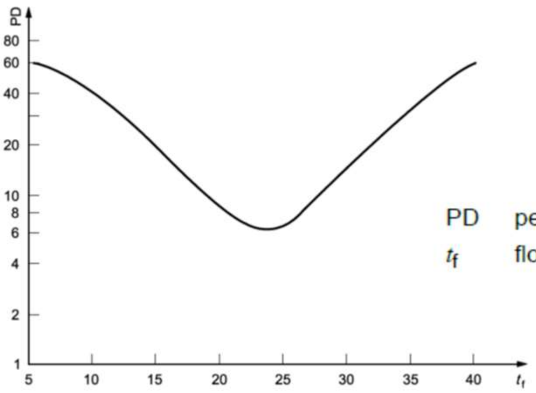
$\Delta t_{a,v}$ vertical air temperature difference between head and feet, °C

Warm and cool floor



- Vertical air temperature difference is "the difference between values at ankle and neck level".

Warm and cool floor



PD percentage dissatisfied, %

t_f floor temperature, °C

$$PD = 100 - 94 \cdot \exp(-1{,}387 + 0{,}118 \cdot t_f - 0{,}002\,5 \cdot t_f^2)$$

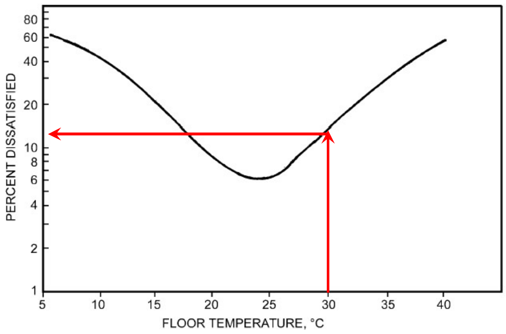
Examples – Local Discomfort

Radiant floor

Subject parameters:
M = 1.2 met e I_{CL} = 1 clo

Environmental parameters:
$t_a = t_{m,r}$ = 21 °C, φ = 50 %
v_a = 0,1 m/s

PMV = -0.1 and PPD = 5.2 %



t_{FLOOR} = 30 °C → PPD_{LOC} = 12 %

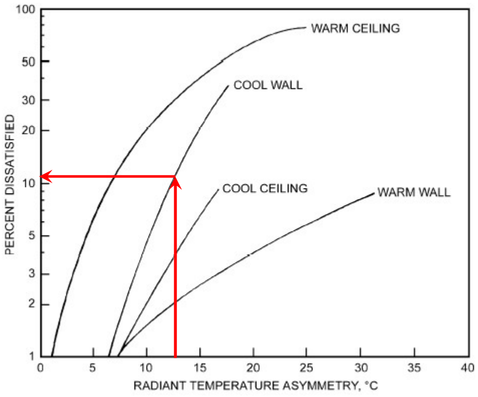
Examples – Local Discomfort

Wall radiant systems

Subject parameters :
M = 1.2 met e I_{CL} = 0.5 clo

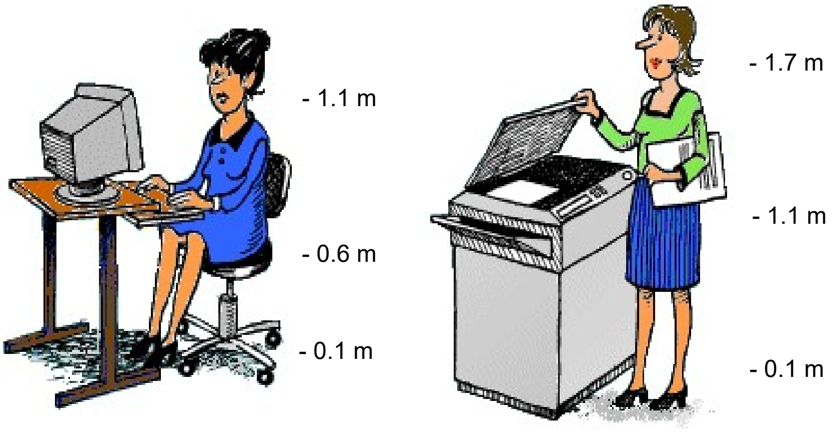
Environmental parameters :
$t_a = t_{mr}$ = 26 °C, φ = 50 %
v_a = 0.2 m/s

PMV = 0.2 e PPD = 5.8 %



Δt_{Rad} = 13 °C → PPD_{LOC} = 11 %

Measurements in Offices



Categories of thermal environment

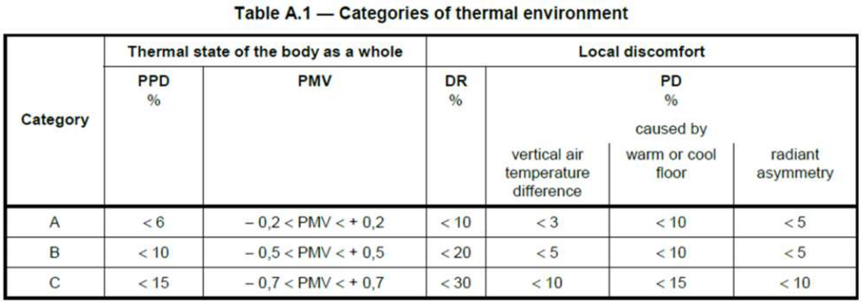
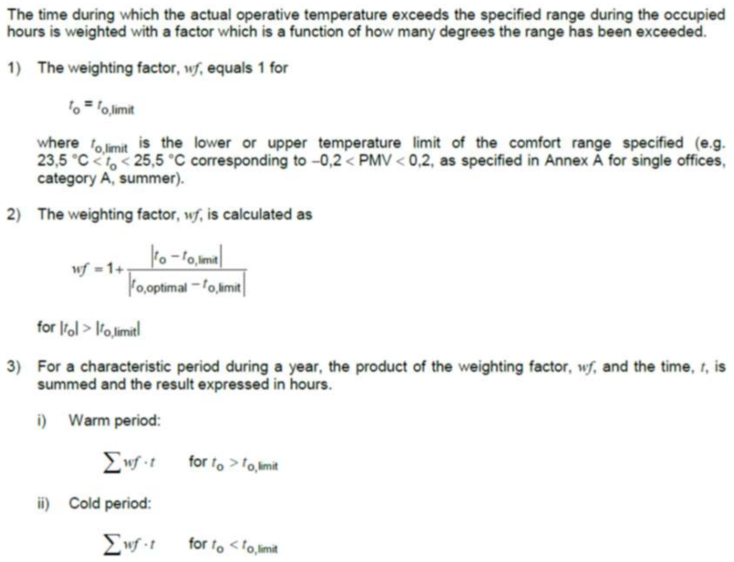


Table A.1 — Categories of thermal environment

Category	Thermal state of the body as a whole		Local discomfort			
	PPD %	PMV	DR %	PD % caused by		
				vertical air temperature difference	warm or cool 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

Long-term evaluation of the general thermal comfort conditions



The time during which the actual operative temperature exceeds the specified range during the occupied hours is weighted with a factor which is a function of how many degrees the range has been exceeded.

1) The weighting factor, *wf*, equals 1 for

$$t_o = t_{o,\text{limit}}$$

where $t_{o,\text{limit}}$ is the lower or upper temperature limit of the comfort range specified (e.g. 23,5 °C < t_o < 25,5 °C corresponding to –0,2 < PMV < 0,2, as specified in Annex A for single offices, category A, summer).

2) The weighting factor, *wf*, is calculated as

$$wf = 1 + \frac{|t_o - t_{o,\text{limit}}|}{|t_{o,\text{optimal}} - t_{o,\text{limit}}|}$$

for $|t_o| > |t_{o,\text{limit}}|$

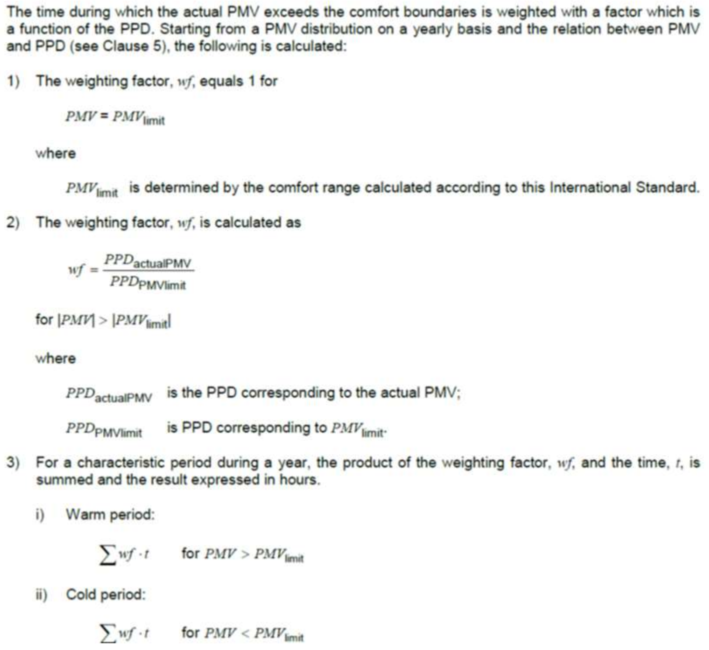
3) For a characteristic period during a year, the product of the weighting factor, *wf*, and the time, *t*, is summed and the result expressed in hours.

   i) Warm period:

$$\sum wf \cdot t \qquad \text{for } t_o > t_{o,\text{limit}}$$

   ii) Cold period:

$$\sum wf \cdot t \qquad \text{for } t_o < t_{o,\text{limit}}$$



The time during which the actual PMV exceeds the comfort boundaries is weighted with a factor which is a function of the PPD. Starting from a PMV distribution on a yearly basis and the relation between PMV and PPD (see Clause 5), the following is calculated:

1) The weighting factor, *wf*, equals 1 for

$$PMV = PMV_{\text{limit}}$$

where

PMV_{limit} is determined by the comfort range calculated according to this International Standard.

2) The weighting factor, *wf*, is calculated as

$$wf = \frac{PPD_{\text{actualPMV}}}{PPD_{\text{PMVlimit}}}$$

for $|PMV| > |PMV_{\text{limit}}|$

where

$PPD_{\text{actualPMV}}$ is the PPD corresponding to the actual PMV;

PPD_{PMVlimit} is PPD corresponding to PMV_{limit}.

3) For a characteristic period during a year, the product of the weighting factor, *wf*, and the time, *t*, is summed and the result expressed in hours.

   i) Warm period:

$$\sum wf \cdot t \qquad \text{for } PMV > PMV_{\text{limit}}$$

   ii) Cold period:

$$\sum wf \cdot t \qquad \text{for } PMV < PMV_{\text{limit}}$$

ASHRAE-55 (2017)

Solar radiation in highly glazed environments:
the problem of comfort

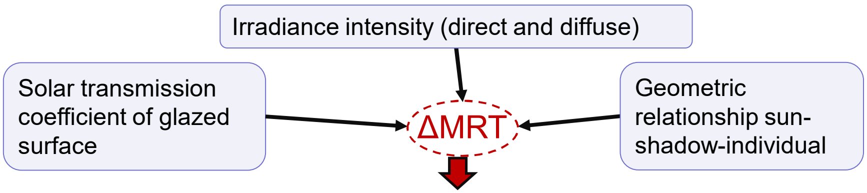
Direct solar radiation: not only an energy problem for the plant, but also for the thermal comfort in summer, measured through the PMV (Predicted Mean Vote)

Development of a new procedure for the objective assessment of individuals' discomfort

Recent update of standards related to comfort state calculations (ASHRAE 55 2017), including introduction of a mean radiant temperature correction

ΔMRT

ASHRAE-55 (2017)



Irradiance intensity (direct and diffuse)

Solar transmission coefficient of glazed surface

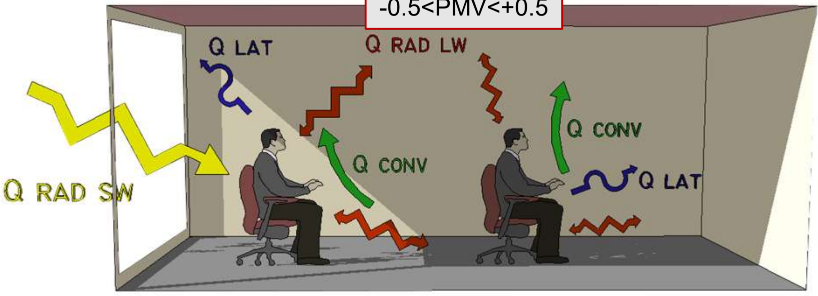
ΔMRT

Geometric relationship sun-shadow-individual

$$PMV = f(t_a; t_{mrt}; M; I_{cl}; v_a; UR)$$

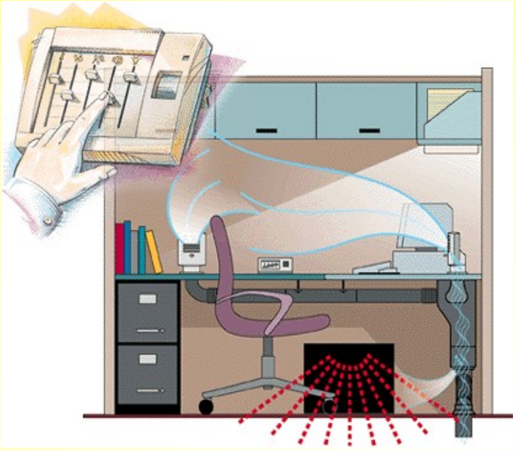
Comfort

-0.5<PMV<+0.5

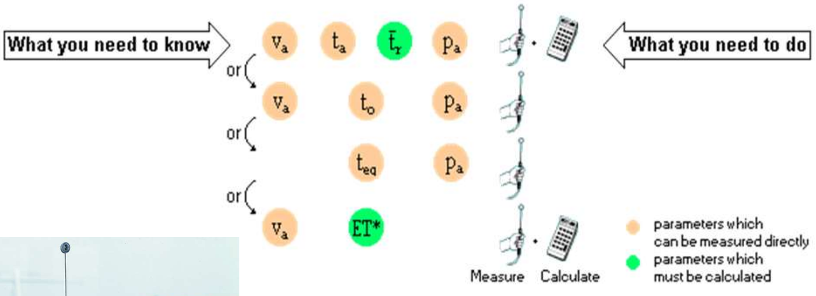


Satisfied?!

Personal Environment Control (PEC)



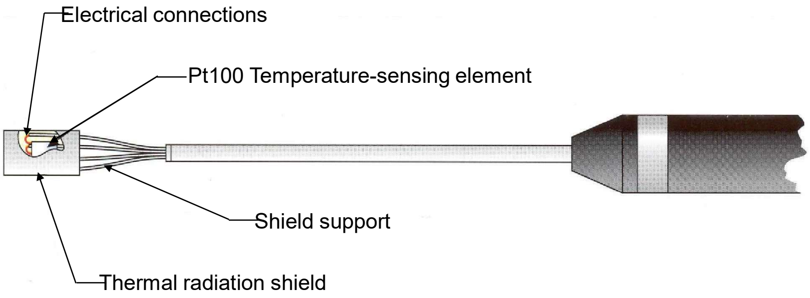
Measurements



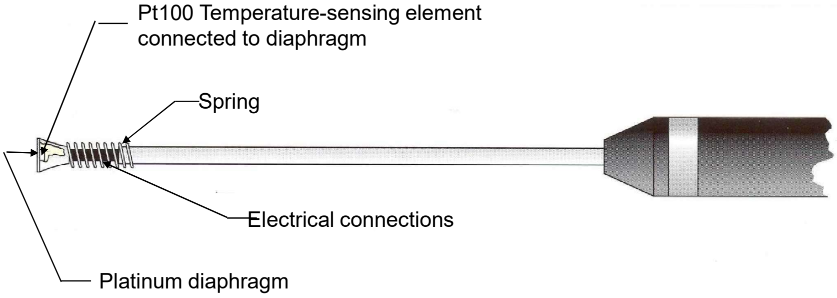
Measurements

Equipment

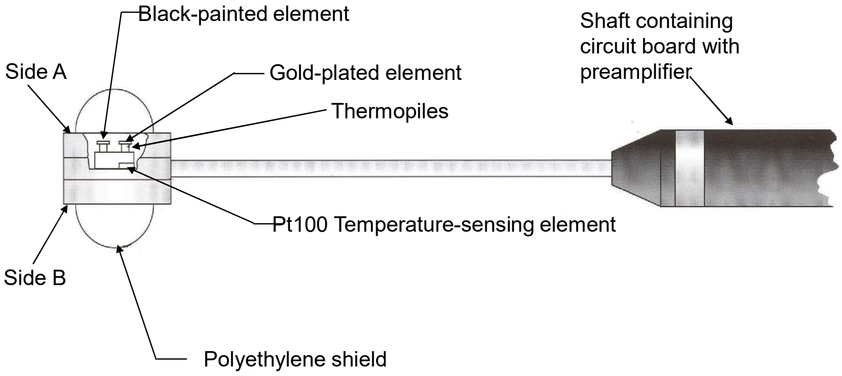
Air Temperature Transducer



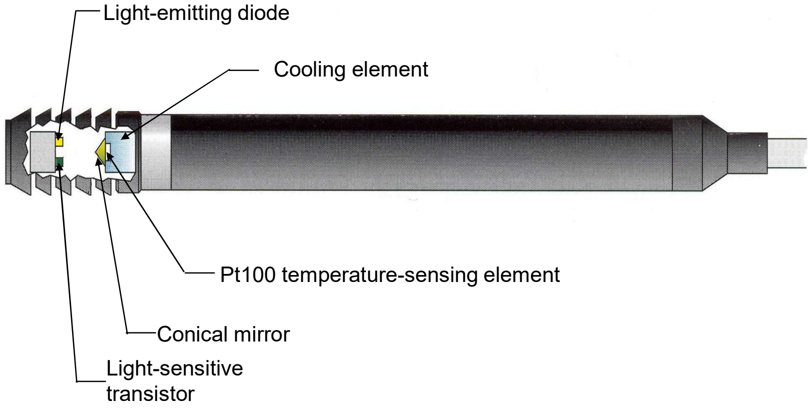
Surface Temperature Transducer



Radiant Temperature Asymmetry Transducer



Humidity Transducer



Light-emitting diode

Cooling element

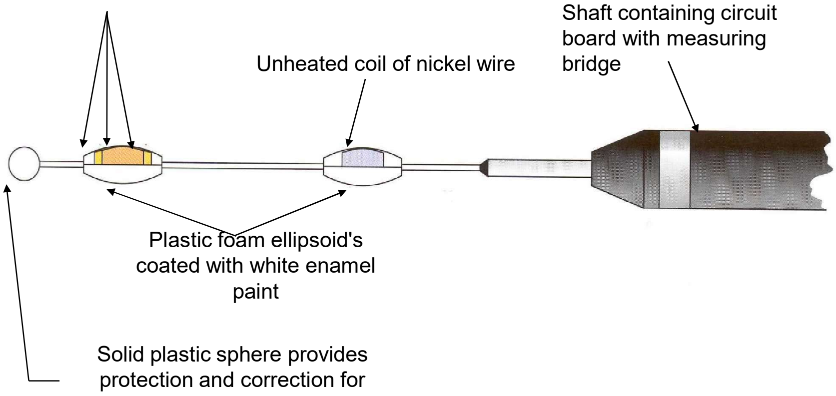
Pt100 temperature-sensing element

Conical mirror

Light-sensitive transistor

Air Velocity Transducer

Three heated coils. For improved frequency response, temperature and heat loss are only measured on the centre coil



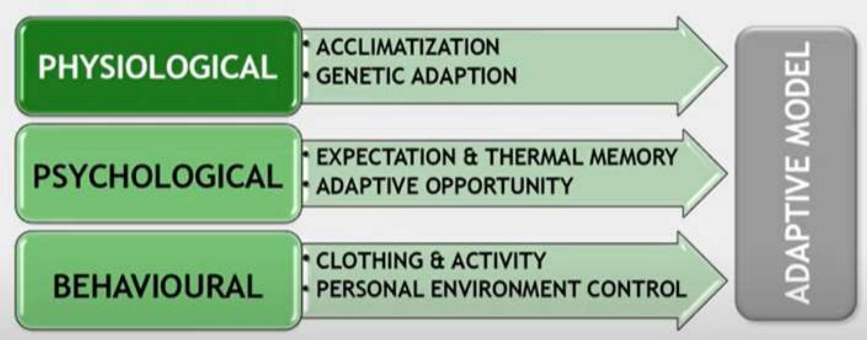
Unheated coil of nickel wire

Shaft containing circuit board with measuring bridge

Plastic foam ellipsoid's coated with white enamel paint

Solid plastic sphere provides protection and correction for directional sensitivity

Adaptive Comfort
(Naturally Ventilated Buildings)



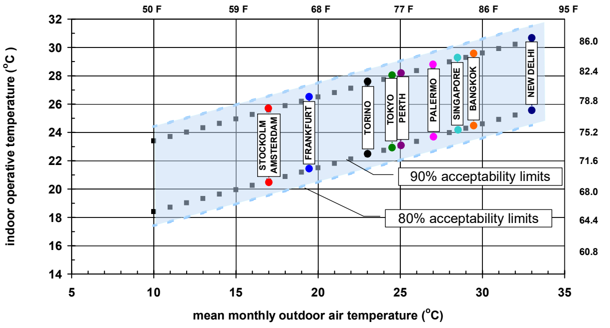
PHYSIOLOGICAL
- ACCLIMATIZATION
- GENETIC ADAPTION

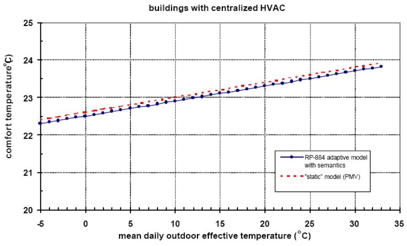
PSYCHOLOGICAL
- EXPECTATION & THERMAL MEMORY
- ADAPTIVE OPPORTUNITY

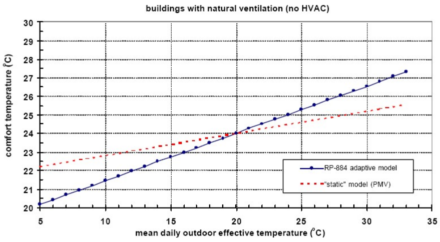
BEHAVIOURAL
- CLOTHING & ACTIVITY
- PERSONAL ENVIRONMENT CONTROL

ADAPTIVE MODEL

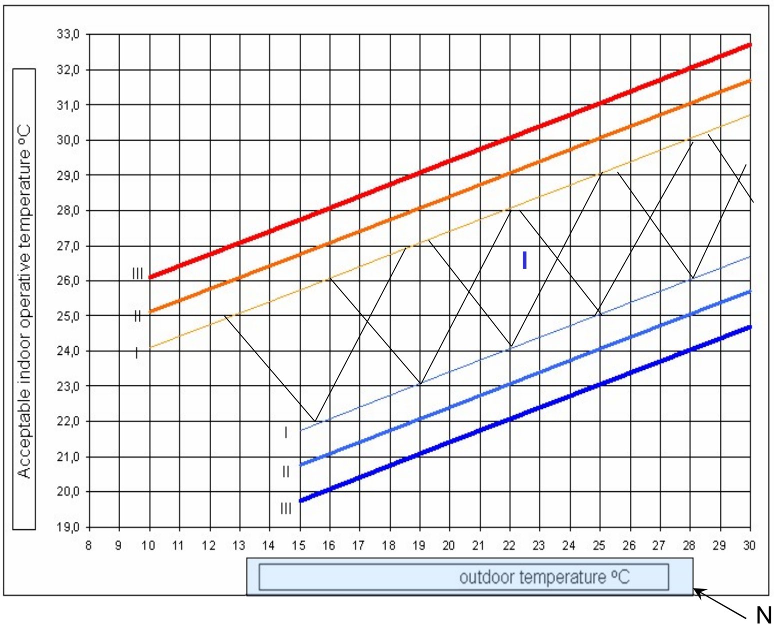
Adaptive Comfort
(Naturally Ventilated Buildings)







Naturally Ventilated Buildings



NB

Reference Temperature

$\Theta_{rm} = (1-\alpha).\{\Theta_{ed-1} + \alpha.\ \Theta_{ed-2} + \alpha^2\ \Theta_{ed-3}.....\}$ (1)

This equation can be simplified to

$\Theta_{rm} = (1-\alpha)\Theta_{ed-1} + \alpha.\ \Theta_{rm-1}$ (2)

Where

Θ_{rm} = Running mean temperature for today

Θ_{rm-1} = Running mean temperature for previous day

Θ_{ed-1} is the daily mean external temperature for the previous day

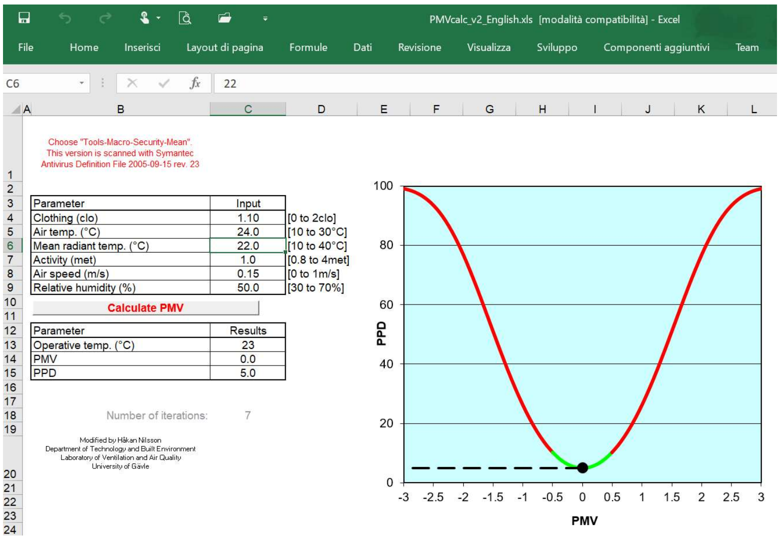
Θ_{ed-2} is the daily mean external temperature for the day before and so on.

α is a constant between 0 and 1. Recommended to use 0,8

The following approximate equation can be used where records of daily mean external temperature are not available:

$\Theta_{rm} = (\Theta_{ed-1} + 0{,}8\ \Theta_{ed-2} + 0{,}6\ \Theta_{ed-3} + 0{,}5\ \Theta_{ed-4} + 0{,}4\ \Theta_{ed-5} + 0{,}3\ \Theta_{ed-6} + 0{,}2\ \Theta_{ed-7})/3{,}8$ (3)

PMVCalc



Choose "Tools-Macro-Security-Mean".
This version is scanned with Symantec
Antivirus Definition File 2005-09-15 rev. 23

Parameter	Input	
Clothing (clo)	1.10	[0 to 2clo]
Air temp. (°C)	24.0	[10 to 30°C]
Mean radiant temp. (°C)	22.0	[10 to 40°C]
Activity (met)	1.0	[0.8 to 4met]
Air speed (m/s)	0.15	[0 to 1m/s]
Relative humidity (%)	50.0	[30 to 70%]

Parameter	Results
Operative temp. (°C)	23
PMV	0.0
PPD	5.0

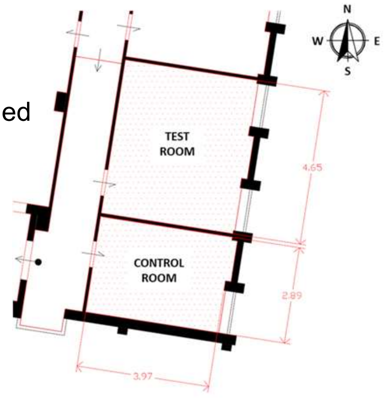
Number of iterations: 7

Modified by Håkan Nilsson
Department of Technology and Built Environment
Laboratory of Ventilation and Air Quality
University of Gävle

The CORE-CARE laboratory

- The test room is the climatic chamber where tests are carried out:
  - Surface: 17.66 m^2
  - Height: 2.79 m
  - Glazed surface: two windows, 1.7 m^2 each
  - East wall facing outside

- In the control room all systems are installed



The CORE-CARE laboratory

Heating and cooling system

Radiant panels in floor, ceiling and each wall operating in heating or cooling mode independently

Ventilation system

VAV system with integration in heating and cooling

Monitoring system

- Four surface temperature sensors for each wall, ceiling, floor;
- Four air temperature sensors
- RH sensor
- CO2 sensor

The CORE-CARE laboratory

Water production systems:

Hot tank with heating through three **electrical resistances** inside the boiler

Cold water production with a **chiller system**

The CORE-CARE laboratory

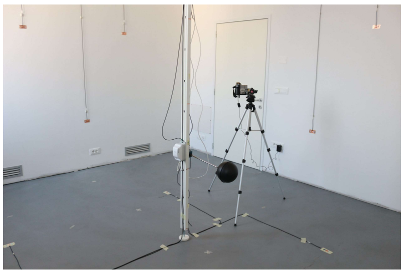
- **Embedded** radiant floor system
- **Radiant panels** in all other chamber surfaces

The CORE-CARE laboratory

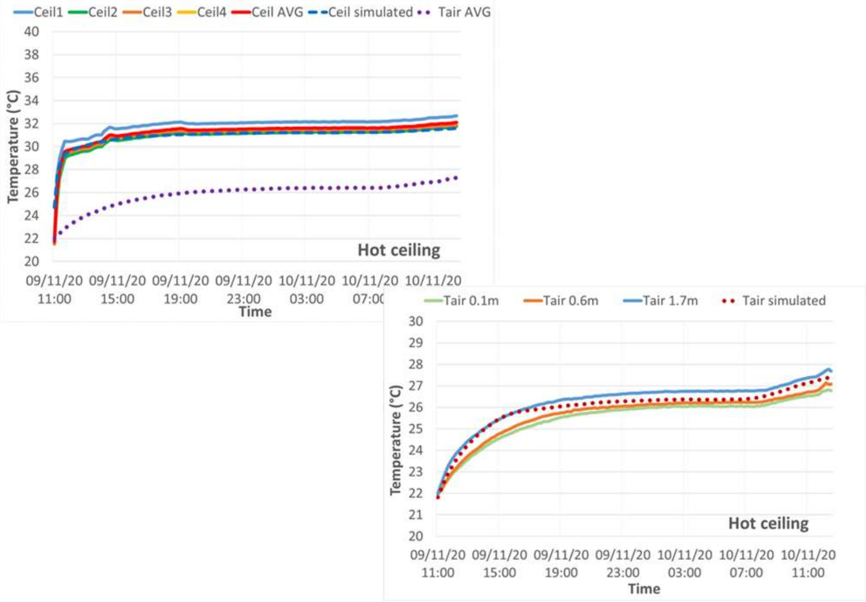
- Ventilation provided by a **VAV system**:
  - Renewal flow rate between 80 and 250 m^3/h
  - Heat recovery through cross-flow heat exchanger
  - Integration in heating season
    - Hot water battery supplied by hot boiler
  - Integration in cooling season
    - Cold water battery supplied by cold boiler
    - Dehumidification provided by a refrigeration cycle on board of the ventilation machine
  - Possibility of free cooling

The CORE-CARE laboratory

- Surface temperatures, air temperature, mean radiant temperature, relative humidity and CO_2 concentration detection:
  - 24 surface temperature sensors for opaque surfaces (4 for each surface)
  - 2 surface temperature sensors for glazed surfaces (1 for each window)
  - 4 air temperature sensors (in the column, at 0.1 m, 0.6 m, 1.1 m, 1.7 m height)
  - RH and CO_2 sensors at 0.6 m height
  - Globothermometer at 0.6 m height



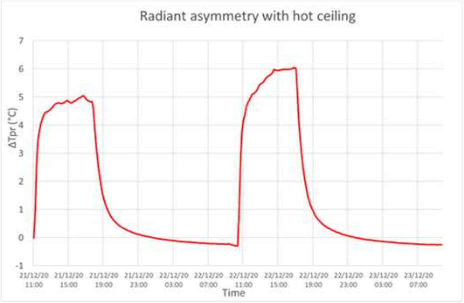
The CORE-CARE laboratory



The CORE-CARE laboratory

- Plane radiant temperature difference ($\Delta T_{p,r}$) profile along the duration of the tests

- At 38°C supply temperature, the $\Delta T_{p,r}$ is acceptable, but at 42°C supply temperature, the limit is exceeded, and a condition of radiant asymmetry discomfort may occur according to EN ISO 7730



Supply water temperature	Average ceiling temperature	$\Delta T_{p,r}$
38°C	31.7°C	4.74°C
42°C	34.7°C	5.63°C