Thermal Comfort

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TTP 289A

What Is Thermal Comfort?

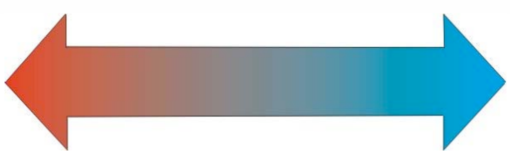
Definition

- That condition of mind which expresses satisfaction with the thermal environment.

ISO 7730

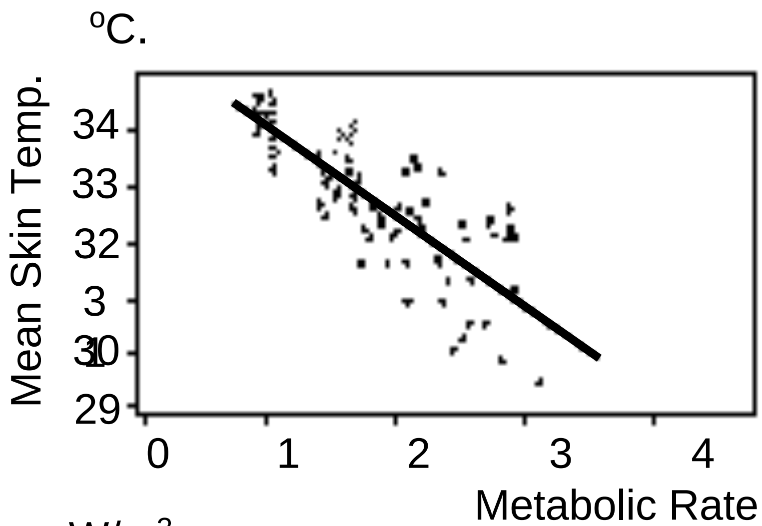
Body Temperature

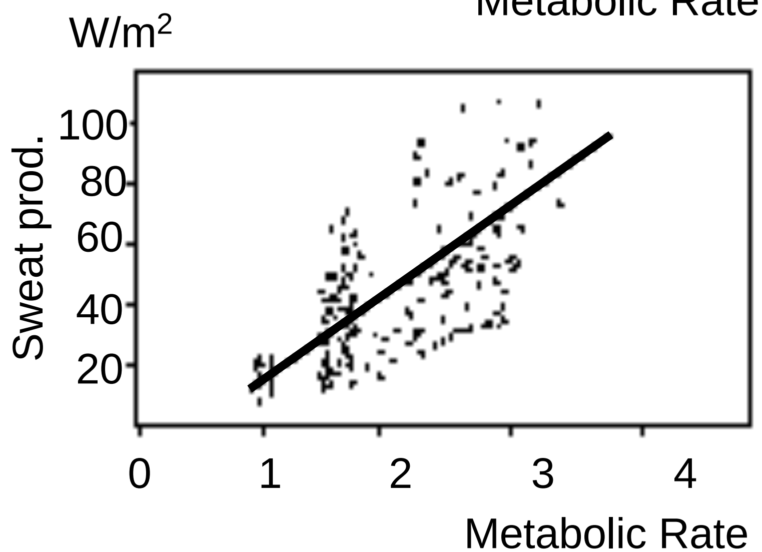
37 ^{o}C 34 ^{o}C

Hot  Cold

- The normal body core temperature is 37 ^{o}C.
- We have separate heat and cold sensors.
- Heat sensors are located in the skin. Signals when temperature is higher than 37 ^{o}C.
- Cold sensors are located in the skin. They send signals when skin temperature is below 34 ^{o}C.
- There are more cold sensors that warm sensors.
- Heating mechanism:
  - Reduced blood flow.
  - Shivering.
- Cooling mechanism:
  - Increased blood flow.
  - Sweating (Evaporation).

Conditions for Thermal Comfort





- Two conditions must be fulfilled to maintain Thermal Comfort:
  - Heat produced must equal heat lost.
  - Signals from Heat and Cold sensors must neutralise each other.

- Mean Skin Temp. and Sweat Loss are the only physiological parameters which influence the heat balance at a given Metabolic Rate
- The sweat production is used instead of body core temperature, as measure of the amount of warm impulses.
- Relation between the parameters found empirically in experiments.
- No difference between sex, age, race or geographic origin.

Thermal comfort measurements in climate chambers and in real life

Workplace Measurements

- 1.1 m

- 0.6 m

- 0.1 m

- 1.7 m

- 1.1 m

- 0.1 m

• Measurements of Vertical Temp. difference and Draught at ankle and neck.
• Other measurements should be performed at persons centre of gravity.

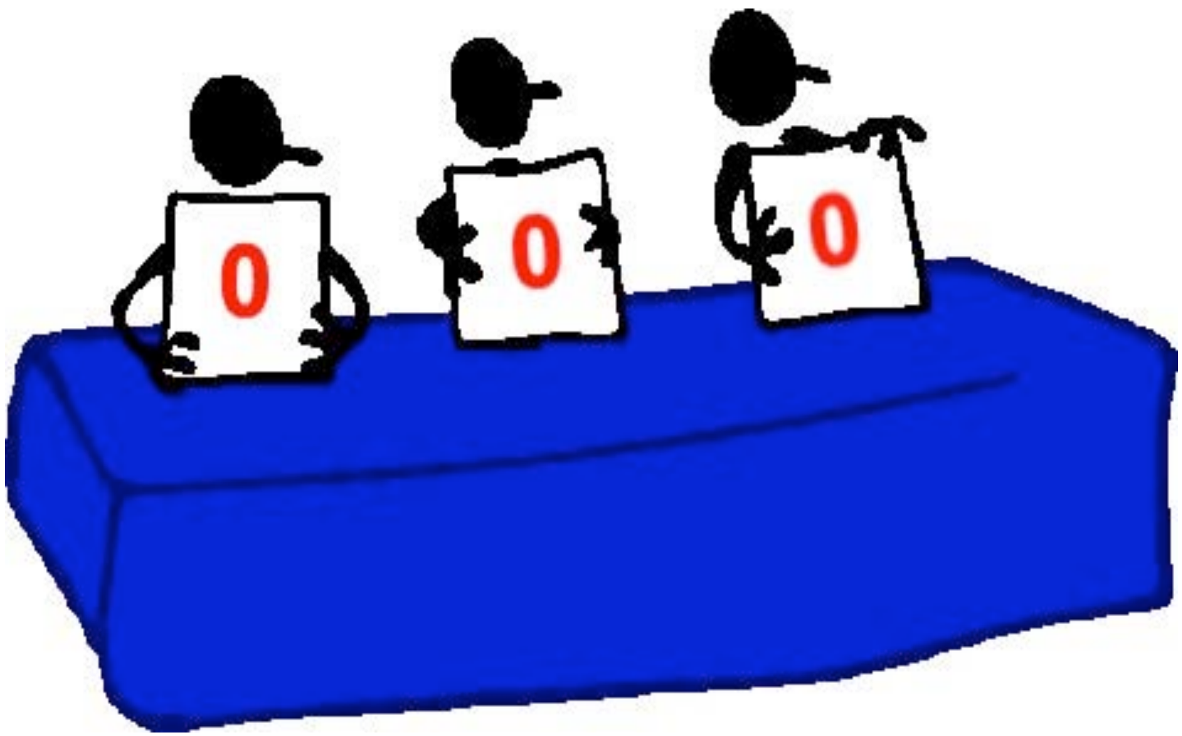
Collection of Thermal Comfort Data

Transducers

- Operative Temperature
- Air Velocity
- Radiant Temperature Asymmetry
- Air Temperature
- Humidity
- Surface Temperature
- WBGT
- Dry Heat Loss

Comfort Temperature

What is Comfort Temperature?



The Comfort Equation

Comfort Equation:

$$M - W = H + E_c + C_{res} + E_{res}$$

$$E_c = 3.05 \cdot 10^{-3} \cdot \left[5733 - 6.99 \cdot (M - W - P_a\right] + 0.42 \cdot (M - W - 58.15)$$

$$C_{res} = 0.0014 \cdot M \cdot (34 - t_a)$$

$$E_{res} = 1.72 \cdot 10^{-5} \cdot M \cdot (5867 - P_a)$$

H is either measured directly or calculated

What to measure

Air Temperature + Mean Radiant Temperature
+ Air Velocity + Humidity

OR

Operative Temperature + Air Velocity + Humidity

OR

Equivalent Temperature + Humidity

H (Dry Heat Loss)

E_c Evaporative heat exchange at the skin

C_{res} Respiratory convective heat exchange

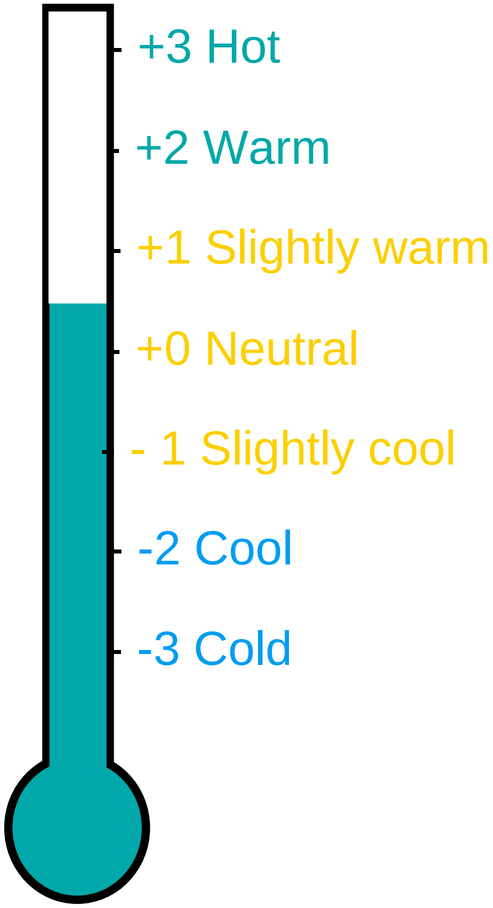
E_{res} Respiratory evaporative heat exchange

What to estimate

MET - VALUE (Metabolism)
CLO - VALUE (Clothing level)

Predicted Mean Vote Scale

The PMV index is used to quantify the degree of discomfort



Calculation of PMV Index

$$PMV = (0,303e^{-2,100*M} + 0,028)*[(M-W)- H - E_c - C_{res} - E_{res}]$$

$$\Rightarrow$$

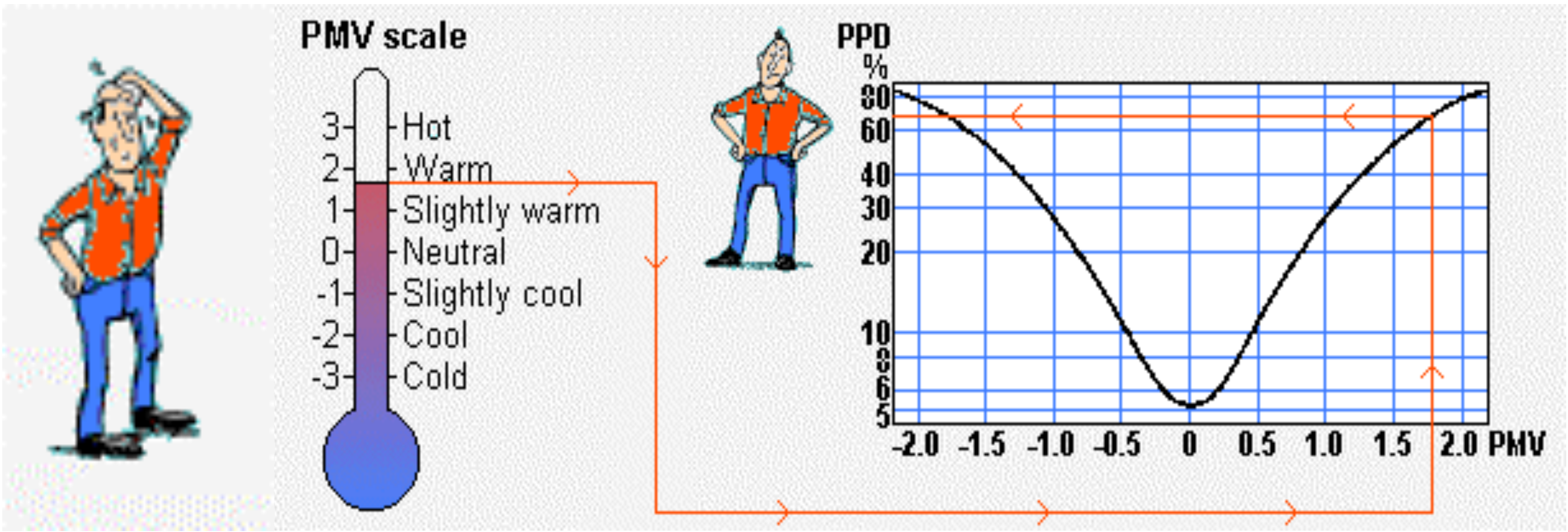
$$PMV = (0,303e^{-2,100*M} + 0,028)*[58,15*(M-W)$$
$$-3,05*10^{-3}*[5733-406,7*(M-W)-p_a]-24,21*[(M-W)-1]$$
$$-10^{-3}*M*(5867-p_a)-0,0814*M*(34-t_a)$$
$$-3,96*10^{-8}*f_{cl*}[(t_{cl}+273)^4 - (t_{eq}+273)^4] - f_{cl}*h_{c,eq}*(t_{cl}-t_{eq})]$$

$$h_{c,eq} = 2,38*(t_{cl} - t_{eq})^{0,25} \qquad f_{cl} = \begin{cases} 1,00+0,2*I_{cl} \text{ for } I_{cl} < 0,5 \text{ clo} \\ 1,05+0,1*I_{cl} \text{ for } I_{cl} > 0,5 \text{ clo} \end{cases}$$

M [MET)]

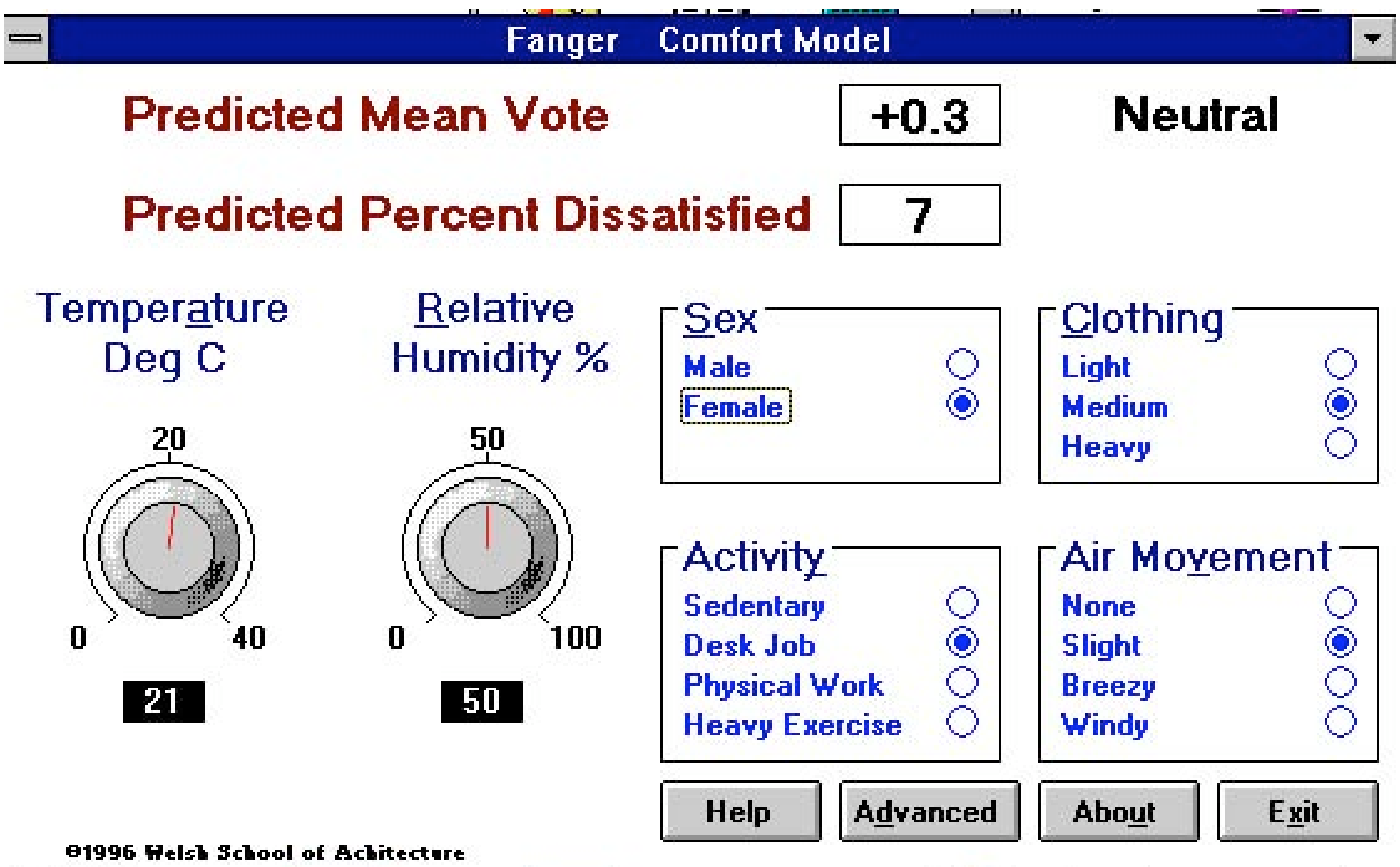
Icl [CLO]

PMV And PPD

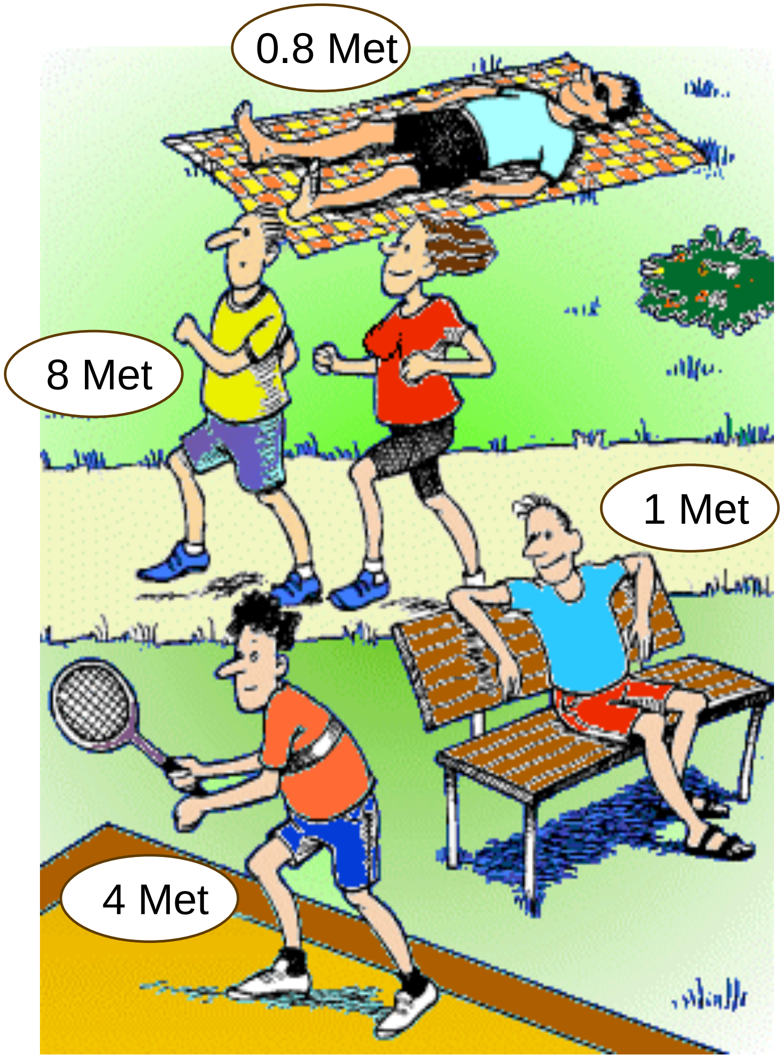


- PMV-index (Predicted Mean Vote) predicts the subjective ratings of the environment in a group of people.
- PPD-index predicts the number of dissatisfied people.

Predicting Thermal Comfort

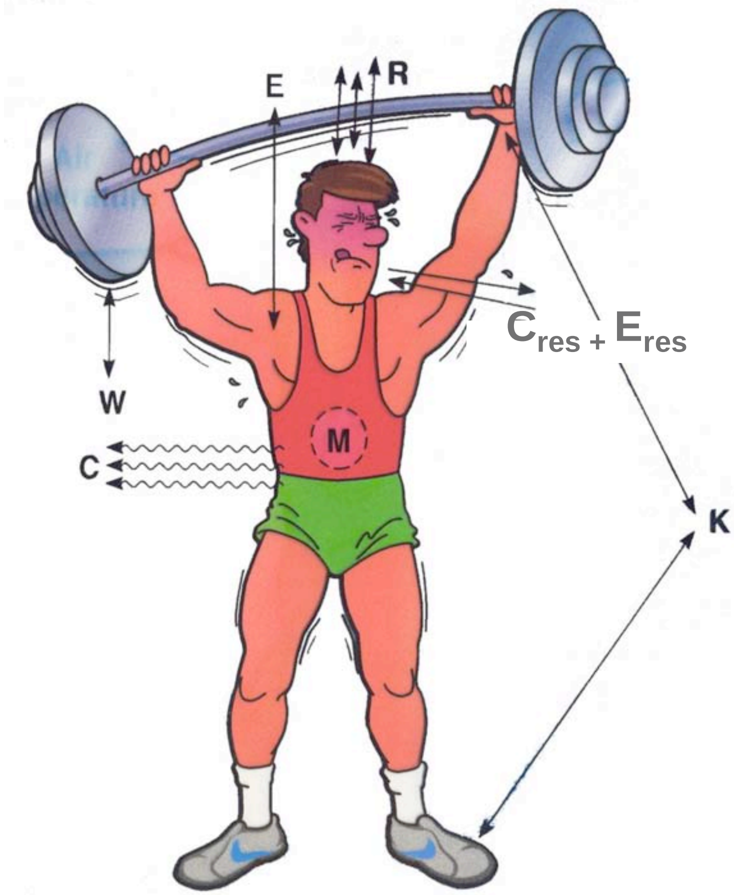


Metabolic Rate



- Energy released by metabolism depends on muscular activity.
- Metabolism is measured in Met (1 Met=58.15 W/m^2 body surface).
- Body surface for normal adult is 1.7 m^2.
- A sitting person in thermal comfort will have a heat loss of 100 W.
- Average activity level for the last hour should be used when evaluating metabolic rate, due to body's heat capacity.

The Energy Balance



Parameters influencing the heat loss from a person

- The dry heat loss (**R+C**) represents ~70% at low Clo-values and ~60% at higher Clo-values.
- The evaporative heat loss (**E**) represents ~25% at moderate activities
- Heat Loss by Conduction (**K**) and Respiration (**RES**) are normally insignificant compared to the total heat exchange.
- Man is a poor machine. The efficiency is less than 20% even for well-trained athletes. Normally set to zero in the comfort equation.

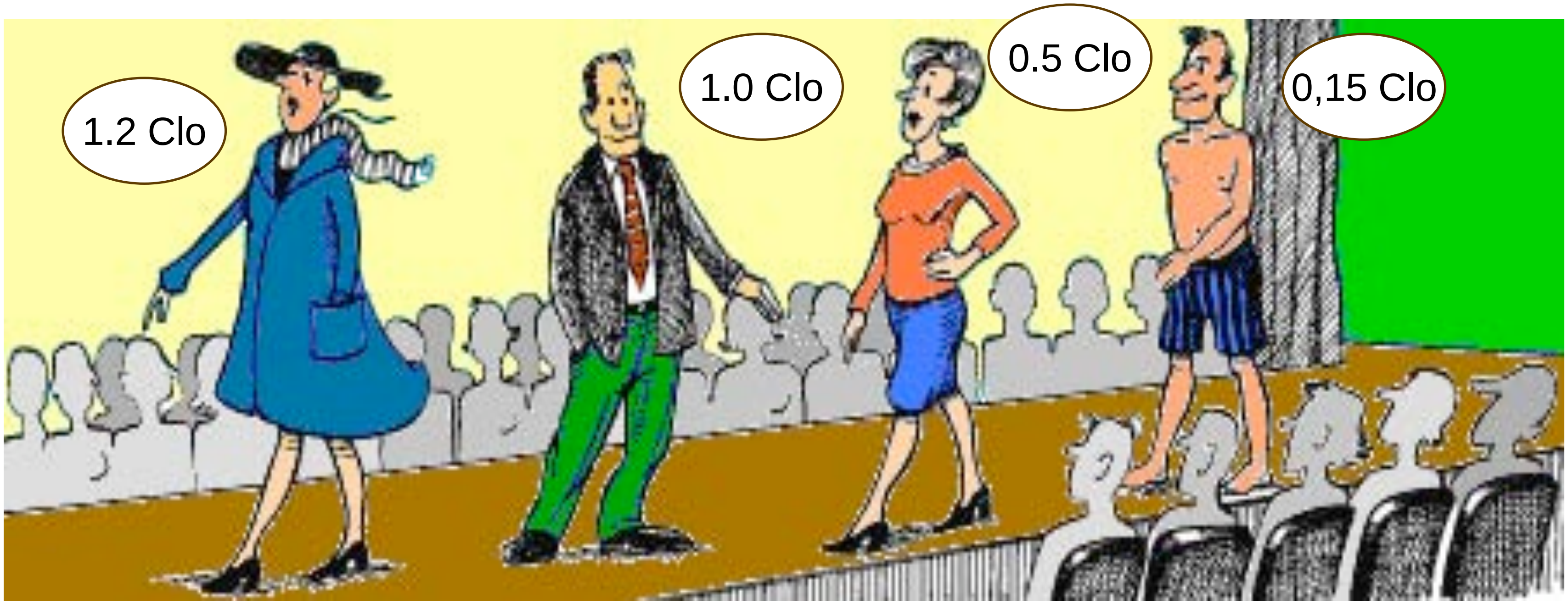
Met Value Table

Activity	Metabolic Rates [M]	
Reclining	46 W/m^2	0.8 Met
Seated relaxed	58 W/m^2	1.0 Met
Clock and watch repairer	65 W/m^2	1.1 Met
Standing relaxed	70 W/m^2	1.2 Met
Car driving	80 W/m^2	1.4 Met
Standing, light activity (shopping)	93 W/m^2	1.6 Met
Walking on the level, 2 km/h	110 W/m^2	1.9 Met
Standing, medium activity (domestic work)	116 W/m^2	2.0 Met
Washing dishes standing	145 W/m^2	2.5 Met
Walking on the level, 5 km/h	200 W/m^2	3.4 Met
Building industry	275 W/m^2	4.7 Met
Sports - running at 15 km/h	550 W/m^2	9.5 Met

The table below can be used to estimate the sensible and latent heat from people. The values can be used to calculate the heat load handled by the air condition system.

Degree of Activity	Typical Application	Average Metabolic rate - male adult (W)	Room Dry Bulb Temperature (^oC)											
			28		27		26		24		22		20	
			Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.
Seated at rest	Cinema, theatre, school	100	50	50	55	45	60	40	67	33	72	28	79	21
Seated, very light work	Computer working	120	50	70	55	65	60	60	70	50	478	42	84	36
Office work	Hotel reception, cashier	130	50	80	56	74	60	70	70	60	78	52	86	44
Standing, walking slowly	Laboratory work	130	50	80	56	74	60	70	70	60	78	52	86	44
Walking, seated		150	53	97	58	92	64	86	76	74	84	66	90	60
Moderate work	Servant, hair dresser	160	55	105	60	100	68	92	80	80	90	70	98	62
Light bench work	Mechanical production	220	55	165	52	158	70	150	85	135	100	120	115	105
Moderate Dancing	Party	250	62	188	70	180	78	172	94	156	110	140	125	125
Fast walking	Mountain walking	300	80	220	88	212	96	204	110	190	130	170	145	155
Heavy work	Athletics	430	132	298	138	292	144	286	154	276	170	260	188	242

Calculation of Insulation in Clothing



- 1 Clo = Insulation value of 0,155 m^2 $^oC/W$

Clo Values Table

Garment description		**I_{clu} Clo**	**I_{clu} m^2 °C/W**
Underwear	Pantyhose Briefs Pants long legs	0.02 0.04 0.10	0.003 0.006 0.016
Underwear, shirts	Bra T-shirt Half-slip, nylon	0.01 0.09 0.14	0.002 0.014 0.022
Shirts	Tube top Short sleeves Normal, long sleeves	0.06 0.09 0.25	0.009 0.029 0.039
Trousers	Shorts Normal trousers Overalls	0.06 0.25 0.28	0.009 0.039 0.043
Insulated coveralls	Multi-component filling Fibre-pelt	1.03 1.13	0.160 0.175
Sweaters	Thin sweater Normal sweater Thick sweater	0.20 0.28 0.35	0.031 0.043 0.054

Clo Values Table

Garment description		**I_{clu} Clo**	**I_{clu} m^2 °C/W**
Jackets	Vest Jacket	0.13 0.35	0.020 0.054
Coats over-trousers	Coat Parka Overalls	0.60 0.70 0.52	0.093 0.109 0.081
Sundries	Socks Shoes (thin soled) Boots Gloves	0.02 0.02 0.10 0.05	0.003 0.003 0.016 0.008
Skirt, dresses	Light skirt, 15cm above knee Heavy skirt, knee-length Winter dress, long sleeves	0.10 0.25 0.40	0.016 0.039 0.062
Sleepwear	Shorts Long pyjamas Body sleep with feet	0.10 0.50 0.72	0.016 0.078 0.112
Chairs	Wooden or metal Fabric-covered, cushioned Armchair	0.00 0.10 0.20	0.000 0.016 0.032

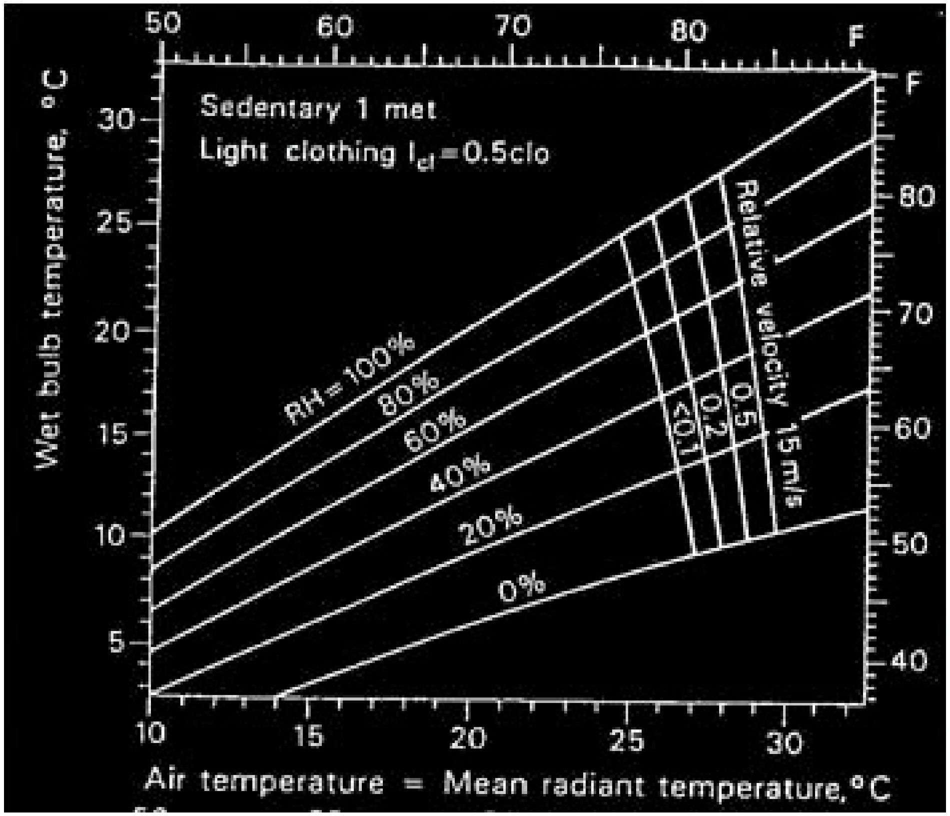
Calculation of Clo Value (Clo)

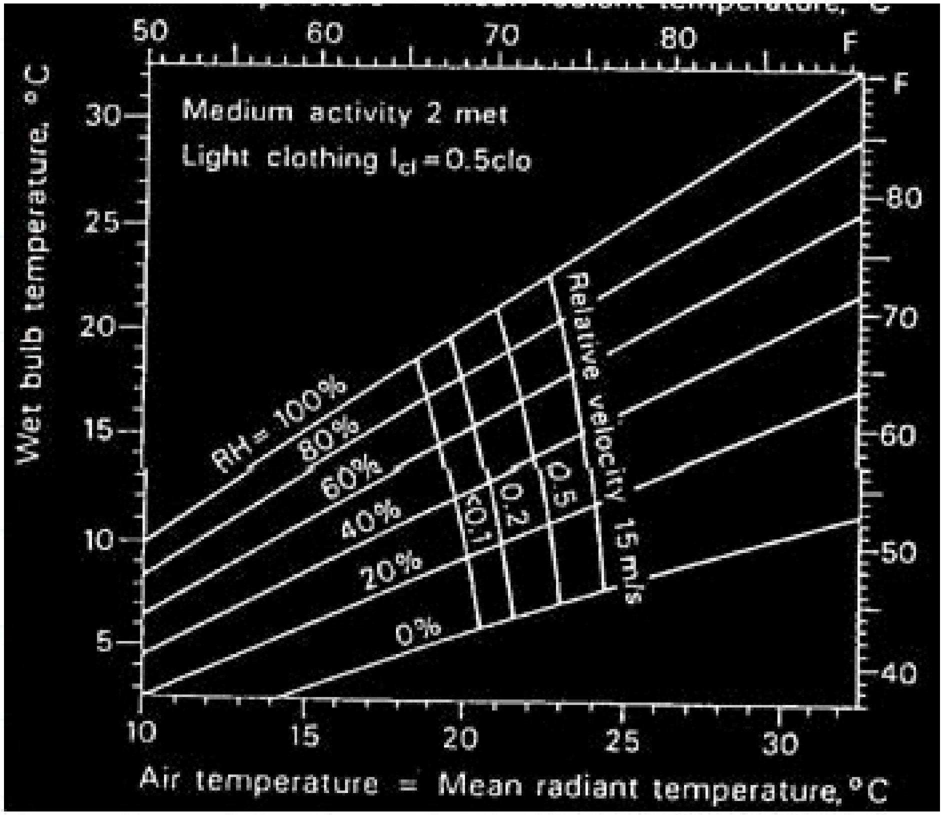
Insulation for the entire clothing: $I_{cl} = \sum I_{clu}$

0.19 + 0.04 + 0.11 + 0.02 + 0.02 = 0.38

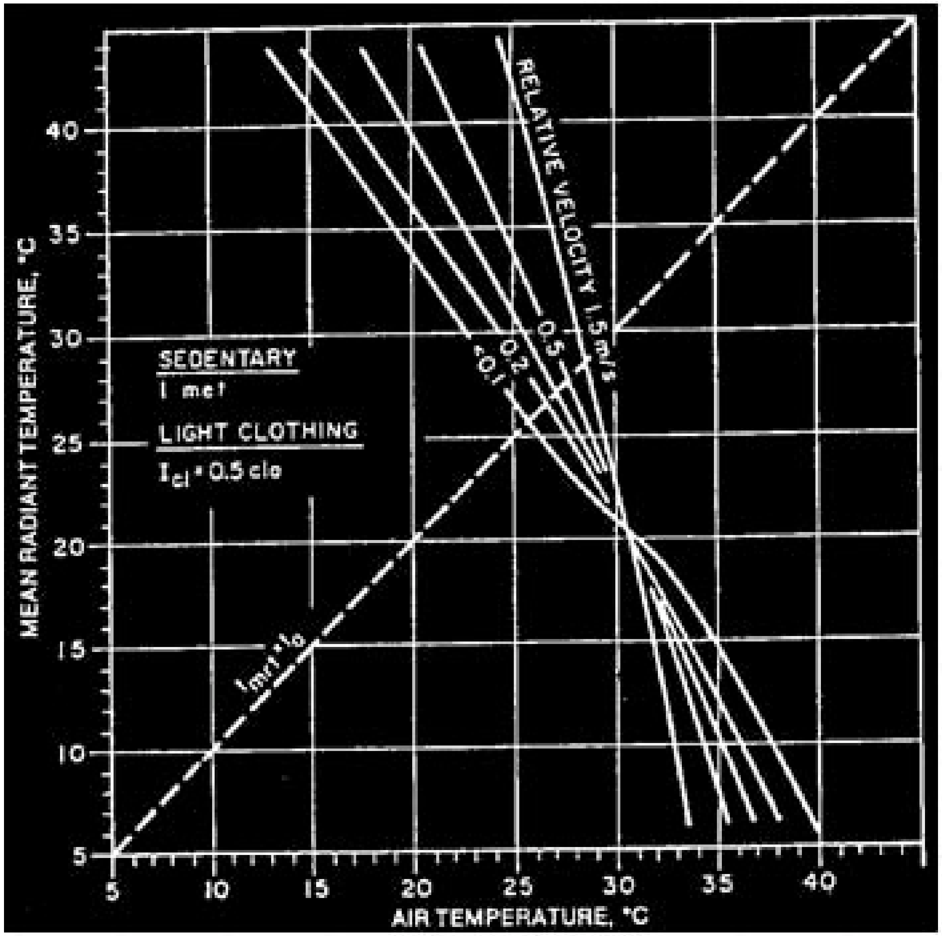
0.28 + 0.25 + 0.04 + 0.25 + 0.05 + 0.04 = 0.91

Effect of Activity on Comfort





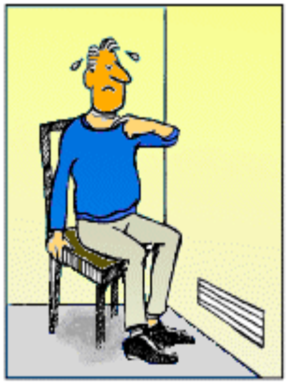
Impact of Air Speed on Comfort



Local Thermal Discomfort

- Draught

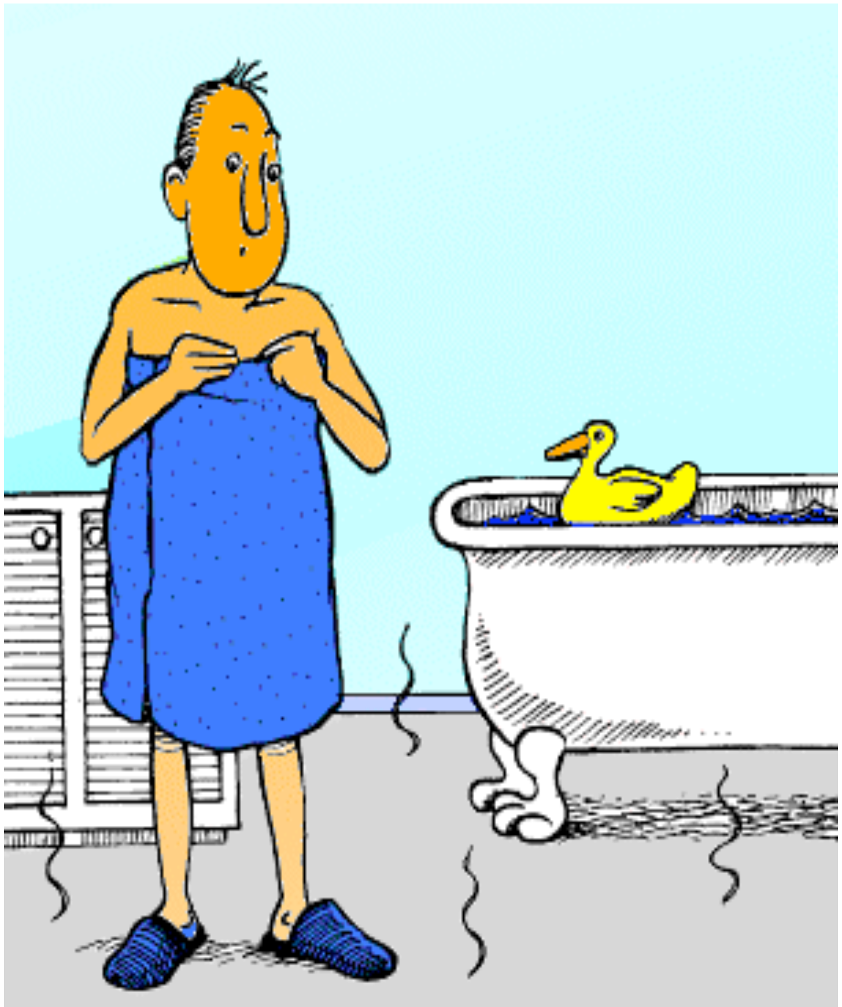
- Radiation Asymmetry

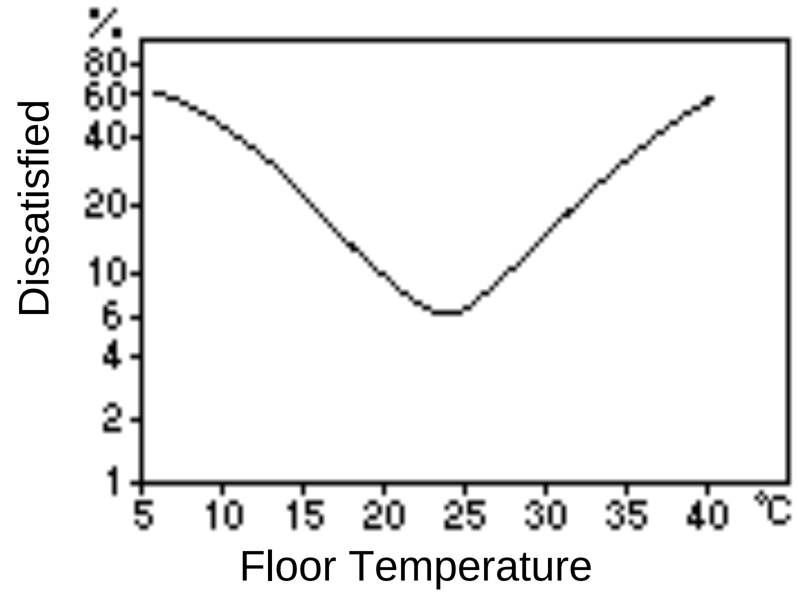


- Vertical Air Temperature Differences

- Floor Temperature

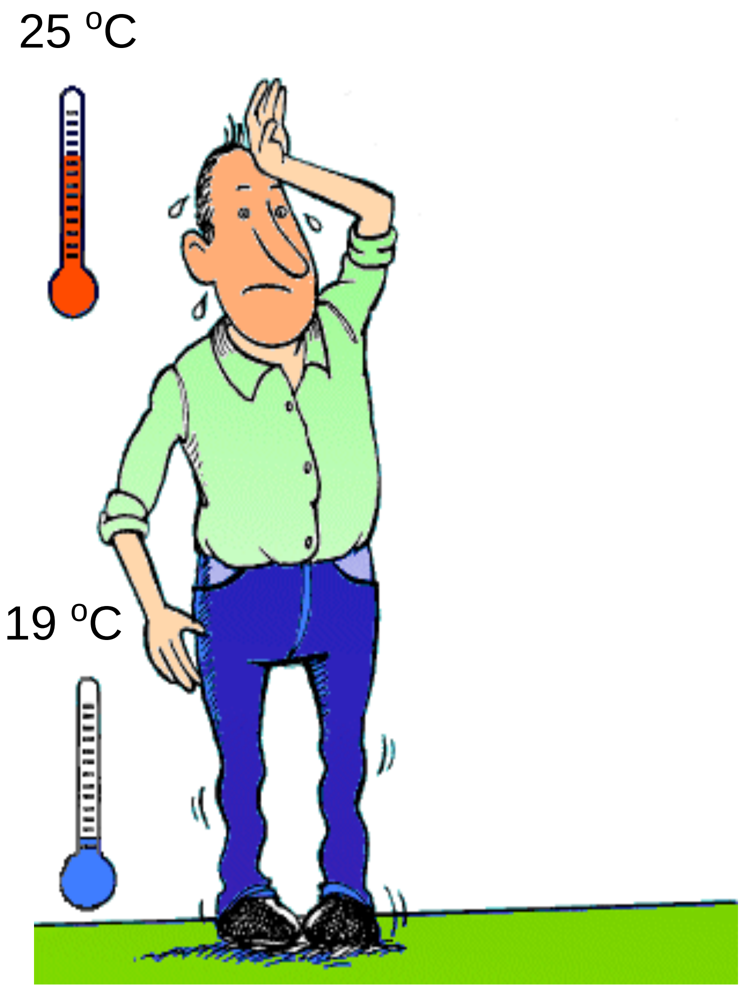
Floor Temperature

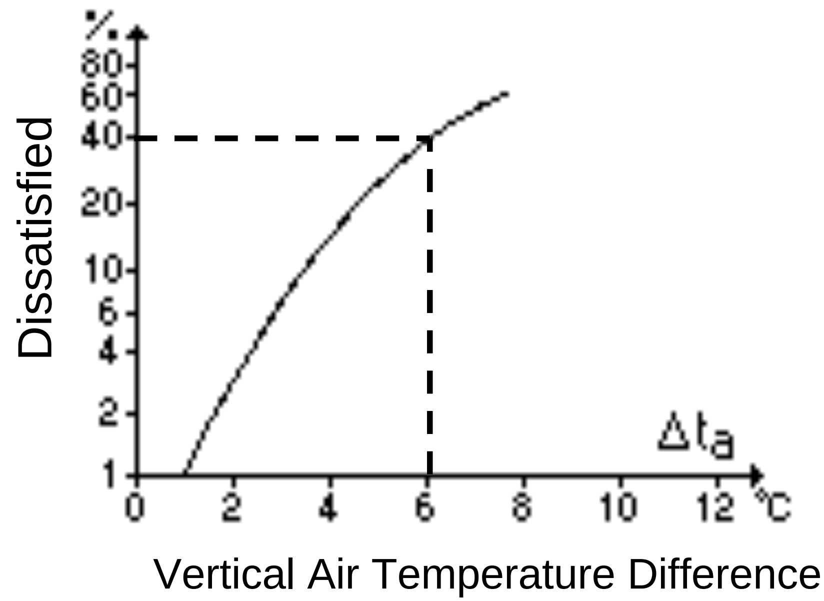




- Acceptable floor temperatures ranging from 19 to 29 ^{o}C.
- The graph is made on the assumption that people wear “normal indoor footwear”.

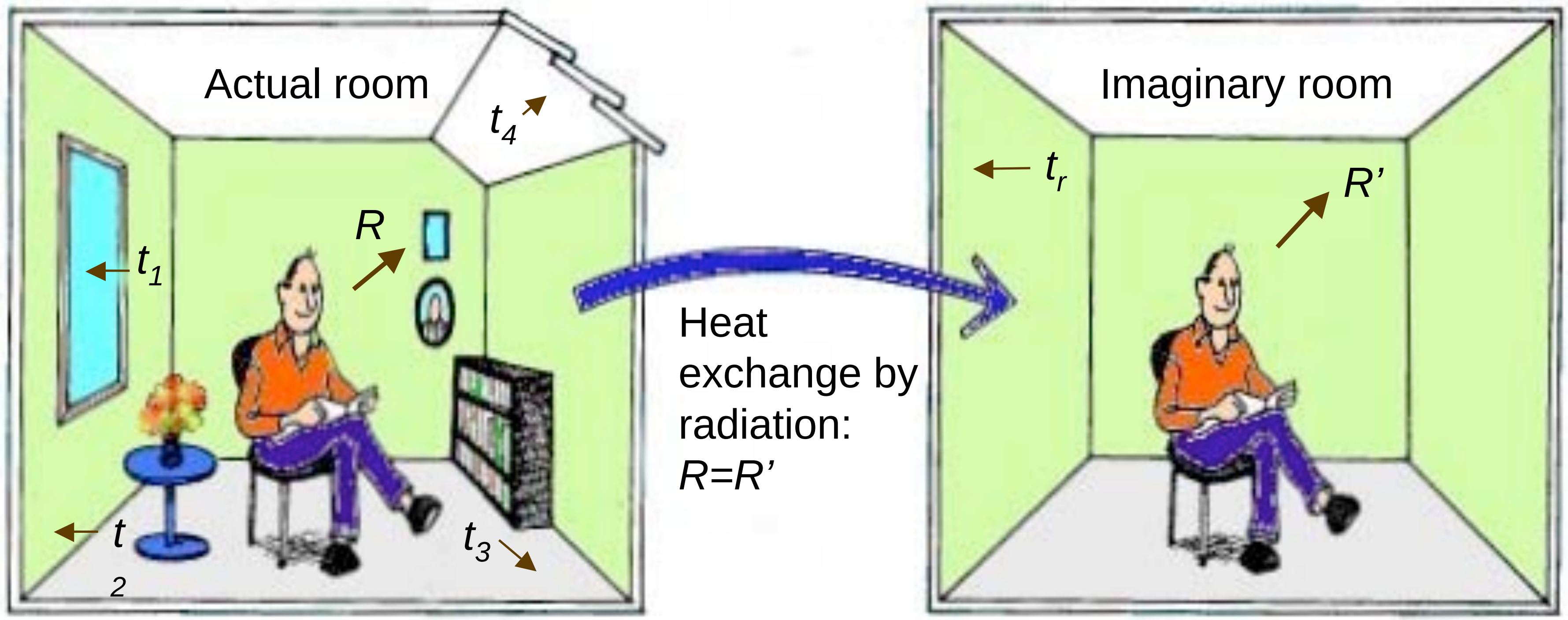
Vertical Air Temperature Difference





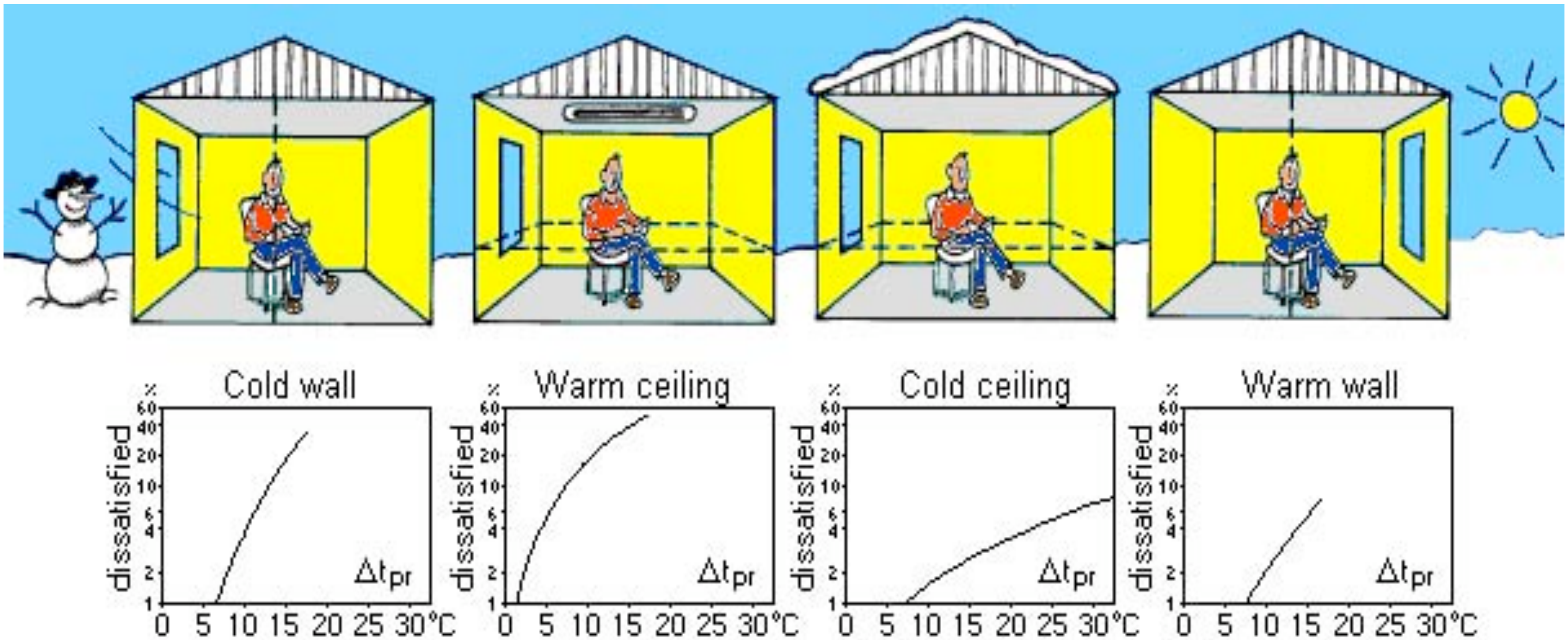
- Vertical Air Temperature Difference is the difference between Air Temperature at ankle and neck level.

Mean Radiant Temperature



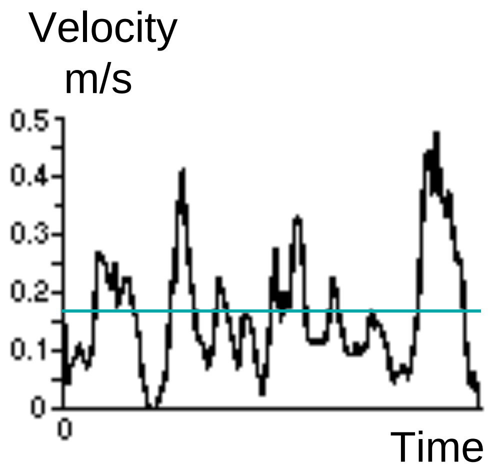
- The Mean Radiant Temperature is that uniform temperature of an imaginary black enclosure resulting in same heat loss by radiation from the person, as the actual enclosure.
- Measuring all surface temperatures and calculation of angle factors is time consuming. Therefore use of Mean Radiant Temperature is avoided when possible.

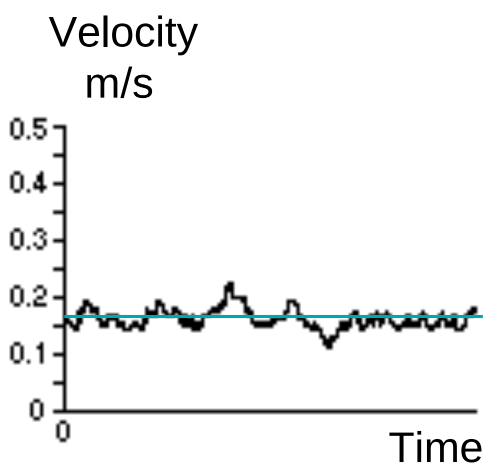
Radiation Asymmetry

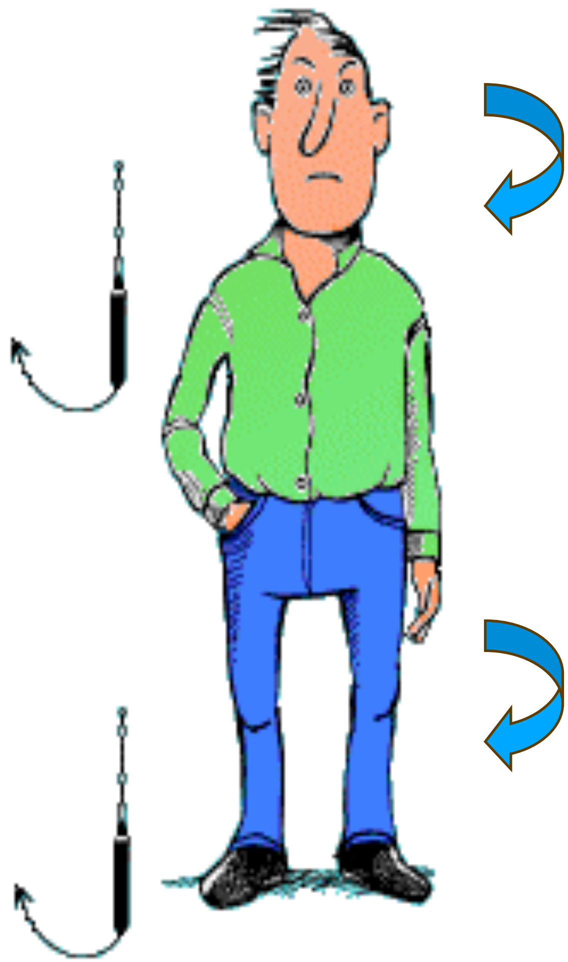


- Radiant Temperature Asymmetry is perceived uncomfortable.
- Warm ceilings and cold walls causes greatest discomfort.

Drafts

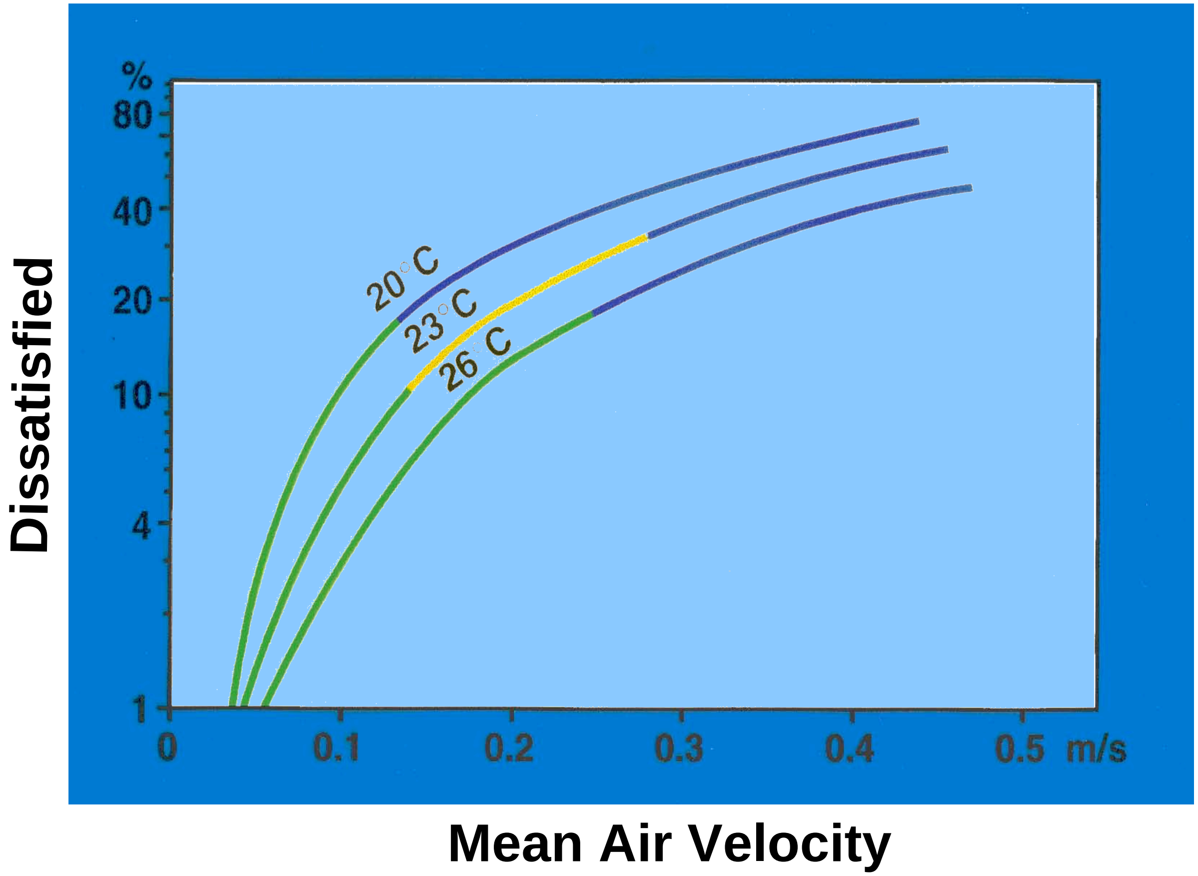






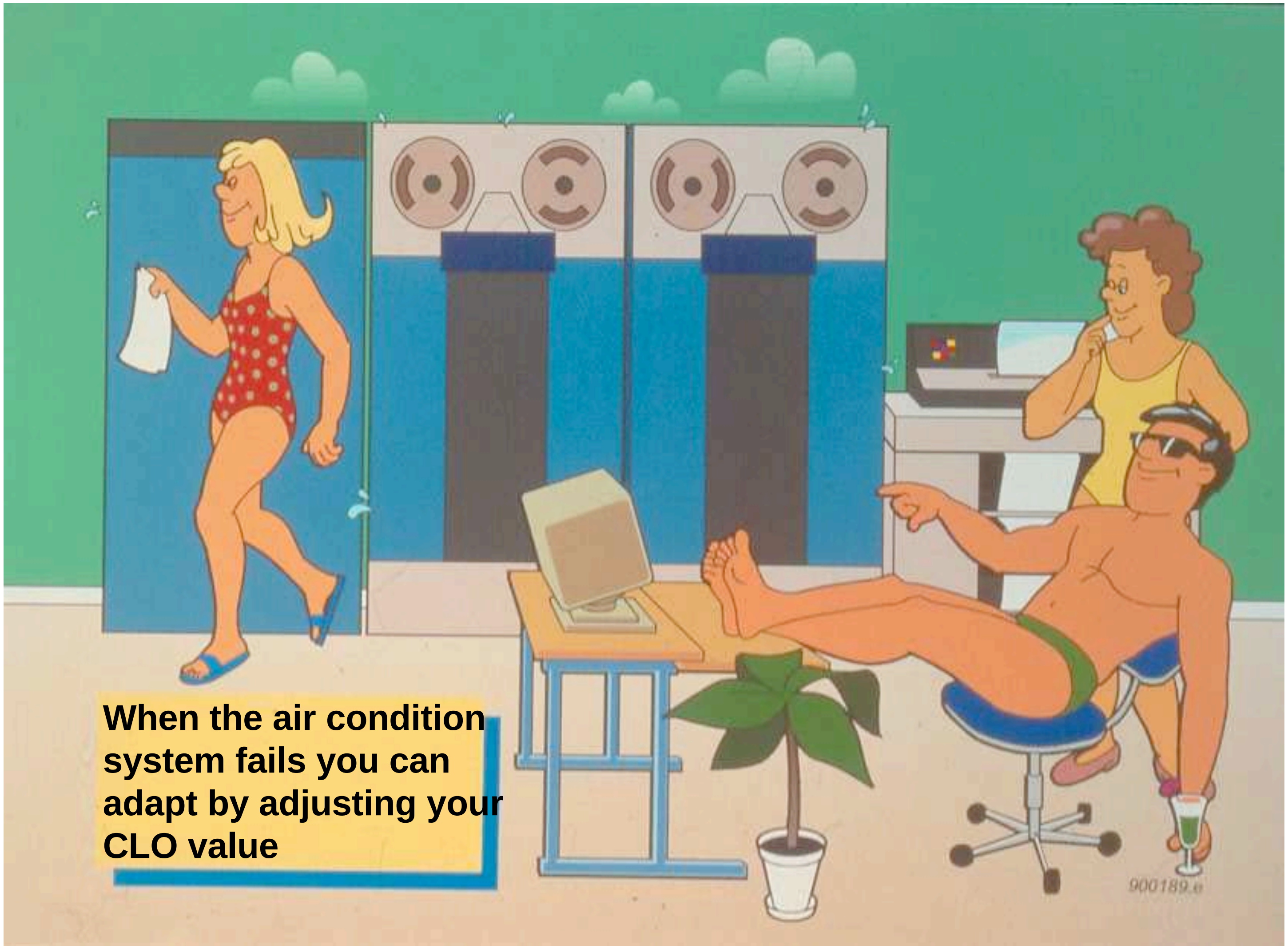
- Drafts are the most common complaint indoors.
- What is felt is Heat Loss.
- Heat Loss is depending on average Air Velocity, Temperature and Turbulence.
- High Turbulence is more uncomfortable, even with the same Heat Loss.

Air Movement



- The sensation of air movement depends on the air temperature.
- At lower air temperatures a higher number will be dissatisfied.

Acclimatisation!



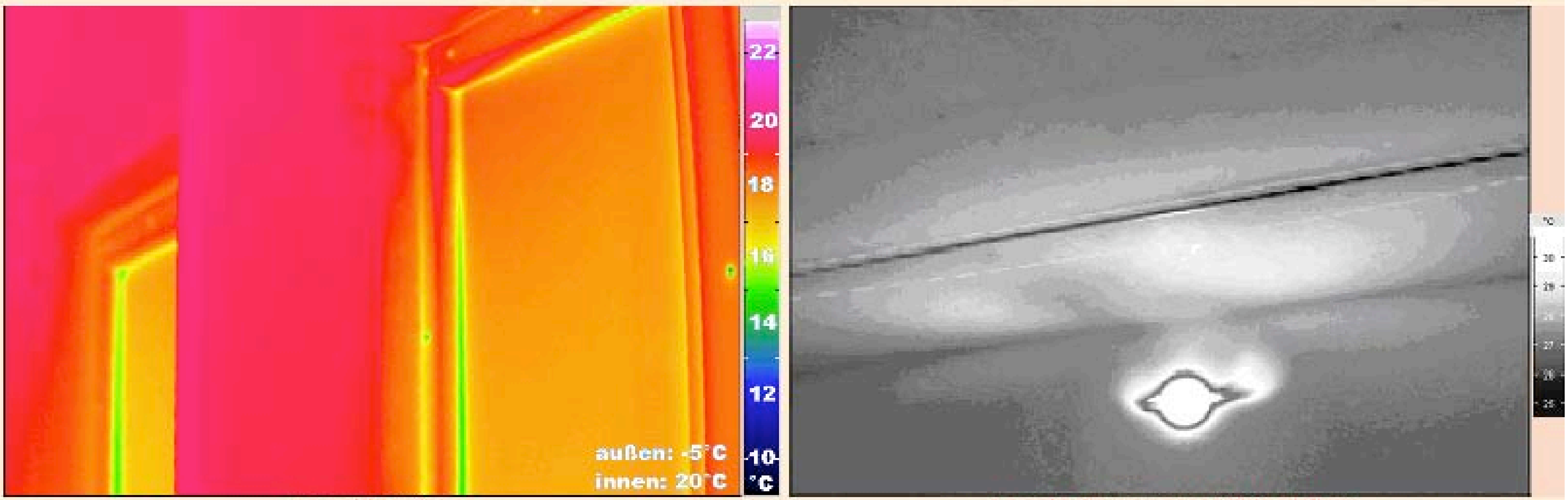
The First Oil Crisis - 1974

President Jimmy Carter goes on TV and urges conservation by wearing a sweater, using a fireplace, and turning the thermostat down

Prime Minister Koizumi wearing CoolBiz

Infrared photos demonstrate that heavily-insulated homes have mean radiant temperatures closer to air temperature and are more comfortable

Optimal thermal comfort in Passive Houses



no cold surfaces,
not even on windows

no cold air, no perceptible airflow,
not even on account of the ventilation system

Occupants explicitly praise thermal comfort in the living space again and again. A number of further analyses dealing with this topic are on the way. For the future, it is important to learn by experiences from already realised projects. That is why thermal comfort is the topic of