FACULTY OF MECHANICAL ENGINEERING CTU IN PRAGUE

DEPARTMENT OF ENVIRONMENTAL ENGINEERING

Environmental Engineering

1. Indoor Environment and Thermal Comfort

Bachelor degree course

Vladimír Zmrhal

Winter semester 9/2021

Environmental Engineering

CONTENT

Week	Topic	Lecturer
1	Indoor Environment and Thermal Comfort	Dr. Zmrhal
2	Psychrometrics	Dr. Zmrhal
3 – 7	Ventilation and Air-conditioning	Dr. Zmrhal
8 – 11	Heating	Dr. Vavřička
12	Hot water preparation	Dr. Vavřička
13	Examination Test !!!	

Study Information System - KOS !!!

Timetable

Environmental Engineering

EXAM

Exchange Students (Erasmus)

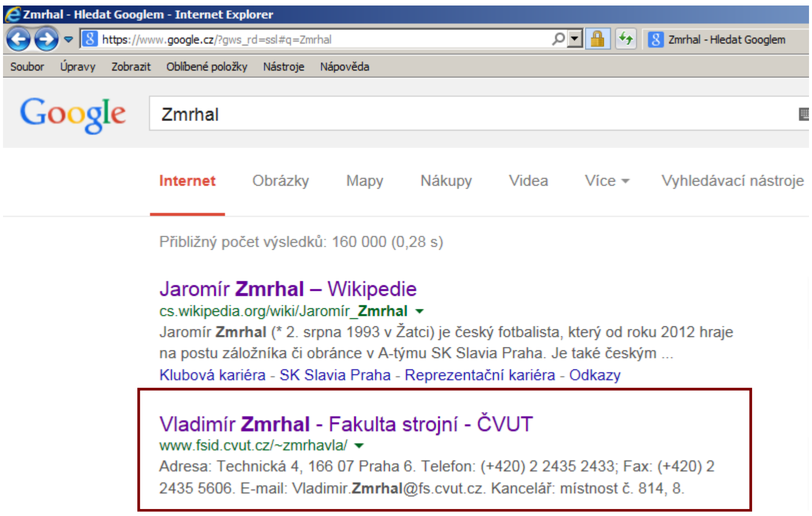
- test (minimum 25 points from 50)

Students of Master Study Programme Mechanical Engineering (Field of study: Environmental Engineering)

- test (minimum 25 points from 50)
- oral examination (in January)
- Environmental Eng. ⟶ subject of State Final Exam !!!

A	B	C	D	E	F
100 - 90	<90 - 80	<80 - 70	<70 - 60	<60 - 50	<50

Environmental Engineering



Environmental Engineering

Ústav Techniky Prostředí

Vladimír Zmrhal

Search ...

Contact | Courses | Publications

Environmental Engineering

Master Course (E161004) – winter semester

Terms of lectures (Lecture: 9.00 – 11.30; Tutorials (obligatory): 11.45 – 13.15)

Week	Date	Topic	Lecturer	Note	Literature
1	27/9/2019 9.00 – 13.15	Indoor Environment and Thermal Comfort	V. Zmrhal		ASHRAE Handbook 2001 Fundamentals Chapter F08
2	04/10/2019 9.00 – 13.15	Heat Transfer and Fluid Mechanics in EE	M. Barták		ASHRAE Handbook 2001 Fundamentals: Chapters 2, 3 and 30

For Industry

- Kurz Větrání a klimatizace 2018
- Kurz Klimatizace a větrání 2020

For Students

- Návod na prezentaci DP/BP

Užitečné odkazy

- ČVUT v Praze
- ČVUT v Praze, Fakulta strojní
- Společnost pro techniku prostředí
- Časopis VVI
- TZB info
- IBPSA

http://users.fs.cvut.cz/vladimir.zmrhal/language/en/courses/ee/

Environmental Engineering

LITERATURE

ASHRAE Handbook

2008	HVAC Systems and Equipment
2009	Fundamentals
2010	Refrigeration
2011	HVAC Application

Indoor Environment

Factors of Indoor Environment

- Thermal environment
- Indoor contaminants (CO_2, combustion products, VOC, tobacco smoke, …)
- Outdoor pollutants
- Odours
- Acoustic environment
- Lightning
- Ionizing radiation
- Electromagnetic waves
- …

IAQ – Indoor Air Quality

SBS Syndrome

Physiology

Heat Production

$$Q = Q_m - W \quad \Big| : A_D \qquad \text{[W]}$$

$$\frac{Q}{A_D} = \frac{Q_m}{A_D} - \frac{W}{A_D} \qquad \text{[W/m}^2\text{]}$$

$$q = q_m - w \qquad \text{[W/m}^2\text{]}$$

q_m …total metabolic rate

w …external mechanical work

A_D …body surface area [m^2]

Physiology

DuBois surface area

$$A_D = 0.202 m^{0.425} h^{0.725} \qquad [m^2]$$

$$f_{cl} = \frac{A_{cl}}{A_D}$$ … clothing area factor - correction factor for clothed body

A_{cl} … area of clothed body [m²]

$A_D = 1.8\ m^2$ … for man 70 kg and 1.73 m

$f_{cl} = 1.1 \div 1.83$

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Physiology

Human Thermoregulation

- metabolic activities of the body result almost completely in heat that must be continuously dissipated and regulated to maintain normal body temperature
- internal temperature rise with the activity ~ 37 °C

  temperature regulatory centre in the brain (hypothalamus)

  (36.8 °C at rest of comfort; 37.4 when walking)
- skin temperature 33 to 34 °C
- resting adults produces about 100 W of heat (sensible and latent)

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Energy Balance

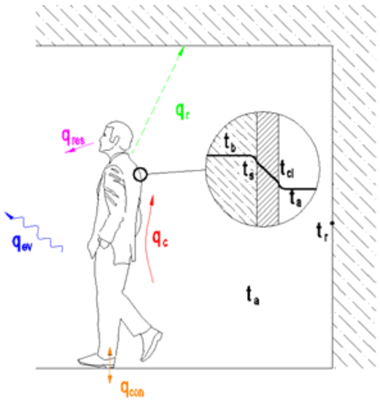

Figure on the board

$$q = q_m - w = \pm q_c \pm q_r + q_{ev} \pm q_{res} \underbrace{\pm q_{con}}_{0} \qquad [W/m^2]$$

Energy Balance

Total metabolic rate

q_m … 1 met = 58.1 W/m^2

External mechanical work

$$w = \eta \cdot q_m \qquad [W/m^2]$$

η …mechanical efficiency $\eta = 0$ …for most activities

$\eta_{max} = 0.2$ …bicycle ergometer

Energy Balance

Metabolic heat generation

Activity	q_m	
	[W/m^2]	[met]
Sleeping	46	0.8
Reading, seated	58	1
Filing, seated	70	1.2
Walking 2 km/h	110	1.9
Dancing	140 to 255	2.4 to 4.4

Energy Balance

Heat transfer by convection

$$q_c = h_c f_{cl} \left(t_{cl} - t_a \right) \qquad \text{[W/m}^2\text{]}$$

Convective heat transfer coefficient h_c [W/m^{2}K]

$$h_c = 2.38 \left(t_{cl} - t_a \right)^{0.25}$$ … natural convection

$$h_c = 12.1 \sqrt{w}$$ … forced convection

Energy Balance

Heat exchange by radiation

$$q_r = h_r f_{cl} \left(t_{cl} - t_r \right)$$ [W/m²]

Radiant heat transfer coefficient h_r [W/m²K]

$$h_r = \varepsilon\sigma \frac{A_r}{A_D} \frac{T_{cl}^4 - T_r^4}{t_{cl} - t_r} \approx 4.7\varepsilon$$ [W/m²K]

ε ...emissivity of the clothing, usually 0.95 [-]

σ ...Stefan-Boltzmann constant $5.67 \cdot 10^{-8}$ [W/m²K⁴]

A_r ...effective radiation area of the body [m²], $A_r/A_D \approx 0.7$

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Energy Balance

Conduction through clothing

$$q_r + q_c = \frac{1}{R_{cl}} \left(t_{sk} - t_{cl} \right)$$ [W/m²]

$$R_{cl} = \sum \left(\frac{s}{\lambda} \right)_{cl} + \sum \left(\frac{s}{\lambda} \right)_{air}$$ [W/m²K]

$$R_{cl} = 0.155 \cdot I$$ ... 1 clo = 0.155 m²K/W

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Energy Balance

Clothing insulation

Clothing ensembles	*R* [m²K/W]	*I* [clo]
Trousers, long-sleeved shirt, long-sleeved sweater, T-shirt	0.155	1
Walking shorts, short-sleeved shirt	0.055	0.36
…	…	…

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Energy Balance

Respiration heat loss

$$q_{res} = \frac{M\left(h_{ex} - h_{in}\right)}{A_D} \qquad \text{[W/m}^2\text{]}$$

M …pulmonary ventilation rate [kg/s]

h_{ex} …enthalpy of exhaled air [J/kg]

h_{in} …ethalpy of inspired (ambient) air [J/kg]

$$M = 1.43 \cdot 10^{-6} \cdot q_m \cdot A_D \qquad \text{[kg/s]}$$

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Energy Balance

$$t_{ex} = 32.6 + 0.066 \cdot t_{in} + 32 \cdot x_{in}$$ [°C]

$$\varphi_{ex} = 100$$ [%]

or

$$x_{ex} = 0.0277 + 0.000065 \cdot t_{in} + 0.2 \cdot x_{in}$$ [$kg_{w.v.}/kg_{d.a.}$]

t_{in} … temperature of inspired (ambient) air [°C]

x_{in} … humidity ratio [$kg_{w.v.}/kg_{d.a.}$]

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Energy Balance

Evaporative heat loss from the skin

$$q_{ev} = q_{ev,dif} + q_{ev,rsw}$$ [W/m^2]

- natural diffusion of water through the skin

$$q_{ev,dif} = 3.05 \cdot 10^{-3} \left(256 \cdot t_{sk} - 3373 - p_v \right)$$

p_v … water vapor pressure in ambient air [Pa]

t_{sk} … temperature of skin [°C]

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Energy Balance

- heat loss by evaporation of sweat secretion

$$q_{ev,rsw} = h_{ev} \frac{A_{ev}}{A_D} \left(p''_{v,sk} - p_v \right)$$

h_{ev} … evaporative heat transfer coefficient [W/m²K]

A_{ev} … effective evaporative area of the body [m²]

$p''_{v,sk}$ … saturated water vapor pressure at skin temperature [Pa]

$$h_{ev} = \frac{16.7 h_c}{1 + 2.22 h_c \left[R_{cl} - \left(1 - \frac{1}{f_{cl}} \right) \Big/ \left(h_c + h_r \right) \right]}$$

Parameters Influenced Thermal Comfort

Indoor Environment Parametres

- air temperature t_a [°C]
- relative humidity (*RH*) φ [%]
- mean radiant temperature (*MRT*) t_r [°C]
- air velocity w_a [m/s]
- turbulence intensity *Tu* [-]

Personal Parameters

- metabolism q_m and work *w*
- thermal insulation of the clothing

and also age, sex (male/female), …

?!

Thermal Comfort

- condition of mind that expresses satisfaction with the thermal environment
- effect on health and performance

Prediction of Thermal Comfort

Rohles and Nevins (1971) indicate values that provides thermal comfort (optimum)

- required temperature of skin

$$t_{sk,req} = 35.7 - 0.0275\left(q_m - w\right)$$

- required evaporative heat loss

$$q_{ev,rsw,req} = 0.42\left(q_m - w - 58.15\right)$$

Thermal Comfort

Thermal comfort equation (TCE)

$$q_m - w = \underbrace{h_c f_{cl}\left(t_{cl} - t_a\right)}_{q_c} + \underbrace{h_r f_{cl}\left(t_{cl} - t_r\right)}_{q_r} +$$

$$\underbrace{+3.06 \cdot 10^{-3}\left(256\left[\underbrace{35.7 - 0.0275\left(q_m - w\right)}_{t_{sk,req}}\right] - p_a - 3373\right)}_{q_{ev,dif}} +$$

$$\underbrace{+0.42\left(q_m - w - 58.15\right)}_{q_{ev,rsw,req}} + \underbrace{1.43 \cdot 10^{-6} q_m\left(h_{ex} - h_{in}\right)}_{q_{res}}$$

Thermal Comfort

where t_{cl} calculates from the heat flow through clothing

$$q_c + q_r = \frac{1}{R_{cl}}\left(t_{sk} - t_{cl}\right)$$

$$\underbrace{h_c f_{cl}\left(t_{cl} - t_a\right)}_{q_c} + \underbrace{h_r f_{cl}\left(t_{cl} - t_r\right)}_{q_r} = \frac{1}{R_{cl}}\left[\underbrace{35.7 - 0.0275\left(q_m - w\right)}_{t_{sk,req}} - t_{cl}\right]$$

$$t_{cl} = 35.7 - 0.0275\left(q_m - w\right) - R_{cl}\left[h_c f_{cl}\left(t_{cl} - t_a\right) + h_r f_{cl}\left(t_{cl} - t_r\right)\right]$$

- iteration

Thermal Comfort

ASHRAE Thermal Sensation Scale

+3	hot
+2	warm
+1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

Thermal Sensation

=

Predicted Mean Vote

(PMV)

Thermal Comfort

Fanger's Model of Thermal Comfort (Standard Model)

- thermal load on the body

L = actual heat flow from the body – heat loss to the actual environment for a person hypothetically kept at comfort values of t_{sk} and $q_{ev,rsw}$ at the actual activity level

respectively

L = left side of theTCE – right side of the TCE

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Thermal Comfort

Predicted Mean Vote – PMV index

- PMV predicts the mean response of a large group of people according to thermal sensation scale

$$PMV = \left(0.303e^{-0.036q_m} + 0.028\right)L$$

Predicted Percent of Dissatisfied – PPD index

$$PPD = 100 - 95\exp\left[-(0.03353PMV^4 + 0.2179PMV^2)\right]$$

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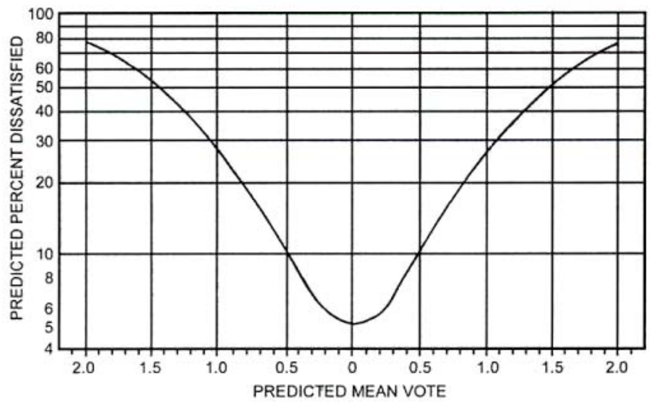
Thermal Comfort



PMV = 0 → about 5 % of the people will be dissatisfied

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Thermal Comfort

Category of global thermal comfort	PPD [%]	PMV
A	<5	- 0.2 < PMV < + 0.2
B	<10	- 0.5 < PMV < + 0.5
C	<15	- 0.7 < PMV < + 0.7

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Thermal Comfort

Operative temperature - uniform temperature of a imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment.

$$q_c + q_r = (h_c + h_r) f_{cl} (t_{cl} - t_o)$$

$$h_c (t_{cl} - t_a) + h_r (t_{cl} - t_r) = (h_c + h_r)(t_{cl} - t_o)$$

$$t_o = \frac{h_c t_a + h_r t_r}{h_c + h_r} \quad [°C]$$

Thermal Comfort

$$A = \frac{h_c}{h_c + h_r}$$

$$t_o = A t_a + (1 - A) t_r$$

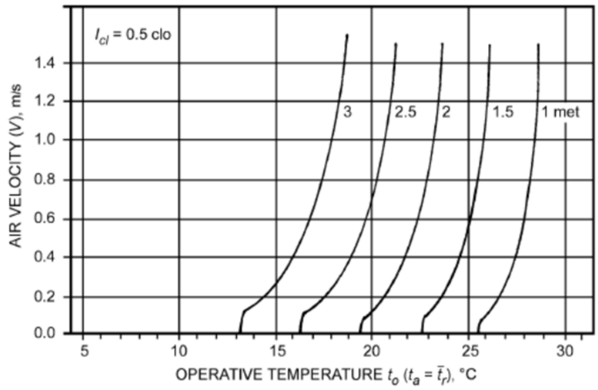
w [m/s]	<0.2	0.3	0.4	0.6	0.8	1
A [-]	0.5	0.53	0.6	0.65	0.7	0.75

for $w \leq 0.2$ m/s

$$t_o = \frac{t_a + t_r}{2}$$

Thermal Comfort

Operative temperature necessary for comfort (*PMV* = 0) of person in summer clothing at *RH* = 50 %



Thermal Comfort

Mean radiant Temperature

➢ the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human equals the radiant heat transfer in the actual nonuniform enclosure

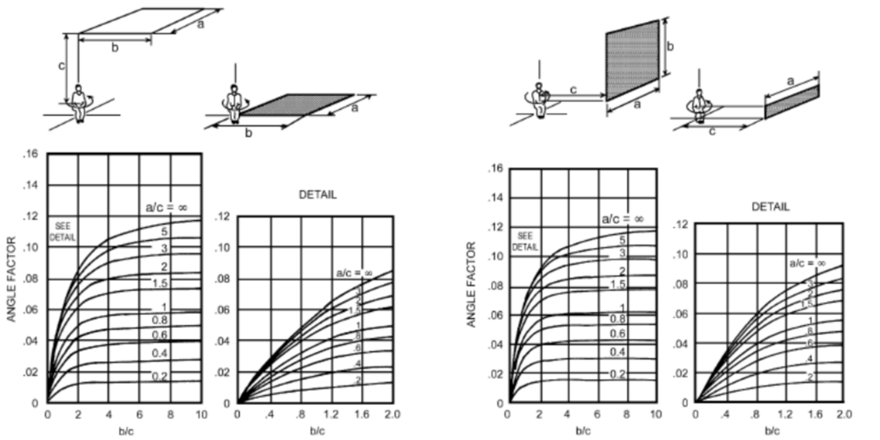
[°C]

$$t_r = \sqrt[4]{F_{p-1}T_1^4 + F_{p-2}T_2^4 + \dots + F_{p-n}T_n^4} - 273.15$$

$F_{p\text{-}n}$ ...angle factor between a person and surface n

T_n ...surface temperature of the surface [K]

Thermal Comfort



A. HORIZONTAL RECTANGLE (ON CEILING OR ON FLOOR)

B. VERTICAL RECTANGLE (ABOVE OR BELOW CENTER OF PERSON)

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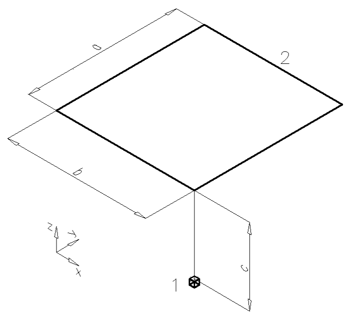
Thermal Comfort

Simplification - elementary case (rectangle vs. point)

- Eckert

$$F_{1-2} = \frac{1}{8} - \frac{1}{4\pi} \mathrm{arctg} \frac{c\sqrt{a^2 + b^2 + c^2}}{ab}$$



In the room:

$$\sum F_{1-2} = 1$$

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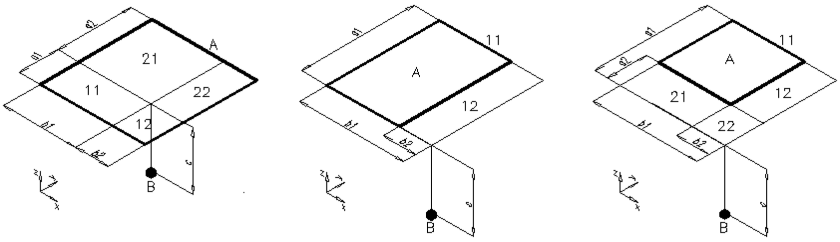
Thermal Comfort

Angle factor algebra



$$F_{B-A} = F_{B-11} + F_{B-12} + F_{B-21} + F_{B-22}$$

$$F_{B-A} = F_{B-11} - F_{B-12}$$

$$F_{B-A} = F_{B-11} - \left(F_{B-12} + F_{B-21}\right) + F_{B-22}$$

Local Discomfort

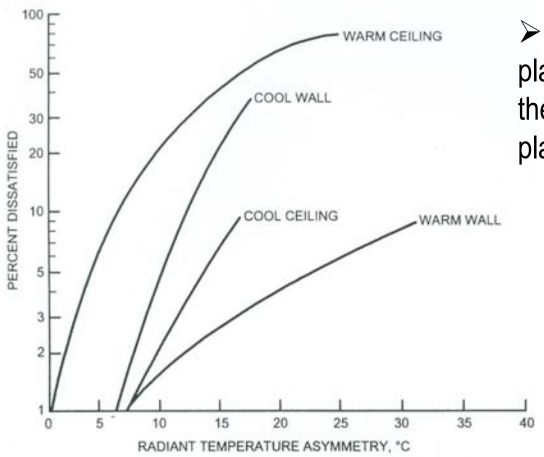
Thermal non-uniform conditions

- radiant temperature asymmetry
- draft
- vertical air temperature difference
- warm or cold floors

Source: Thermal comfort. The booklet. INNOVA 2002. <http://www.blowtex-educair.it/DOWNLOADS/Thermal Comfort.htm>

Local Discomfort

Radiant temperature asymmetry



- the difference between the plane radiant temperature of the opposite sides of a small plane element

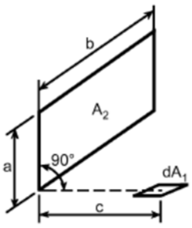
$$\Delta t_{pr} = t_{pr1} - t_{pr2}$$

Local Discomfort

Radiant temperature asymmetry Δt_{pr} [°C]		
Category of thermal comfort	A,B	C
Warm ceiling	<5	<7
Cool wall	<10	<13
Cool ceiling	<14	<18
Warm wall	<23	<35

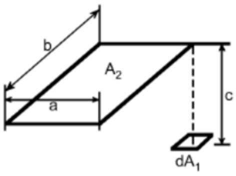
Local Discomfort

Small plane element



$x = \frac{a}{b}$ $y = \frac{c}{b}$

$$F_{d1-2} = \frac{1}{2\pi}\left(\tan^{-1}\frac{1}{y} - \frac{y}{\sqrt{x^2+y^2}}\tan^{-1}\frac{1}{\sqrt{x^2+y^2}}\right)$$

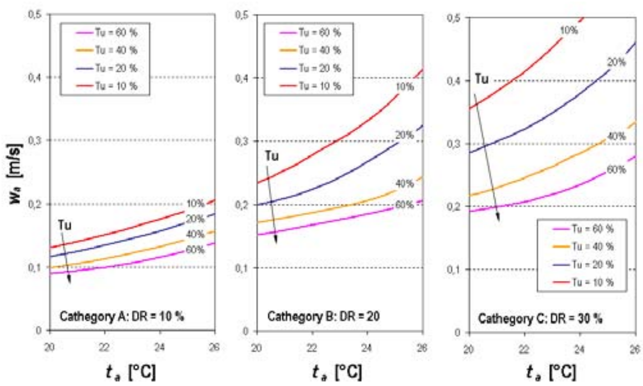


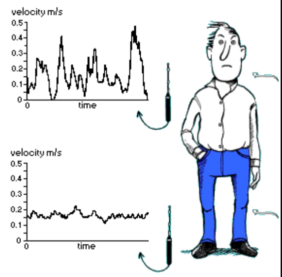
$x = \frac{a}{c}$ $y = \frac{b}{c}$

$$F_{d1-2} = \frac{1}{2\pi}\left(\frac{x}{\sqrt{1+x^2}}\tan^{-1}\frac{y}{\sqrt{1+x^2}} + \frac{y}{\sqrt{1+y^2}}\tan^{-1}\frac{x}{\sqrt{1+y^2}}\right)$$

Local Discomfort

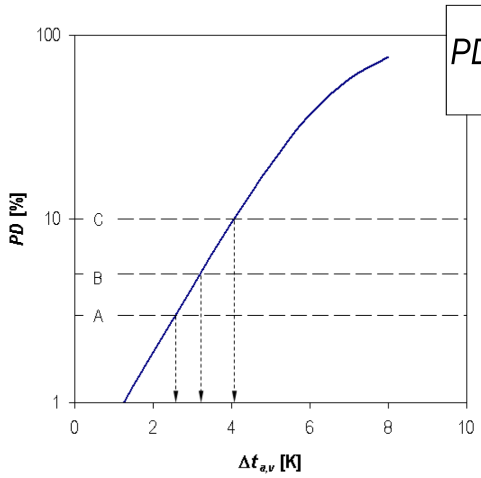
Draft Rate $DR = (34 - t_a)(w_a - 0.05)^{0.62}(0.37 w_a \cdot Tu + 3.14)$



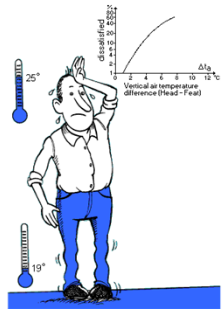


Local Discomfort

Vertical air temperature difference



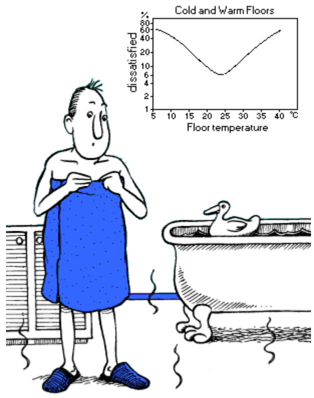
$$PD = \frac{100}{1 + \exp\left(5.67 - 0.856\Delta t_{a,v}\right)}$$



Local Discomfort

Warm or cold floors

Category of thermal comfort	Percentage of dissatisfied *PD* [%]	Floor temperature t_{floor} [°C]
A,B	<10	19 to 29
C	<15	17 to 31



Adaptive Model of Thermal Comfort

- people naturally adapt and may also make various adjustments to themselves and their surroundings
- acceptable degree of comfort in residences and offices is possible over the range of t_a from 17 to 31 °C (Humphreys, Nicol 1998)
- comfort temperature

$$t_c = 24.2 + 0.43(t_{out} - 22)\exp\left(\frac{t_{out} - 22}{24\sqrt{2}}\right)^2$$

t_{out} … monthly mean outdoor temperature [°C]

$$t_{oc} = 18.9 + 0.255 \cdot t_{out}$$

… buildings where cooling and central heating is not required

Adaptive Model of Thermal Comfort

Adaptation – people can acclimatize themselves

- changing posture and activity
- clothing changing
- leaving the space / move
- opening a window, shading …

For buildings without mechanical cooling (air-conditioning) or with low-energy cooling systems (night ventilation, …)

Thermal Comfort

Example 1: Calculation of PMV and PPD

Room air temperature	t_a = 26 °C
Mean radiant temperature	MRT = 24 °C
Relative humidity	RH = 50 %
Air velocity	w = 0.2 m/s
Thermal resistance of clothing	R_{cl} = 0.0775 m^{2}K/W = 0.5 clo … light summer clothing
Metabolic rate	q_m = 69.8 W/m^2 = 1.2 met … seated activity (office)
Mechanical efficiency	η_m = 0 %
External mechanical work	w = 0
Heat transfer by convection	h_c = 5.41 W/m^{2}K
Heat transfer by radiation	h_r = 4.16 W/m^{2}K

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Thermal Comfort

Example 2: Calculation of *MRT* and t_o

Room: L = 6 m, W = 4 m, H = 2.7 m

t_a = 28 °C

$t_{wall} = t_{floor} = t_a$

$t_{ceiling}$ = 18 °C

w = 0.15 m/s

Calculate *MRT* and t_o in the middle of the room at hight of h = 1.5 m.

MRT = ?

t_o = ?

$$F_{1-2} = \frac{1}{8} - \frac{1}{4\pi}\,\mathrm{arctg}\frac{c\sqrt{a^2+b^2+c^2}}{ab}$$

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Thank you for your attention