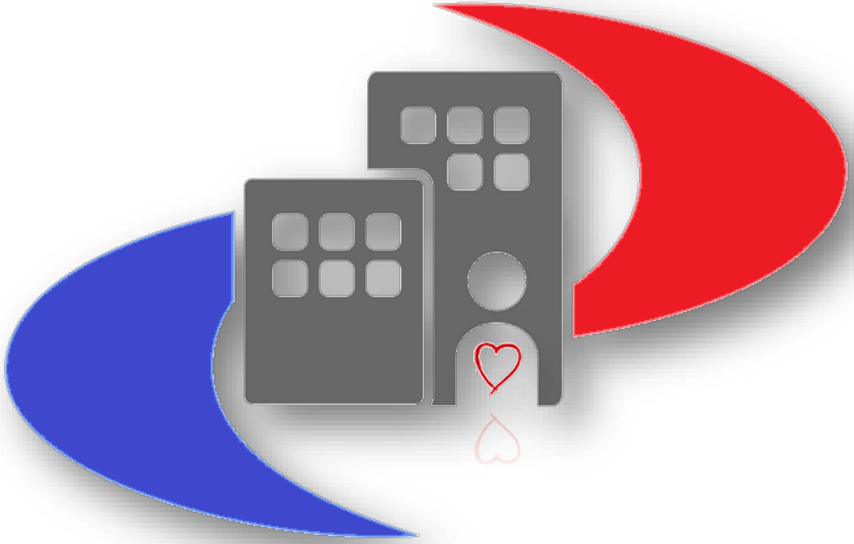

CIVIL - 450: THERMODYNAMICS of COMFORT in BUILDINGS

Assist. Professor
Dolaana Khovalyg

Lecture 04:
Human-Environment Heat Exchange: measured parameters and instrumentation

14 March 2025

Course Information - Schedule

Classroom GC D0 386 is on the Lausanne campus

WEEK	Date	Content	Location
1	21.02.2025	Intro to thermal comfort and human thermoregulation	GC D0 386
2	28.02.2025	Human body energy balance	GC D0 386
3	07.03.2025	Exergy analysis in the built environment (*guest lecture*)	GC D0 386
4	14.03.2025	Lab #1 in Fribourg (climatic chamber). Measurements and instrumentation.	EPFL-Fribourg
5	21.03.2025	Group work on Lab #1	GC D0 386
6	28.03.2025	Group work on Lab #1	GC D0 386
7	04.04.2025	Invisible radiant heat: transparent & translucent building elements and their effect on comfort (*guest lecture*)	GC D0 386
8	11.04.2025	Lab #1 presentations, reports submission	GC D0 386
9	18.04.2025	Good Friday (holiday)	No class
10	25.04.2025	Easter break	No class
11	02.05.2025	Lab #2 in Fribourg (building prototype)	EPFL-Fribourg
12	09.05.2025	Building-environment interaction and energy balance	GC D0 386
		Group work on Lab #2	
13	16.05.2025	Group work on Lab #2	GC D0 386
14	23.05.2025	Group work on Lab #2	GC D0 386
15	30.05.2025	Lab #2 presentations, reports submission. Course summary and course evaluation.	GC D0 386

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CONTENT:

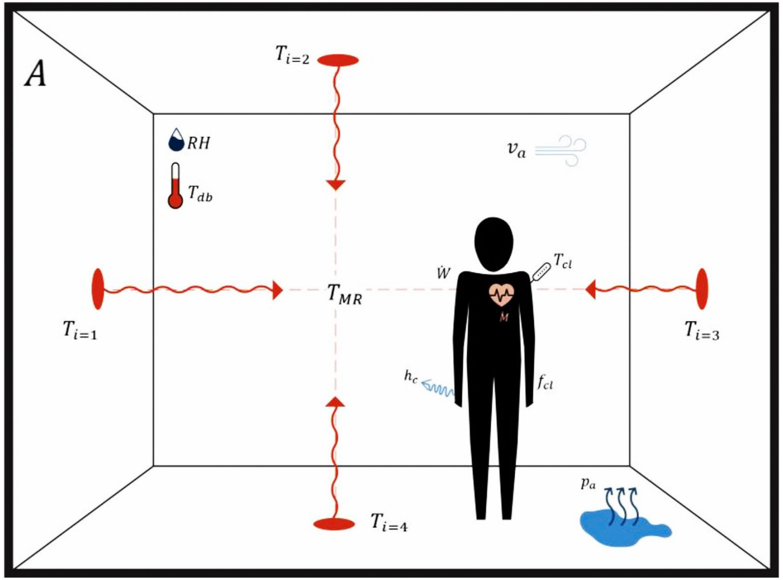
- Overview of environmental parameters
- Measurements of environmental parameters:
  - Temperature, heat flux sensing
  - Air temperature, velocity/speed, humidity
  - Operative / Globe / Mean radiant temperature
  - Plane radiant temperature / Radiant asymmetry
- Measurements of personalized parameters
  - Thermal parameters (temperature, heat flux)
  - Metabolic rate
  - Clothing insulation

Thermal Energy Exchange: Human-Environment

- The **energy exchange** between **the human** and **the ambient environment** occurs:

  A. across the outer surface of the body
  1. via radiation Q_R
  2. via convection $Q_{conv,sk}$
  3. via conduction Q_{cond}
  4. via evaporation $Q_{E,sk}$

  B. through respiration
  1. via convection $Q_{conv,res}$
  2. via evaporation $Q_{E,rsp}$



Source: Ma et al. (2021)

$$Q_M = Q_R + Q_{conv,sk} + Q_{conv,res} + Q_{cond} + Q_{E,sk} + Q_{E,rsp} + \Delta Q_S \quad (2\text{-}1)$$

Sensible heat ($Q_R + Q_{conv,sk} + Q_{conv,res} + Q_{cond}$)

Latent heat ($Q_{E,sk} + Q_{E,rsp}$)

Analysis of Heat Exchange: Parameters

Table 1 — Main independent quantities involved in the analysis of the thermal balance between man and the thermal environment

Elements in the thermal balance	Quantities							
	T_a	T_{mrt}	v_a	p_a	I_{cl}	R_{cl}	M	W
	Air temperature	Mean radiant temperature	Air velocity	Absolute humidity of the air (partial pressure of water vapour)	Insulation of clothing	Evaporative resistance of clothing	Metabolism	External work
Internal heat production, $M - W$							x	x
Heat transfer by radiation, R		x			x			
Heat transfer by convection, C 1)	x		x		x			
Heat losses through evaporation:								
— evaporation from the skin, E			x	x		x		
— evaporation by respiration, E_{res}				x			x	
Convection by respiration C_{res}	x						x	

1) Heat transfer by convection is also influenced by body movements. The resultant air velocity at skin level is called relative air velocity (v_{ar}). Heat conduction (surface temperature) has only a limited influence on the total heat balance.

Source: ISO 7726:1998

Note: Abbreviations used in Lect 02 slides are $\boldsymbol{Q_R} = R, \boldsymbol{Q_{conv,sk}} = C, \boldsymbol{Q_{conv,res}} = C_{res}, \boldsymbol{Q_{E,sk}} = E, \boldsymbol{Q_{E,res}} = E_{res}$

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Analysis of Heat Exchange: Parameters

Table 2 — Characteristics of measuring instruments

Quantity	Symbol	Class C (comfort)			Class S (thermal stress)			Comments
		Measuring range	Accuracy	Response time (90%)	Measuring range	Accuracy	Response time (90 %)	
Air temperature	t_a	10 °C to 40 °C	Required: ± 0,5 °C Desirable: ± 0,2 °C These levels shall be guaranteed at least for a deviation $\lvert t_r - t_a \rvert$ equal to 10 °C.	The shortest possible. Value to be specified as characteristic of the measuring instrument.	− 40 °C to + 120 °C	Required: − 40 °C to 0 °C: ± (0,5 + 0,01 $\lvert t_a \rvert$) °C > 0 °C to 50 °C: ± 0,5 °C > 50 °C to 120 °C: ± [0,5 + 0,04 (t_a−50)] °C Desirable: $\frac{\text{required accuracy}}{2}$ These levels shall be guaranteed at least for a deviation $\lvert t_r - t_a \rvert$ equal to 20 °C.	The shortest possible. Value to be specified as characteristic of the measuring instrument.	The air temperature sensor shall be effectively protected from any effects of the thermal radiation coming from hot or cold walls. An indication of the mean value over a period of 1 min is also desirable.
Mean radiant temperature	t_{mrt}	10 °C to 40 °C	Required: ± 2 °C Desirable: ± 0,2 °C These levels are difficult or even impossible to achieve in certain cases with the equipment normally available. When they cannot be achieved, indicate the actual measuring precision.	The shortest possible. Value to be specified as characteristic of the measuring instrument.	− 40 °C to + 150 °C	Required: − 40 °C to 0 °C: ± (5 + 0,02 $\lvert t_a \rvert$) °C > 0 °C to 50 °C: ± 5 °C > 50 °C to 150 °C: ± [5 + 0,08 (t_r−50)] °C Desirable: − 40 °C to 0 °C: ± (0,5 + 0,01 $\lvert t_r \rvert$) °C > 0 °C to 50 °C: ± 5 °C > 50 °C to 150 °C: ± [0,5 + 0,04 (t_r−50)] °C	The shortest possible. Value to be specified as characteristic of the measuring instrument.	When the measurement is carried out with a black sphere, the inaccuracy relating to the mean radiant temperature can be as high as ± 5 °C for class C and ± 20 °C for class S according to the environment and the inaccuracy for v_a, t_a and t_g.

Source: ISO 7726:1998

Analysis of Heat Exchange: Parameters

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Table 2 — Characteristics of measuring instruments (*continued*)

Quantity	Symbol	Class C (comfort)			Class S (thermal stress)			Comments
		Measuring range	Accuracy	Response time (90%)	Measuring range	Accuracy	Response time (90 %)	
Plane radiant temperature	t_{pr}	0 °C to 50 °C	Required: ± 0,5 °C Desirable: ± 0,2 °C These levels shall be guaranteed at least for a deviation $\lvert t_{pr} - t_a \rvert < 10$ °C	The shortest possible. Value to be specified as characteristic of the measuring instrument.	0 °C to 200 °C	Required: – 60 °C to 0 °C: ± (1+ 0,1 $\lvert t_{pr} \rvert$) °C 0 °C to 50 °C: ± 1 °C 50 °C to 200 °C: ± [1 + 0,1 (t_{pr} – 50)] °C Desirable: $\frac{\text{required accuracy}}{2}$ These levels shall be guaranteed at least for a deviation $\lvert t_{pr} - t_a \rvert < 20$ °C	The shortest possible. Value to be specified as characteristic of the measuring instrument.	
Air velocity	v_a	0,05 m/s to 1 m/s	Required: ± (0,05 + 0,05 v_a) m/s Desirable: ± (0,02 + 0,07 v_a) m/s These levels shall be guaranteed whatever the direction of flow within a solid angle (:) = 3 π sr	Required: 0,5 s Desirable: 0,2 s	0,2 m/s to 20 m/s	Required: ± (0,1 + 0,05 v_a) m/s Desirable: ± (0,05 + 0,05 v_a) m/s These levels shall be guaranteed whatever the direction of flow within a solid angle (:) = 3 π sr	The shortest possible. Value to be specified as characteristic of the measuring instrument. For measuring the degree of turbulence a small response time is needed.	Except in the case of a undirectional air current, the air velocity sensor shall measure the velocity whatever the direction of the air. An indication of the mean value and standard deviation for a period of 3 min is also desirable.

Source: ISO 7726:1998

Analysis of Heat Exchange: Parameters

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Table 2 — Characteristics of measuring instruments (*concluded*)

Quantity	Symbol	Class C (comfort)			Class S (thermal stress)			Comments
		Measuring range	Accuracy	Response time (90%)	Measuring range	Accuracy	Response time (90 %)	
Absolute humidity expressed as partial pressure of water vapour	p_a	0,5 kPa to 3,0 kPa	± 0,15 kPa This level shall be guaranteed for a difference $\lvert t_r - t_a \rvert$ of at least 10 °C.	The shortest possible. Value to be specified as characteristic of the measuring instrument.	0,5 kPa to 6,0 kPa	± 0,15 kPa This level shall be guaranteed for a difference $\lvert t_r - t_a \rvert$ of at least 20 °C.	The shortest possible. Value to be specified as characteristic of the measuring instrument.	
Surface temperature	t_s	0 °C to 50 °C	Required: ± 1 °C Desirable: ± 0,5 °C	The shortest possible. Value to be specified as characteristic of the measuring instrument.	− 40 °C to + 120 °C	Required: < −10 °C: ± [1+0,05 (−t_s −10)] − 10 °C to 50 °C: ± 1 °C > 50 °C: ± [1 + 0,05 (t_s −50)] Desirable: $\frac{\text{required accuracy}}{2}$	The shortest possible. Value to be specified as characteristic of the measuring instrument.	
Radiation directional	I_d	From − 35 W/m² to + 35 W/m²	± 5 W/m²	Required: 1,0 s Desirable: 0,5 s	From − 300 to + 100 °C From 100 °C to 1000 °C From 1000 W/m² to 2500 W/m²	± 5 W/m² ± 10 W/m² ± 15 W/m²	Required: 1,0 s Desirable: 0,5 s	

NOTE — At some work places in hot environments (steel, coal, glass industries) there may be a need to measure plane radiant and surface temperatures at higher levels than the range in this table. The manufacturers of instruments are required to state the accuracy for an extended range.

Source: ISO 7726:1998

Homogeneous *vs.* Heterogeneous Environment

- **Homogeneous environment** – air temperature, radiation, air velocity, and humidity can be considered to be **practically uniform around the person** *at a given time*.

- **Heterogeneous environment** – the physical parameters **are not uniform around the person** *at a given time*.

  The physical parameters shall be measured *at several locations* **around the person** and *weighting factor of local measurements* should be considered to determine **the mean value**.

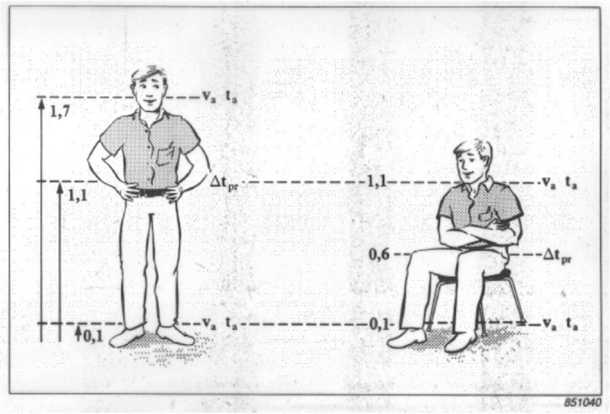

Table 5 — Measuring heights for the physical quantities of an environment

Locations of the sensors	Weighting coefficients for measurements for calculation mean values				Recommended heights (for guidance only)	
	Homogeneous environment		Heterogeneous environment		Sitting	Standing
	Class C	Class S	Class C	Class S		
Head level			1	1	1,1 m	1,7 m
Abdomen level	1	1	1	2	0,6 m	1,1 m
Ankle level			1	1	0,1 m	0,1 m

Class **C** - comfort, Class **S** – heat stress

Source: ISO 7726:1998

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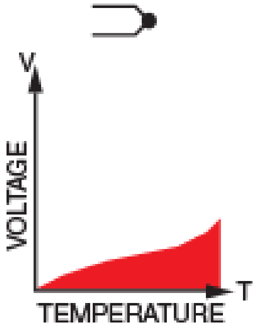
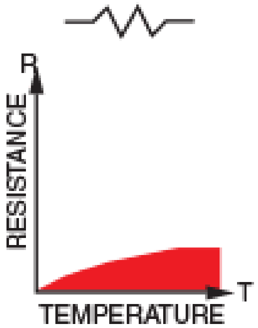
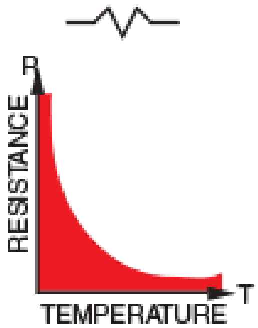
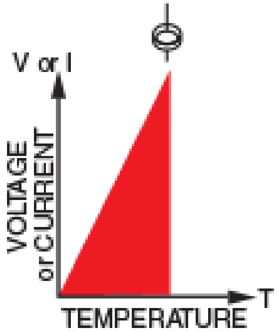
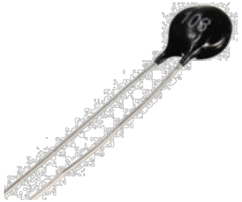
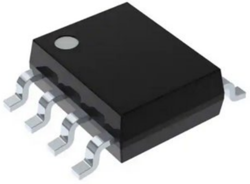
Temperature Sensing Instruments: Overview

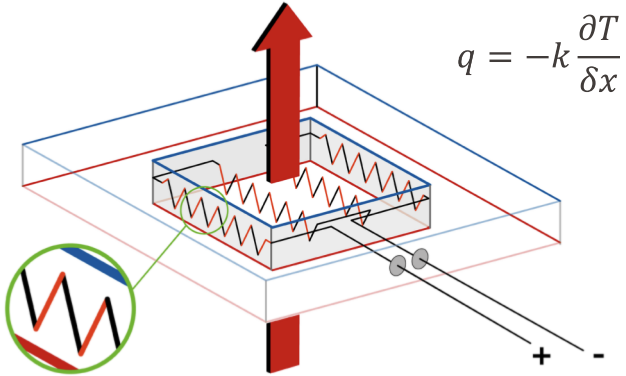
	Thermocouple	RTD	Thermistor	I. C. Sensor
				
Advantages	- Self-powered - Simple - Rugged - Inexpensive - Wide variety - Wide temperature range	- Most stable - Most accurate - More linear than thermocouple	- High output - Fast - Two-wire ohms measurement	- Most linear - Highest output - Inexpensive
Disadvantages	- Non-linear - Low voltage - Reference required - Least stable - Least sensitive	- Expensive - Current source required - Small Δ R - Low absolute resistance - Self-heating	- Non-linear - Limited temperature range - Fragile - Current source required - Self-heating	- T<200°C - Power supply required - Slow - Self-heating - Limited configurations



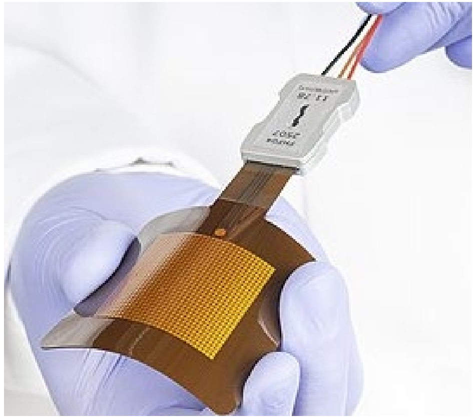


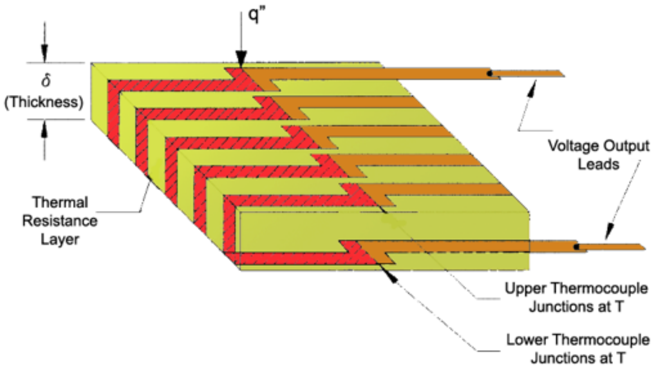
Heat Flux Sensing : Thermopiles

- Heat flux sensing - measurements of **a temperature difference** *across* a thin layer of material.
- Thermopiles are created by **alternating pattern** of **two dissimilar conductors** (metal allows).
- Sensors can be **rigid** or **flexible.**



$$q = -k\frac{\partial T}{\delta x}$$





https://www.hukseflux.com/applications/scientific-research-heat-and-heat-transfer-measurement/heat-flux-sensor-technology

Surface Temperature Measurements

- Measurements of the temperature of *a given surface* is useful to evaluate **radiant heat exchange** between the human body by means of T_{mrt} and/or T_{pr} and evaluate the effect of **direct contact** between the body and a given surface
- Types of measurements:
  - using a sensor *in contact with the surface*
  - *contactless* using infrared sensors

- **Contact thermometers**:
  - Important to have *a very good contact* between the sensor and the surface to assure higher heat exchange between *sensor-surface* rather than surface-environment.
  - Increase contact through large contact surface pressure, heat conductive paste, and insulating the sensor towards the environment
  - The contact *influences* the heat exchange surface-environment and then the measured surface temperature

- **Infrared radiometers** (**point** and **scanning**):
  - Measure the energy level of the *radiation incident on the detector* (radiation emitted by the object + radiation reflected from the surface of the object)
  - Accurate measurements require knowledge of *long-wave emissivity* of the object and *radiant field surrounding the object*
  - Temperature resolution *decreases* as an object temperature decreases

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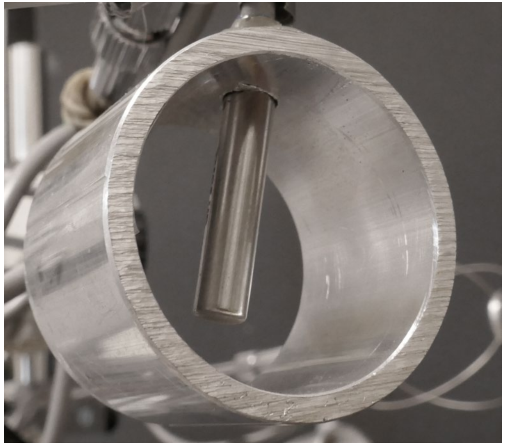
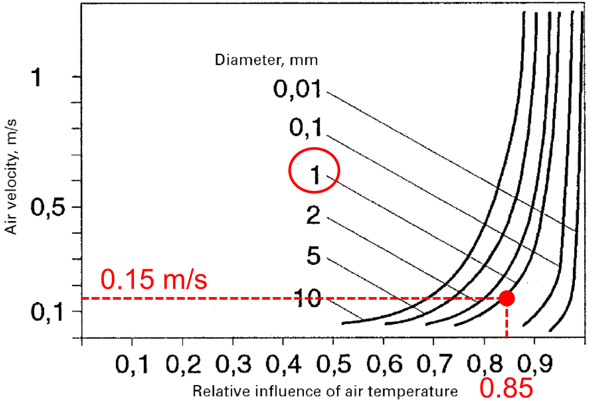
Air (Dry Bulb) Temperature Measurements

- It is important to measure **actual air temperature** by *reducing* **the effect of radiation** from *neighboring* **heat sources** (otherwise, the measured temperature will be *between* air and mean radiant temperature):
  - **By reducing of the emission factor of the sensor** (use polished sensors, made of metal or covered with a reflective paint)
  - **By using "reflective screens"** made from thin sheets *of reflective material* (i.e., aluminum). The inner screen shall be *separated from the sensor* by an air space large enough to allow air to circulate inside by natural convection
  - **By increasing the coefficient of heat transfer by convection**, by an increase in the air velocity around the sensor by forced ventilation and *by reduction of the sensor size* (i.e., use a thermistor/thermocouple)





Source: ISO 7726:1998

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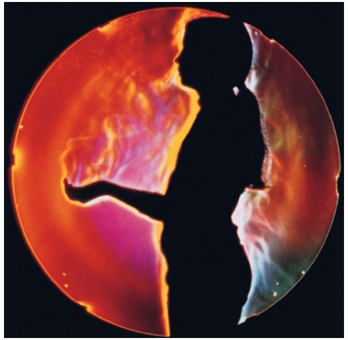
Measurements of Air Velocity/Speed

- *Air currents* can occur *near* cold/hot surfaces, near **ventilation inlets**; **convective air** current occur *naturally* **around the human body**
- *Air velocity* should be considered when determining **heat transfer** by **convection** and **evaporation** *at the position of a person*



Schlieren image of the thermal boundary layer and plume of a person (by Gary S. Settles)

- **Air Velocity (v_x, v_y, v_z):** a *vector* quantity (directional), **the distance that air flows per unit time**; it fluctuates randomly for turbulent flow, often changes direction in a relatively small spatial angle.
- **Air Speed:** a *scalar* quantity, the *magnitude* of the *velocity vector* of the flow *at the measuring point*

$$v_a = \sqrt{v_x^2 + v_y^2 + v_z^2} \quad (4\text{-}1)$$

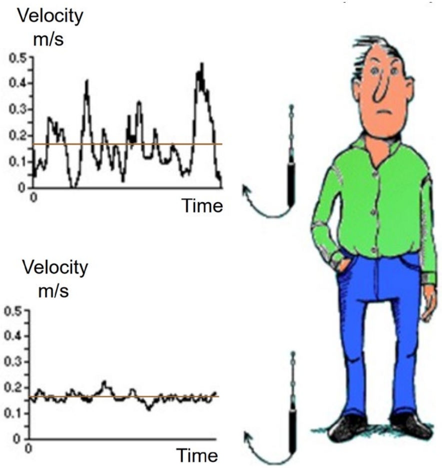
- **Turbulence Intensity (%):** fluctuations in air velocity

(4-2) $Tu = v_{RMS}/v_{a,mean}$ where $v_{RMS} = \sqrt{\frac{1}{N}\left(\sum_{t=1}^{t=N} v_i^2\right)}$ (4-3)

- **Draught Rate (%):** local cooling of the body due to air movement

$$DR = (34 - t_{op})(v_{a,mean} - 0.05)^{0.62}(0.37 \cdot v_{a,mean} \cdot Tu + 3.14) \quad (4\text{-}4)$$

Standardized acceptable draught rating (ISO 7730): **10%** (cat. I), **20%** (Cat. II), **30%** (Cat. III)



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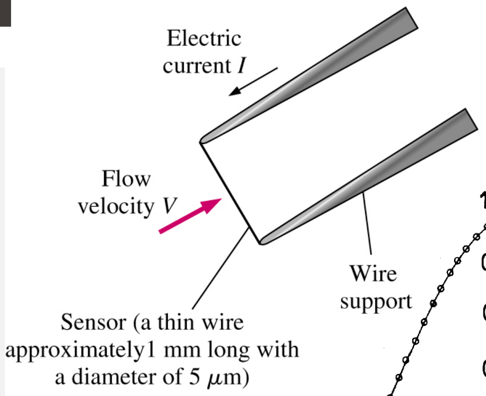
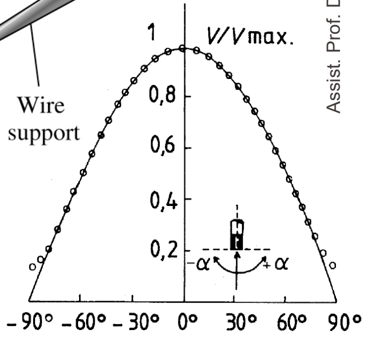
Measurements of Air Velocity/Speed

- **Characteristics of instruments to consider**:
  - *sensitivity* to the *direction* of airflow,
  - *sensitivity* to the *velocity fluctuations;*
  - possibility to obtain *mean* and *STD* over a measuring period
- **Measurements of air speed:**
  - Using ***omnidirectional anemometers*** *(sensitive to the magnitude of the velocity whatever its direction);*
  - using **3** ***unidirectional sensor*** that can measure **3** *components of the air velocity* in **3** *perpendicular axis* (in practice, it is hard to measure *accurately* in one direction)





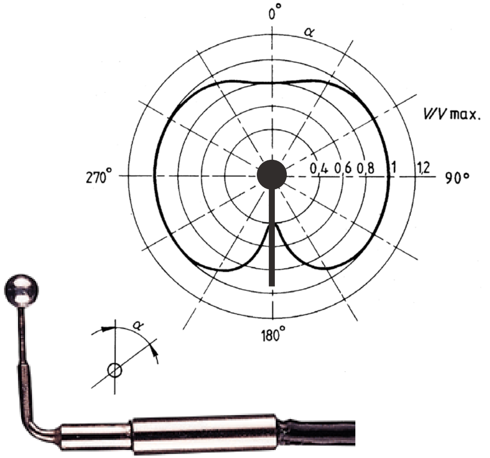
Examples of anemometers:

- **Hot-wire anemometers (directional)**

  When an electrically heated wire is placed in a flowing air stream, heat is transferred from the wire to the air and, hence, the temperature of the wire reduces, and due to this, the resistance of the wire also changes. This change in resistance of the wire becomes a measure of the flow rate.

- **Hot-sphere anemometers (insensitive to flow direction):**

  Based on the measurements of the heat transfer between a hot solid sphere and the ambient air, electrically heated sphere at temperature higher than the air temperature loses heat to its surrounding mainly by convection. The sensor has 2 temperature sensors (air temperature and a hot element temperature)



Humidity Measurements

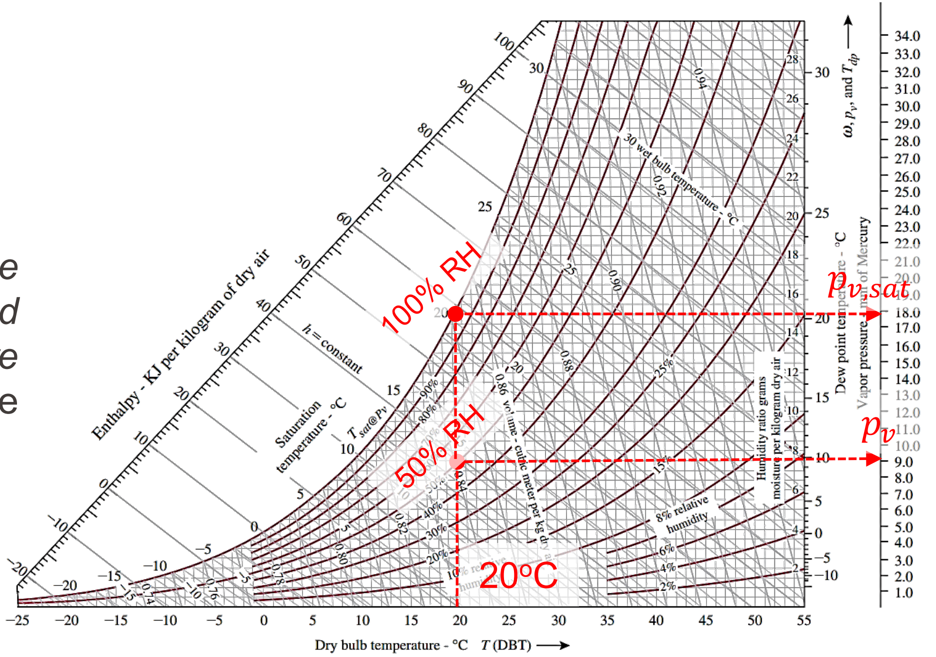
- **Absolute humidity** is determined by **specific humidity** and the **partial pressure of water vapor**
  - **Specific humidity q** is the ratio of the *mass of water vapour* **(kg)** on the sample to the *mass of dry air* **(kg)** in the sample (see Lect. 2, slide 19)
  - **Partial pressure** of **water vapor p_v** of the humid air is the pressure which the water vapor would exert *if it alone occupied the volume* occupied *by the humid air at the same temperature*

$$q = \frac{m_v}{m_a} = 0.622 \frac{p_v}{p_a - 0.378 \cdot p_v}$$

- p_v - partial pressure of water vapor (Pa or kPa)
- p_a – total atmospheric pressure (Pa or kPa)

  - **Relative humidity** is the ratio between *the partial pressure* p_a of water vapor *in humid air* and *the water vapor saturation pressure* p_{sa} at the same temperature and the same total pressure:

$$RH(\%) = \frac{p_v}{p_{v,sat}} \cdot 100\%$$



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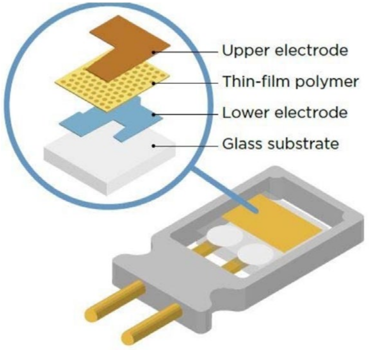
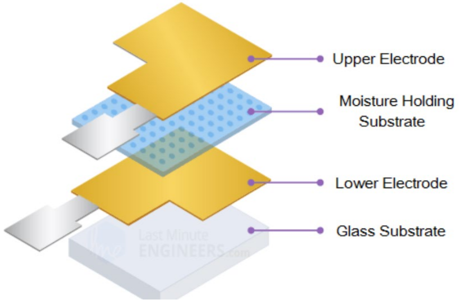
Humidity Measurements

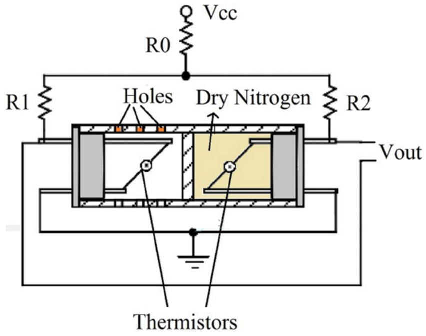
- Humidity sensors work by *detecting changes* that *alter electrical currents* or *temperature* in the air.
- There are *three* basic types of humidity sensors: **capacitive** and **resistive** for *relative humidity (RH) measurements*, and **thermal** for *absolute humidity (AH) measurements.*



- **Capacitive humidity sensor** (parameter-RH):
  These are the only types **of full-range relative humidity** measuring devices from 0% to 100% relative humidity. Electrical capacity of a *thin strip of metal oxide* between two electrodes changes with the atmosphere's relative humidity.



- **Resistive humidity sensor** (parameter-RH):
  Uses ions in salts to measure the electrical impedance of atoms, the **resistance of the electrodes** on either side of the salt medium changes **as humidity changes**.
- **Thermal humidity sensors** (parameter-AH):
  Use two probes (thermistors); one thermistor is hermetically sealed in a chamber filled with *dry nitrogen* while the other is *exposed to open environment* through small venting holes. When the circuit is powered on, **the resistance** of the two thermistors are calculated and **the difference between those two values** is directly proportional to **absolute humidity**.



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Operative Temperature (T_{op})

Reminder from L2

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- T_{op} is the **uniform temperature** of **an enclosure** in which *an occupant* would exchange *the same amount of heat* by **radiation** plus **convection** as *in the actual non-uniform environment*

$$\boldsymbol{T_{op}} = \frac{h_c}{h_c + h_r} \cdot T_a + \frac{h_r}{h_c + h_r} \cdot T_{mrt} \quad (2\text{-}8a)$$

$$\boldsymbol{T_{op}} = \boldsymbol{A} \cdot T_a + (1 - \boldsymbol{A}) \cdot T_{mrt} \quad (2\text{-}8b)$$

where a coefficient A is

$$\boldsymbol{A} = \frac{h_c}{h_c + h_r} = \frac{1}{1 + {h_r}/{h_c}} \quad (2\text{-}9)$$

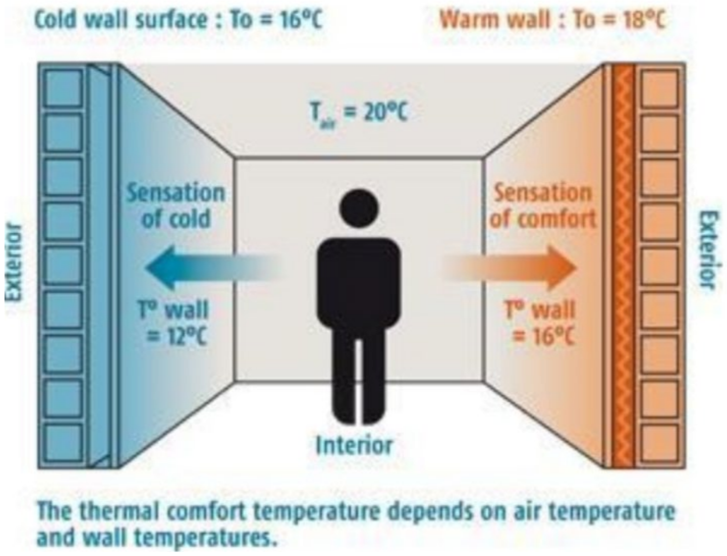
Simplified consideration of A values:

V_a	<0.2 m/s (<40 fpm)	0.2 to 0.6 m/s (40 to 120 fpm)	0.6 to 1.0 m/s (120 to 200 fpm)
A	0.5	0.6	0.7

Special case:
if v_a < 0.2 m/s → A=0.5:

$$\boldsymbol{T_{op}} = \frac{T_a + T_{mrt}}{2} \quad (2\text{-}10)$$

Source: ISO 7726, ASHRAE 55-2017

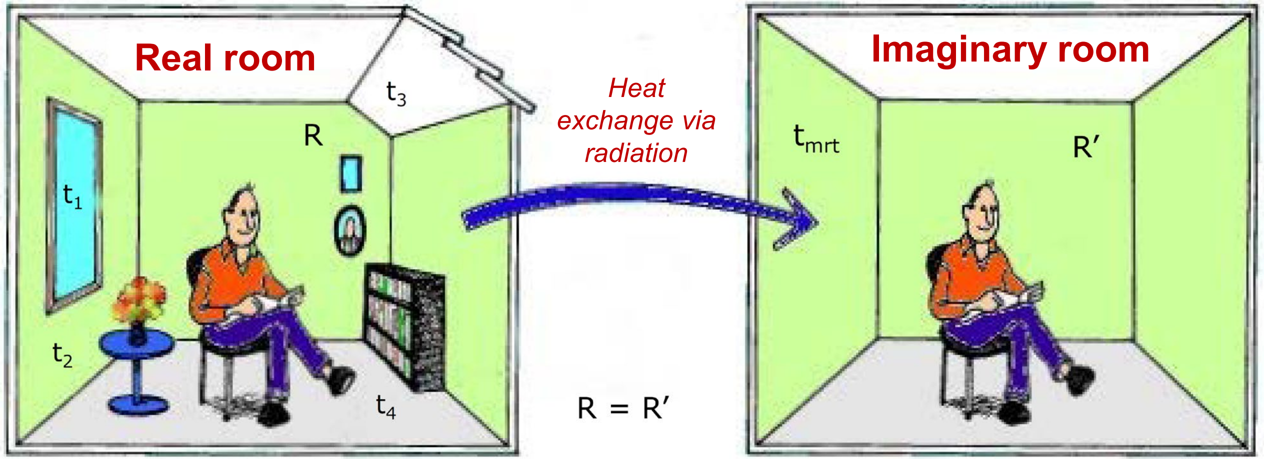


Mean Radiant Temperature: Definition

Reminder from L2

- Almost **half** of **thermal comfort** is driven by **radiant heat exchange** between *the human* and *the surrounding environment*
- **MRT** or T_{mrt} is the uniform **surface temperature** of an **imaginary black enclosure** in which an occupant would *exchange* ***the same amount of radiant heat*** as in the ***actual non-uniform space***.
- **MRT** is an abstract parameter introduced in 1931 (by Barker) *to facilitate* **radiant heat transfer calculations**.

Source: ASHRAE 55-2017



$Q_{rad,i} = \sigma \cdot F_{p\to i} \cdot (T_p^4 - T_i^4)$

$Q_{rad} = \sigma \cdot (T_p^4 - T_{mrt}^4)$

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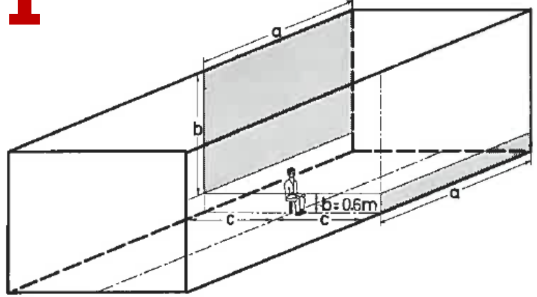
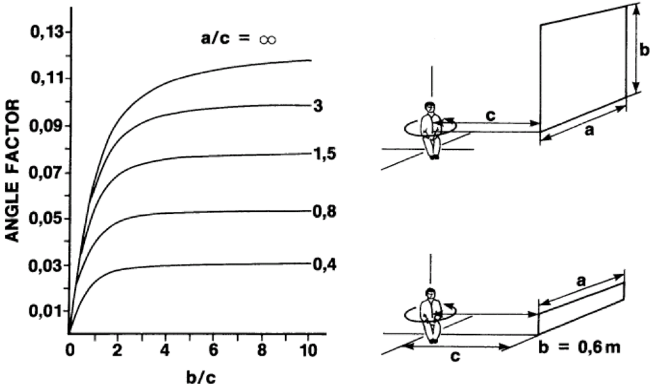
Mean Radiant Temperature: Method 1

1. Calculation using geometrical shape factors (Fanger-Rizzo method):

- The *main method* for indoor environment with **orthogonal geometries**
- MRT can be calculated from measured values of the **temperature of surrounding walls**, the **size** of these **walls** and their **position** *in relation to* a **person** (considering weighted view factors for radiant heat transfer)
- Surfaces are categorized into **vertical** and **horizontal** ones. For every single vertical/horizontal surface, it is then divided into *4 different surfaces* to be analyzed using geometric relationship between a person and a surface in a Cartesian coordinate system
- **Angle/view factor** is *a function* of **dimensionless ratios *a/c*** and ***b/c*** (***a*** – dimension in x-direction, ***b*** – dimension in y-direction, ***c*** – distance from the location of the person to the surface of interest)





$$T^4_{mrt} = \sum F_{p,i} \cdot T^4_{s,i}$$

$$\sum F_{p,i} = 1$$

Angle/View factor from a person to i-th surface

i-th surface temperature

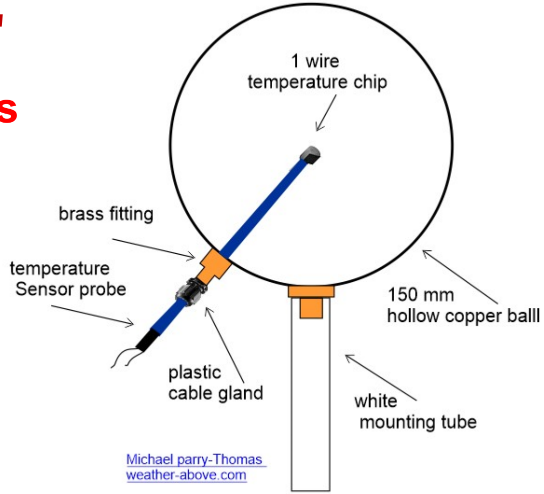
Source: ASHRAE HOF, 2017; Guo H. et al (2020) https://doi.org/10.1016/j.rser.2019.06.014

More details are available in file "Angle Factor Algebra.pdf"

Mean Radiant Temperature: Method 2

2. Estimated from the globe temperature measurements

- The globe thermometer was introduced in 1932 (by Vernon) as **a device** to measure **the radiation** from the *surrounding environment* to *a human body*
- It is **a thermometer** with a *thermally sensitive element* located *at the center* of **a blacked hollow sphere** (the surface darkened using electro-chemical coating or matt black paint).
- ***Assuming the globe thermometer is in equilibrium***, its reading from internal thermometer will reflect the **convective** and **radiative heat exchange** *around* **the globe thermometer**.
- The globe can have any diameter, but *the standard dia*meter is **6 inch (0.15 m). A large globe** has a *greater* response to **incident radiation**.
- The black globe thermometer, **because of its high inertia**, **can not be used** to determine the radiant temperature of environments **which vary rapidly.**



Source: ASHRAE HOF, 2017; ISO 7726; Guo H. et al (2020) https://doi.org/10.1016/j.rser.2019.06.014

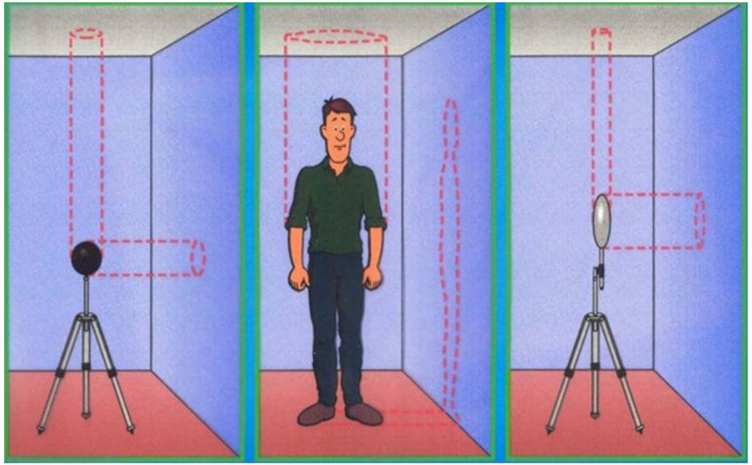
Globe Temperature Sensor: Shape

- As a *person's angle factor to their surroundings* changes as **they change position**
- The globe temperature sensor should also be able to consider *different positions* in order for it to properly sense in different workplaces.

Shape consideration:

- **Spherical sensor** gives only *approximation* of the shape of the body for a *seated person* (better *if* positioned in the centre of a room)
- **An ellipsoid-shaped sensor** provides approximation to **the human shape** both for *seated* and *upright* position (can over evaluate the influence of the wall if positioned ***close*** to heated or cooled wall)

- In case of **heterogeneous radiation**, it is necessary to use **3 globes**. The measurement from *a single globe sensor is not representative* of the *overall radiative field* received by the person.

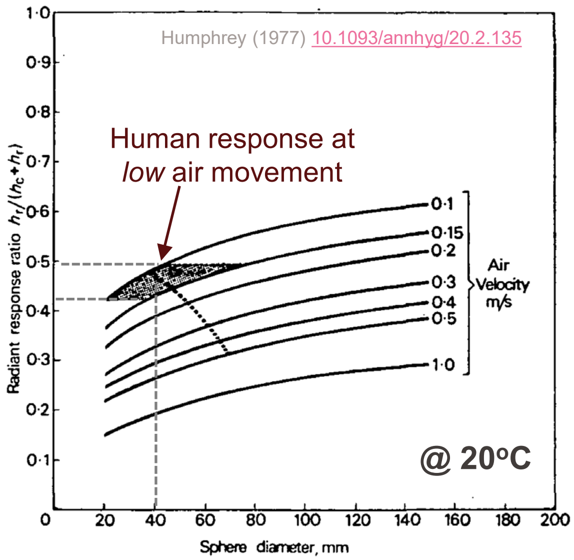


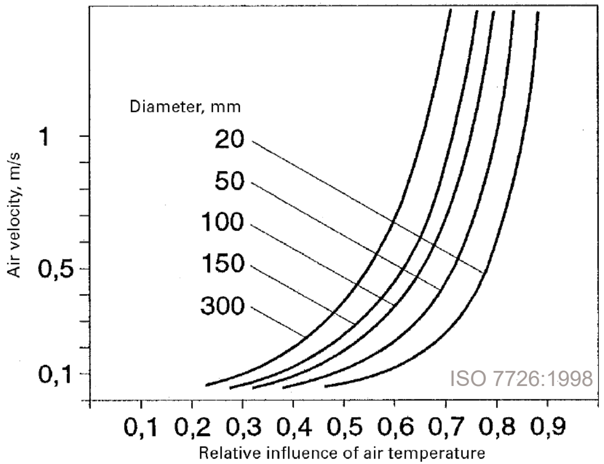
Adopted from Dr. Sam C.M. Hui

Source: Humphrey (1977) 10.1093/annhyg/20.2.135

Globe Temperature Sensor: Size

- The globe should have a **size** which **responds** to **radiation** and **convection** in ***proportions similar*** to those in **the human body.**
- Human response to radiation and convection when air flow is **0.1-0.15** m/s:
  - **0.54** for air and **0.46** for mean radiant temperature
  - Radiant response ratio = 0.42 - 0.50 (95% prob.)
- The surface of the clothed human body *is not entirely convex*, **the effective area for radiation** is, therefore, considerably less than that for convection. As a result, the same ratio of convection to radiation can be obtained from the much smaller convex object.
- The *smaller* the diameter of the globe, *the greater the effect* of the *air temperature* and *air velocity* causing *a reduction in accuracy* of T_{mrt} measurement.
- For **regular and uniform indoor conditions** (22-25°C), a globe of **40 mm** would give *sufficient relative weight* to T_a and T_{mrt}.





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Globe Temperature (T_g) and MRT (T_{mrt})

- Heat balance between **the globe** (sensor inside the globe) and **the surrounding environment**:

$$Q_{rad} + Q_{conv} = 0 \quad (4\text{-}5)$$

- Heat transfer by **radiation** between *the sensor* and *the walls of the enclosure (room)*:

$$Q_{rad} = \varepsilon_g \cdot \sigma \cdot (T_{mrt}^4 - T_g^4) \quad (4\text{-}6)$$

- Heat transfer by **convection** between *the sensor* and *enclosed air:*

$$Q_{conv} = h_{conv} \cdot (T_a - T_g) \quad (4\text{-}7)$$

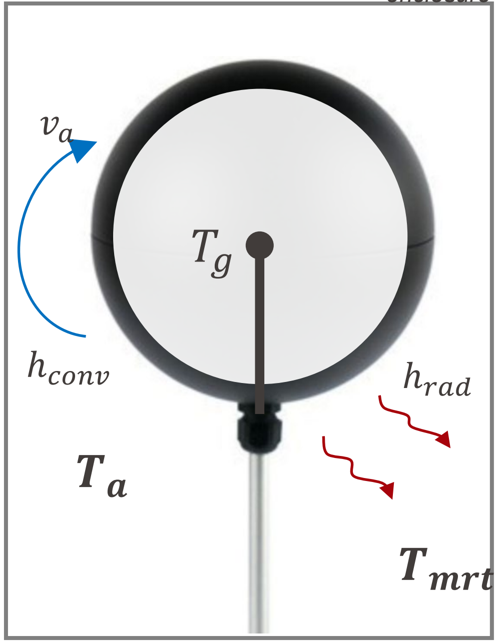
  - **Radiative heat transfer coefficient** for a sphere small compared with its surrounding enclosure of high emissivity:

$$(4\text{-}8) \quad h_{rad} = 4 \cdot \varepsilon_g \cdot \sigma \cdot T_{mrt}^3$$

Stefan-Boltzmann constant:
σ = 5.67$\cdot 10^{-8}$ W/m^2K^4

  - **Convective heat transfer coefficient**: (see next slide)

enclosure



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Globe Temperature (T_g) and MRT (T_{mrt})

- **Convective heat transfer coefficient**:
  - ***Natural convection:*** *(air speed v_a < 0.05 m/s)*

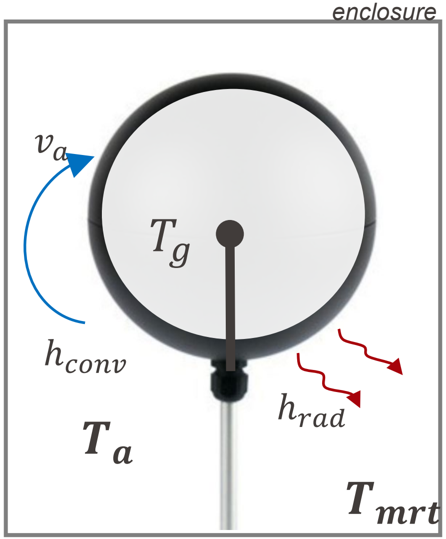
$$h_{conv} = 1.4 \cdot \left(\frac{T_g - T_a}{D}\right)^{1/4} \quad (4\text{-}9)$$

  - ***Forced convection:*** *(air speed v_a > 0.05 m/s, considering air properties variation with temperature)*

$$h_{conv} = 0.32 \cdot k_a \cdot \left(\frac{\rho_a}{\mu_a}\right)^{0.6} \cdot \frac{v_a^{0.6}}{D^{0.4}} \quad (4\text{-}10a)$$

  - ***Forced convection:*** *(for air properties at **20ºC**)*

$$h_c = 6.3 \cdot \frac{v_a^{0.6}}{D^{0.4}} \quad (4\text{-}10b)$$



D – globe diameter, in [m]

- **Relationship between MRT (T_{mrt}) and globe temperature (T_g)** :
  (combining Eqn. 4-6 & Eqn. 4-7 in Eqn. 4-5):
  - **Natural convection**:

$$t_{mrt} = \left[(t_g + 273)^4 + \frac{0.25 \cdot 10^8 \cdot (t_g - t_a)^{1/4}}{\varepsilon_g \cdot D} \cdot (t_g - t_a)\right]^{1/4} - 273 \quad (4\text{-}11)$$

  - **Forced convection**: *(for air properties at **20ºC**)**

$$t_{mrt} = \left[(t_g + 273)^4 + \frac{1.1 \cdot 10^8 \cdot v_a^{0.6}}{\varepsilon_g \cdot D^{0.4}} \cdot (t_g - t_a)\right]^{1/4} - 273 \quad (4\text{-}12)$$

** If actual air properties are not at **20ºC**, thermophysical properties of air corresponding to <u>actual temperature</u> should be used to calculate h_{conv}*

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Mean Radiant Temperature: Method 3

3. Estimated based on the plane radiant temperature (T_{pr}) in six opposite directions weighted according to *the projected area factors* for a person

- MRT can be calculated by multiplying 6 measured T_{pr} values by the *relevant* **projection factors** *adding* the resultant data and *dividing* the result by *the sum of the projected area factors* for a specific position (when orientation is not fixed, the average of the Right/Left and Front/back projected area factors is used)

Projected Area Factors:		UP/ DOWN	LEFT/ RIGHT	FRONT/ BACK
Standing	Person	0.08	0.23	0.35
	Ellipsoid	0.08	0.28	0.28
	Sphere	0.25	0.25	0.25
Seated	Person	0.18	0.22	0.30
	Ellipsoid	0.18	0.22	0.28
	Sphere	0.25	0.25	0.25

ISO 7726:1998

- **Standing person**:

$$t_{mrt} = \frac{0.08 \cdot [t_{pr,UP} + t_{pr,DOWN}] + 0.23 \cdot [t_{pr,R} + t_{pr,L}] + 0.35 \cdot [t_{pr,FRONT} + t_{pr,BACK}]}{2 \cdot (0.08 + 0.23 + 0.35)} \quad (4\text{-}13)$$

- **Sitting person**:

$$t_{mrt} = \frac{0.18 \cdot [t_{pr,UP} + t_{pr,DOWN}] + 0.22 \cdot [t_{pr,R} + t_{pr,L}] + 0.30 \cdot [t_{pr,FRONT} + t_{pr,BACK}]}{2 \cdot (0.18 + 0.22 + 0.30)} \quad (4\text{-}14)$$

Plane Radiant Temperature (T_{pr}): Method A

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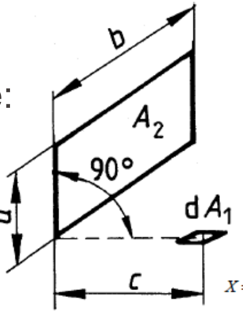
Method A: Using surface temperatures and angle factors:

- Need to know temperature of surrounding surfaces ($T_{s,N}$)
- Angle factor between a small plane element and the surrounding surfaces ($F_{p\to N}$), a function of the shape, the size, and the relative position of the surface in relation to a person

$$T_{pr}^4 = T_{s,1}^4 \cdot F_{p\to 1} + T_{s,2}^4 \cdot F_{p\to 2} + .. + T_{s,N}^4 \cdot F_{p\to N} \quad (4\text{-}15)$$

- Shape factor for a small plane element perpendicular (⊥) to a rectangular surface:

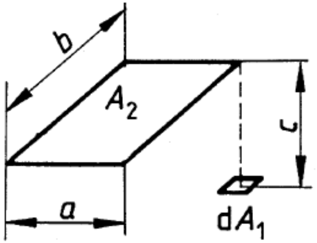


$X = \frac{a}{b}$ $Y = \frac{c}{b}$

(4-16) $$F_{A1\to A2} = \frac{1}{2\cdot\pi}\cdot\left(\tan^{-1}\frac{1}{Y} - \frac{Y}{\sqrt{X^2+Y^2}}\cdot\tan^{-1}\frac{Y}{\sqrt{X^2+Y^2}}\right)$$

- Shape factor for a small plane element parallel (∥) to a rectangular surface:

(4-17) $$F_{A1\to A2} = \frac{1}{2\cdot\pi}\cdot\left(\frac{X}{\sqrt{1+X^2}}\cdot\tan^{-1}\frac{Y}{\sqrt{1+X^2}} - \frac{Y}{\sqrt{1+Y^2}}\cdot\tan^{-1}\frac{X}{\sqrt{1+Y^2}}\right)$$



$X = \frac{a}{c}$ $Y = \frac{b}{c}$

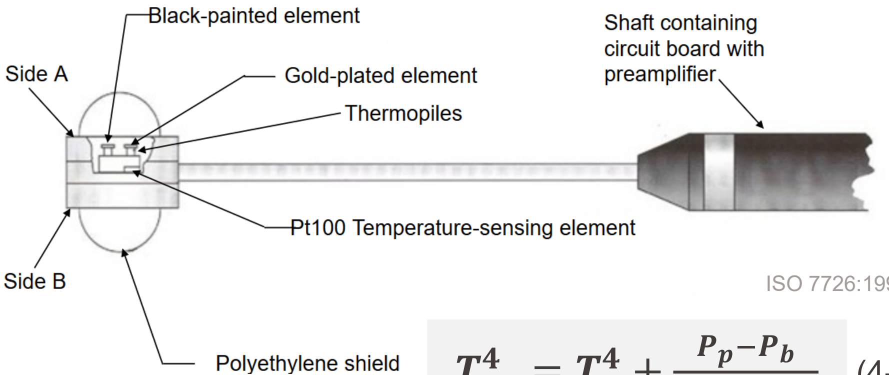
Plane Radiant Temperature (T_{pr}): Method B-1

Methods B: Using compensation approach

B-1. Using a **heated sensor** with **reflective** and **absorbing discs**
B-2. Using **a constant air temperature disk** (see details in ISO 7726)
B-3. Using **a net radiometer**

B-1: A heated sensor with reflective and absorbing discs:

- The *gold-plated disc (reflective)* loses heat *almost entirely by convection*
- The *black painted disc (absorbing)* loses heat *both by convection* and *radiation*.
- If both discs are heated to the same temperature, the *difference in heat supply to the two discs is equal to the heat transfer by radiation* between the painted disc and the environment



ISO 7726:1998

$$T_{pr}^4 = T_s^4 + \frac{P_p - P_b}{\sigma \cdot (\varepsilon_b - \varepsilon_p)} \quad (4\text{-}18)$$

T_s [K] - disk temperature
P_p , P_b $[W/m^2]$- heat supply to the polished (p) and black (b) disks
ε_p , ε_b $[W/m^2]$- emissivity of the polished (p) and black (b) disks
σ $[W/m^2 K^4]$- Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$)

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Plane Radiant Temperature (T_{pr}): Method B-3

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B-3: Net radiometer:

- A sensor consisting of a small **black plane element** with **a heat flow meter** (thermopile) between *the two sides* of the element
- The ***net heat*** between two sides is equal to the *difference between the radiant heat transfer* at the level of the two sides of the element

*Example of the **SW** and **LW** net radiometer NR01 by* ***Hukseflux***

- The net radiation NR (W/m^2) measured:

(4-19) $$NR = \sigma\,(T^4_{pr,1} - T^4_{pr,2})$$

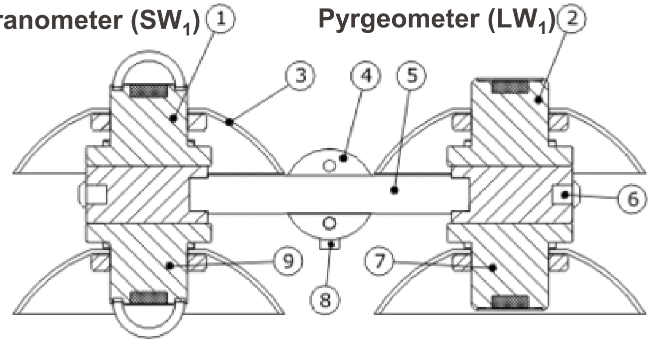
- The plane radiant temperature T_{pr}(K):

(4-20) $$T_{pr,1} = \sqrt[4]{0.95 \cdot T^4 + \frac{NR}{\sigma}}$$

written for side *1*

- Plane radiant temperature asymmetry:

(4-21) $$\Delta\,T_{pr} = NR/(4 \cdot \sigma \cdot T^3)$$



Pyranometer (SW): 0.3-2.8 μm, **Pyrgeometer (LW)**: 4.5-100 μm

EPFL

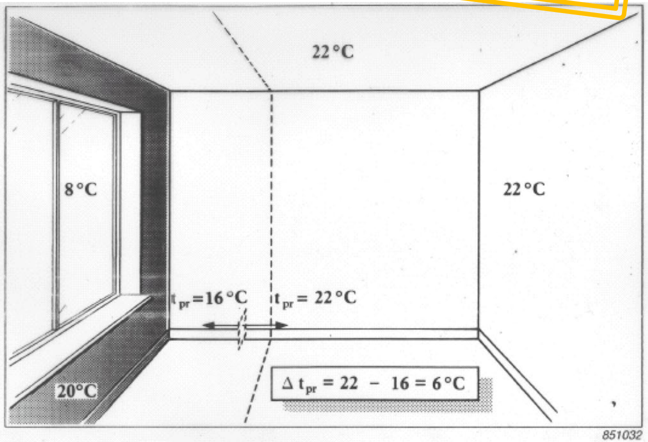
Planar Radiant Temperature Asymmetry

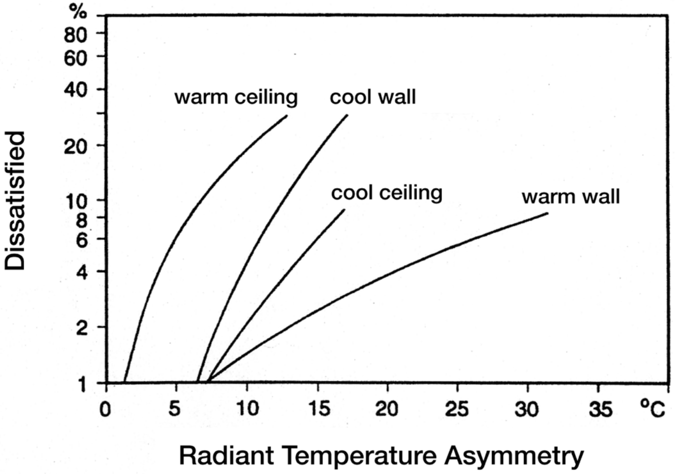
Reminder from L1

- **Radiant temperature asymmetry** is the *difference* between **plane radiant temperature** of the *two opposite sides* of *a small plane element:*

$$\Delta t_{pr} = t_{pr,1} - t_{pr,2} \quad (4\text{-}22)$$

- It is *measured* or *calculated* from the measured value of **the plane radiant temperature** in the **two opposing directions**
- The concept is used when the T_{mrt} *does not completely describe* the radiative environment (i.e., when the radiation is coming from opposite parts of the space varies substantially)
- The asymmetric radiant field is defined *in relation to the position of* **the plane element** used *as a reference*. It is necessary to specify the direction of the normal to this element.





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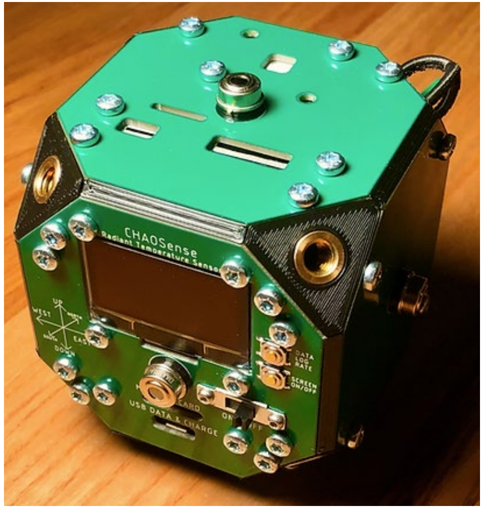
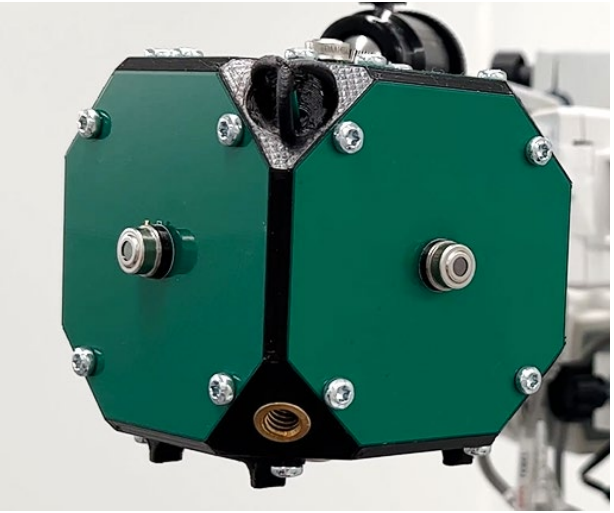
Mean Radiant Temperature (T_{mrt}): Method 4

4. Measurement method using thermopile IR sensors:

- Radiant heat flux (infrared IR) is measured directly **using IR thermopiles** [applicable only for indoor use as LW is measured]
- MRT measurement is more precise than using the globe sensors (± 0.3°C)
- High frequency of measurements (4 Hz)
- Latest development: CUBE sensors (mini.RES) https://www.chaosense.com/



https://www.chaosense.com/product-page/adam



https://www.melexis.com/en/product/MLX90614/Digital-Plug-Play-Infrared-Thermometer-TO-Can

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CONTENT:

- Overview of environmental parameters
- **Measurements of environmental parameters:**
  - Temperature, heat flux sensing
  - Air temperature, velocity/speed, humidity
  - Operative / Globe / Mean radiant temperature
  - Plane radiant temperature / Radiant asymmetry
- **Measurements of personalized parameters:**
  - **Thermal parameters (temperature, heat flux)**
  - **Metabolic rate**
  - **Clothing insulation**

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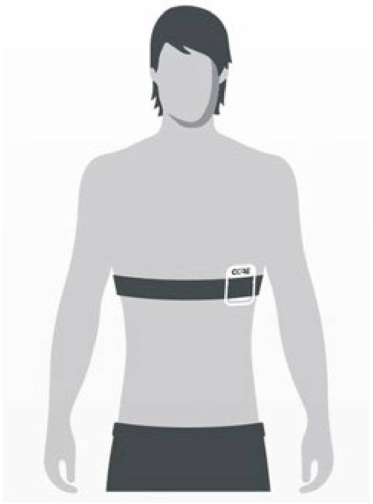
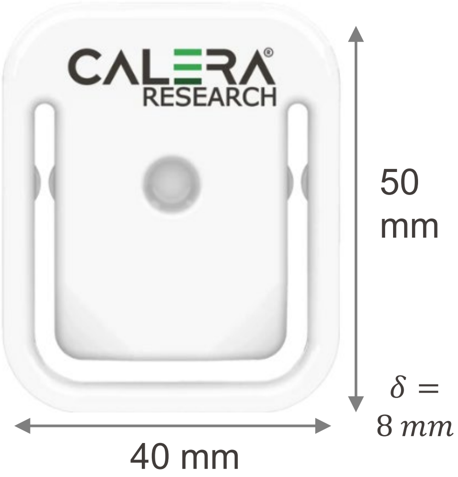
Human: Thermal Parameters

- **Parameters needed from the human:**
  - Clothing temperature (t_{cl})
  - Skin temperature (t_{skin})
  - Heat loss from the human body (Q)
- **Practical sensing issues:**
  - Needs to be wearable and wireless
- **Instruments used by the ICE lab:**
  - **CALERA sensor** (research version) by *greenTEG* (weblink)
  - Sensing based on a thermopile
  - **Temperature** (^oC) and **heat flux** (W/m^2) measurements
  - Heat flux measured includes **convection** + **radiation**
  - High frequency (1 Hz)
  - Wearable, relatively small
  - If placed on the *clothing surface*, measures *clothing* parameters
  - If placed on the *naked skin*, measures *skin* parameters





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Human Metabolic Rate: Different Components

<table>
<tr><td colspan="2">60-70%</td><td colspan="5">10-15%</td><td colspan="3">15% (sedentary) – 50% (highly active)</td><td></td></tr>
<tr><td colspan="10">Total Daily Energy Expenditure (TDEE)</td><td></td></tr>
<tr><td colspan="2">Basal Metabolic Rate (BMR)*
in post-absorptive state</td><td colspan="5">Thermic Effect of Food (TEF)</td><td colspan="3">Activity Thermogenesis (AT)**</td><td rowspan="3">Subcategory</td></tr>
<tr><td rowspan="2">Sleep
metabolic rate
(SMR)</td><td rowspan="2">Arousal
(no physical activity)
≈5% of BMR</td><td rowspan="2">Digestion</td><td rowspan="2">Absorption</td><td rowspan="2">Assimilation</td><td rowspan="2" colspan="2">Storage of nutrients</td><td colspan="2">Non-exercise
(NEAT)</td><td>Exercise
(EAT)</td></tr>
<tr><td>Spontaneous (SPA)
(posture maintenance, fidgeting)</td><td>Occupa-tional & leisure</td><td>Voluntary
(exercise, sports)</td></tr>
<tr><td colspan="2">Fat-free mass (3/4 of BMR), fat mass (obesity), genetic traits</td><td colspan="5">Diet composition, physical activity, obesity, insulin resistance</td><td colspan="3">Muscle tone, genetic traits</td><td rowspan="2">Determinants</td></tr>
<tr><td colspan="10">Gender, age, environmental stimuli*</td></tr>
</table>

* The term "**BMR**" is used only for *neutral condition*, while the term "**RMR**" needs to be used *beyond neutrality*

** **AT** is the *most* variable component of TDEE due to the *inter*- and *intra*-personal variability

Illustration adopted from Lam & Ravussin (2016) Analysis of energy metabolism in humans: A review of methodologies

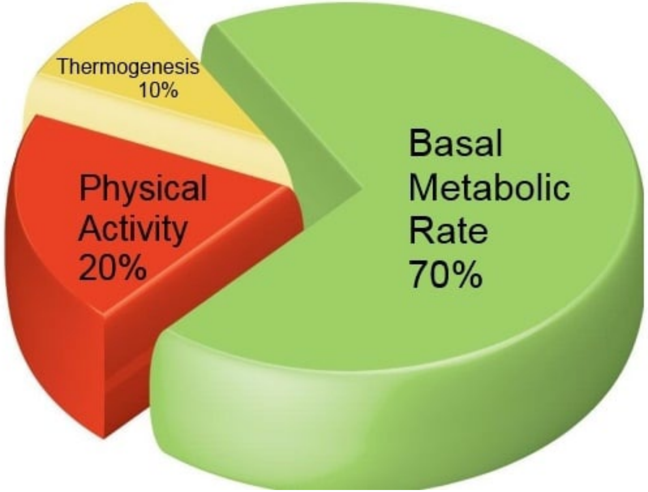
Human Metabolic Rate: BMR

- **Harris-Benedict Equation (kcal/day):**

$$\boldsymbol{BMR} = 88.362 + 13.397 * \boldsymbol{Body\ Mass} + 4.799 * \boldsymbol{Height} - 5.677 * \boldsymbol{Age} \quad (4\text{-}23)$$

$Body\ Mass$ – body mass (in kg), $Height$ – body height in (cm), Age – age of the person

Image from COSMED https://www.cosmed.com/en/products/indirect-calorimetry/quark-rmr



Human Metabolic Rate: Methods

Standard ISO 8996:2004

- **LEVEL 1** -“***Screening***”: the simplest one to use in practice (the least accurate), provides a classification of metabolic rate values per:
  - Method (**1A**): occupation
  - Method (**1B**): kind of activity
- **LEVEL 2** - “***Observational***”: time-weighted average metabolic rates based on the noted transient activity types are calculated using the classification determined in Level 1
- **LEVEL 3** – “***Analysis***”: Metabolic rate is determined *indirectly* from *heart rate (HR)* recordings
- **LEVEL 4** - “***Expertise***”: the most precise, but the most *complex* and *expensive* ones, 3 methods for measuring metabolic rate in humans:
  - Method (**4A**): ***indirect calorimetry*** (based on the O2 consumption, CO2 production)
  - Method (**4B**): using *doubly labelled water* (applicable for 1-2 weeks of measurements)
  - Method (**4C**): ***direct calorimetry***

(3)

https://theheartfoundation.org/

$$HR = HR_0 + RM \times (M - M_0)$$

$$RM = (HR_{max} - HR_0)/(MWC - M_0)$$

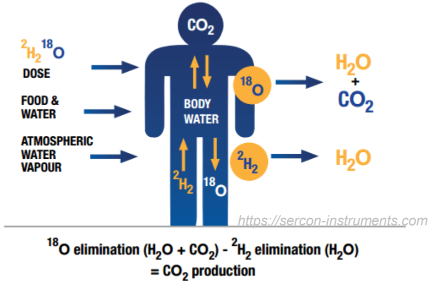
$$HR_{max} = 205 - 0{,}62A$$

Men: $MWC = (41{,}7 - 0{,}22A)P^{0{,}666}$

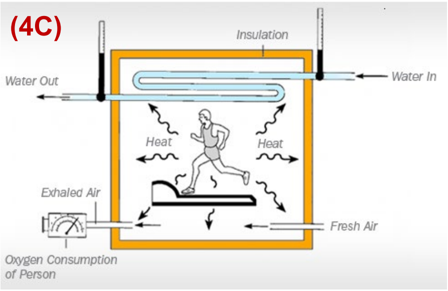
Women: $MWC = (35{,}0 - 0{,}22A)P^{0{,}666}$

(4A)

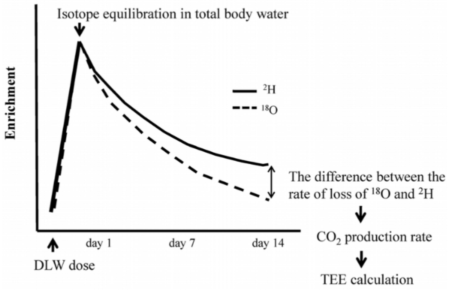
(4B)



(4C)

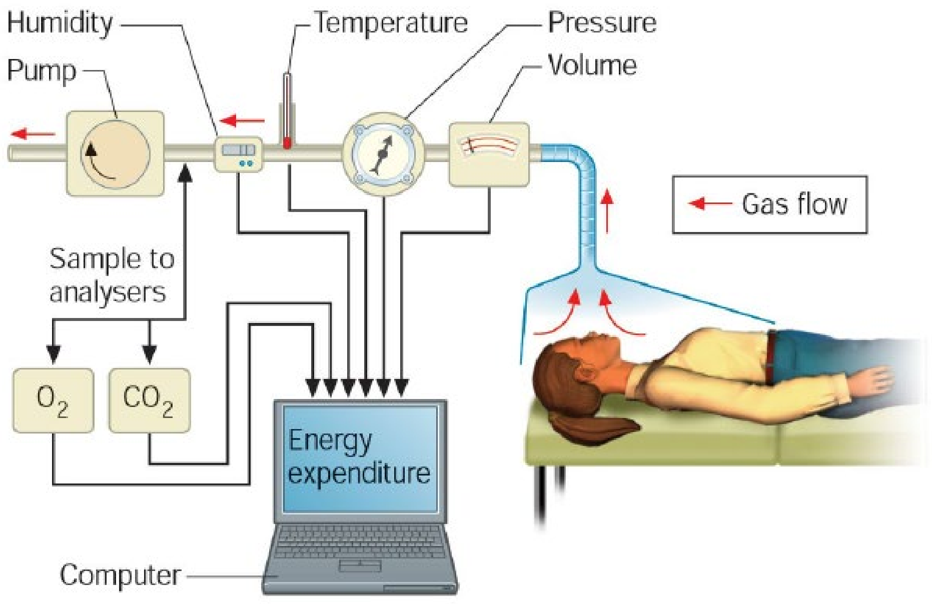


https://payneg13.wordpress.com/



https://www.researchgate.net/

Human Metabolic Rate: Indirect Calorimetry



- **Weir's formula to estimate metabolic rate** $(kcal/min)$:

$$EE = 5.68 \cdot V_{O2} + 1.59 \cdot V_{CO2} - 2.17 \cdot N_u \quad (4\text{-}24)$$

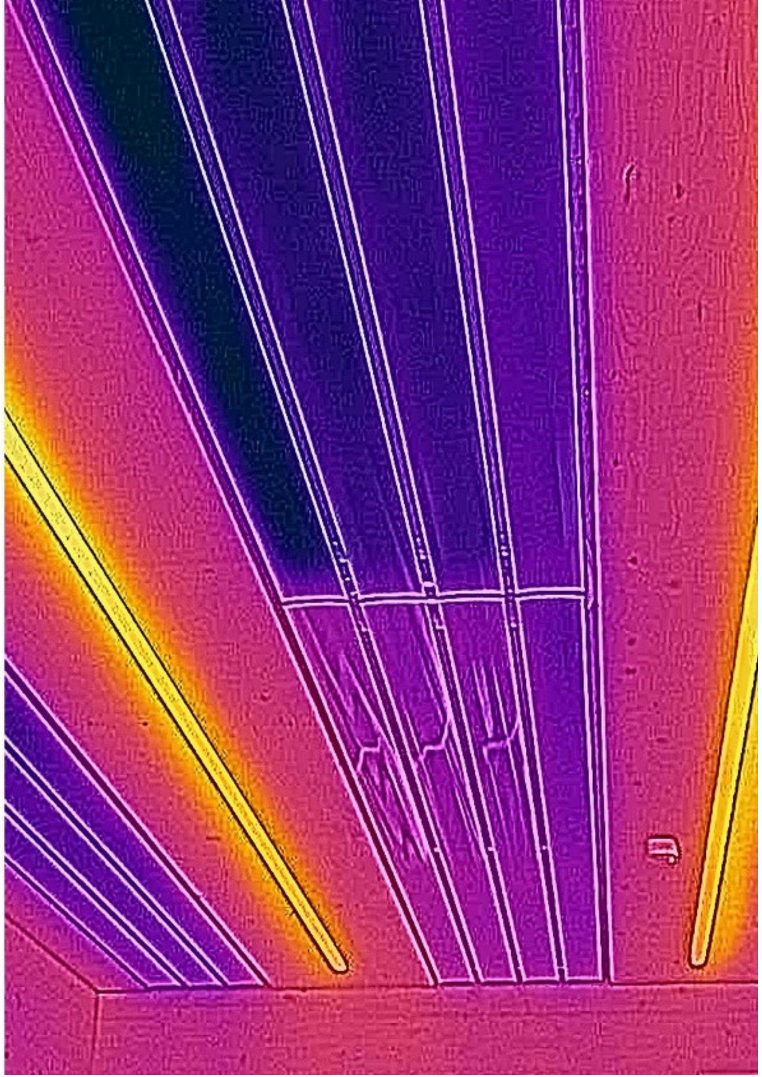
V_{O2} and V_{CO2} - volume of oxygen inhaled and CO2 exhaled (in ml/min),
N_u - nitrogen urea (g/kg), default value is 12 g/kg

Images adopted from Melanson et al. (2010), COSMED

Assist. Prof. Dolaana Khovalyg

Clothing Insulation Measurements: Overview

- **Primarily done with measurements using thermal manikins:**
  - Sophisticated devices resembling human body (from simple to realistic configurations)
  - They can vary **surface temperature** and the **amount of heat supplied** precisely
  - Can be only **thermal** and **thermal** + **sweating** [suitable for vapor resistance testing]
  - There are also manikins for only a specific body part (a head, a foot)



Thank you for your attention

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