EPFL

CIVIL - 450: THERMODYNAMICS of COMFORT in BUILDINGS

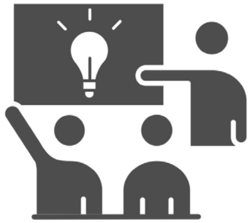
Dolaana Khovalyg

Lecture 02:

Human Body Energy Balance

28 February 2025

EPFL 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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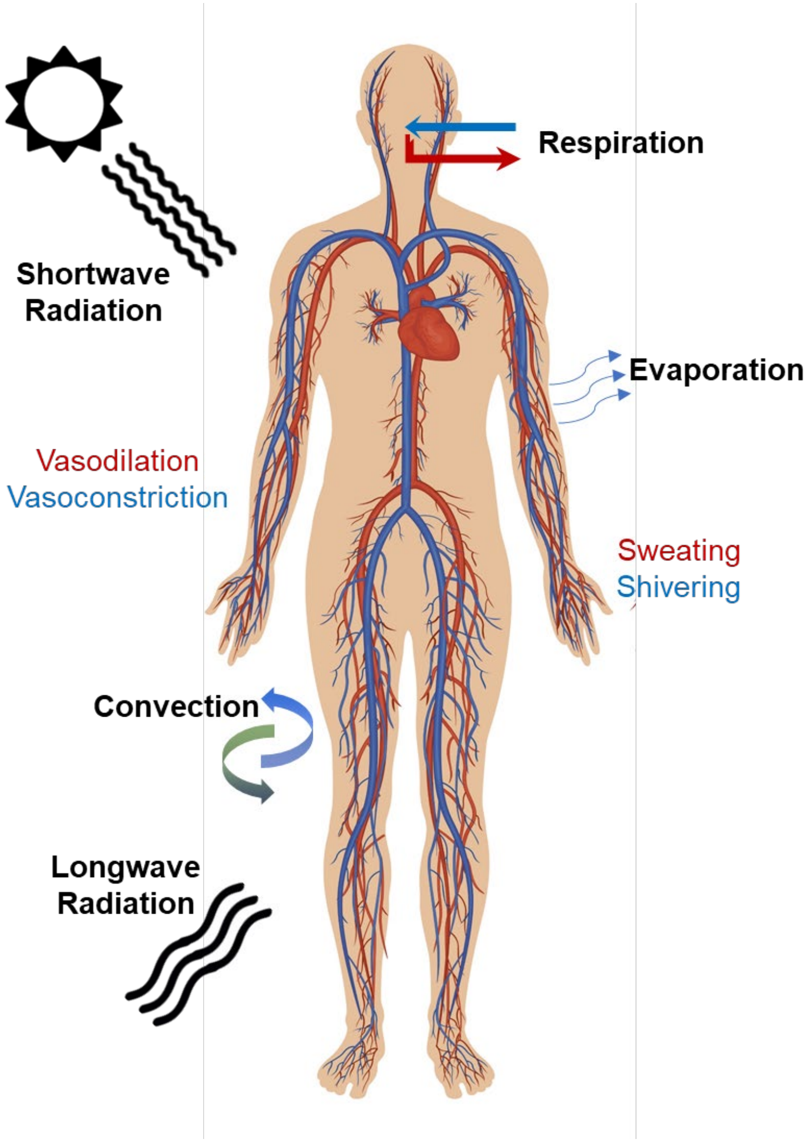

CONTENT:

I. **Human Energy Balance**
- Human metabolic rate
- Convective heat flux
- Radiative heat flux
- Temperatures:
  - Mean radiant temperature (T_{mrt})
  - Operative temperature (T_{op})
  - Clothing temperature (T_{cl})
- Evaporative heat flux and sweating

II. **Thermal sensation model PMV/PPD**

III. **Exercise – energy audit**

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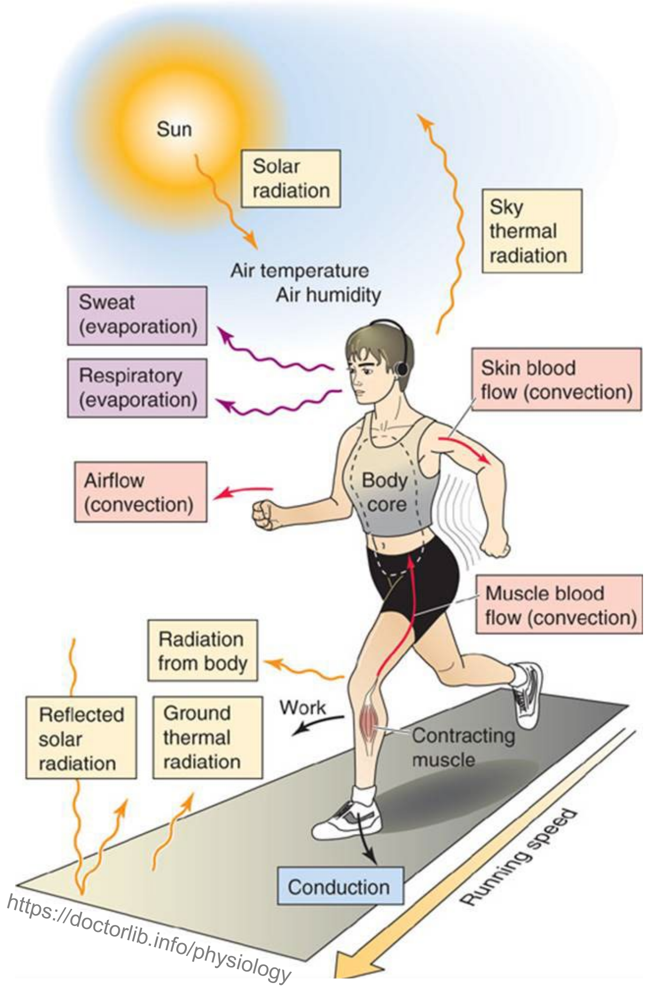
Human Energy Balance

- The **energy exchange** with the ambient environment occur across the outer surface of the body.
  - **Metabolic rate** Q_M is *internal energy* required to *sustain functioning* of *the human body*, generated from the food (energy source). It contains two parts, M (metabolic activity) + W (physical work output). $W \sim 0$ for low physical activities.
  - Heat exchange via **conduction** Q_{cond} is normally *relatively small* as typically just a small proportion of the body's surface area is in contact with a solid surface. Thus, is often considered as $Q_{cond} \sim 0$.
  - The *healthy body* (e.g., non-obese) regulates heat fluxes so that **heat storage** is minimal ($\Delta Q_S \sim 0$).



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

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

Latent heat: $Q_{E,sk} + Q_{E,rsp}$

Note: heat flux in [W/m²] is abbreviated as upper case Q in the lecture slides

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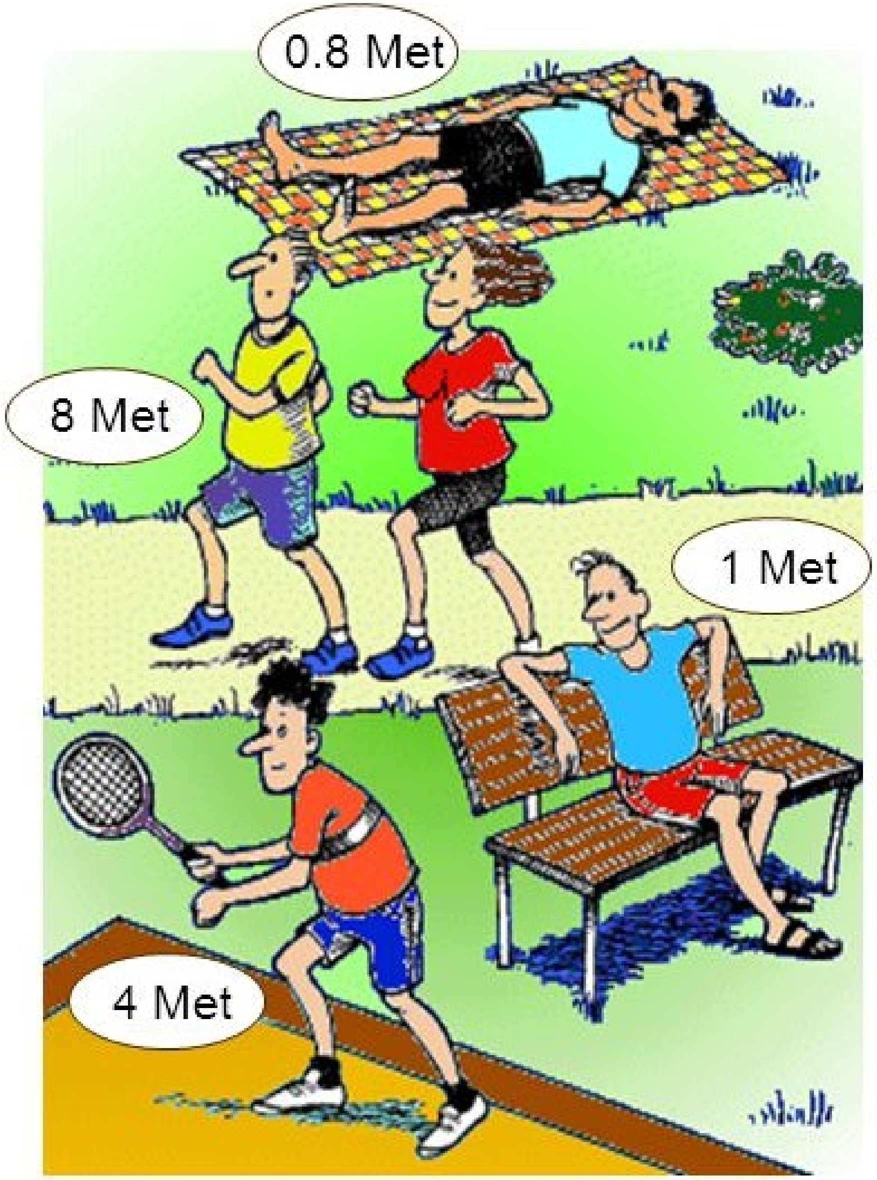
Human Metabolic Rate: Q_M

- **The rate** of **transformation** of **chemical energy** into ***heat*** and **mechanical work** by **metabolic activities of an individual**, per **unit** of **skin surface area** (expressed in units of *Met*) equal to **58.2** W/m^2 (the energy produced per unit skin surface area of an *average person* seated at rest).

(2-2) $$Q_M = H + W$$

H – internal body heat
W – external mechanical power

Activity type	*Met*	W/m^2
Reclining	0.8	45
Seated, relaxed	1.0	58
Sedentary activity (office, dwelling, school, laboratory)	1.2	70
Standing, light activity (shopping, laboratory, light industry)	1.6	93
Standing, medium activity (domestic work, machine work)	2.0	116
Walking on level ground:		
2 km/h	1.9	110
4 km/h	2.8	165
5 km/h	3.4	200



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Convective Heat Flux: Q_{conv}

- **Convective heat flux Q_{conv}** (W/m^2) occurs by **breathing** and by **convective exchange at the skin surface**
  - The breathing rate is a function of metabolism. For moderate activities, *less than 5%* of heat loss by breathing from metabolic rate. Thus, it is often negligible, but can be estimated as:

$$Q_{conv,res} = 0.0014 \cdot M \cdot (34 - t_a) \quad (2\text{-}3)$$

  - The *majority* of *sensible heat transfer* occurs via **the outer surface of the body,** mostly covered by clothing:

$$Q_{conv,sk} = h_{conv} \cdot f_{cl} \cdot (t_{cl} - t_a) \quad (2\text{-}4)$$

- **Convective heat transfer coefficient h_{conv}** (W/m^2K):
  - for a person represented as a cylinder, can be determined using simplified correlations:

For natural convection, $v_a < 0.2$ m/s

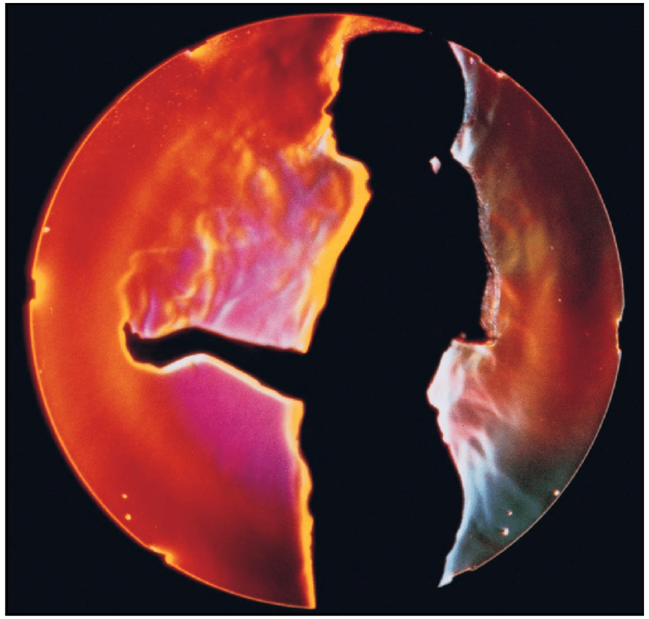
$$h_{conv} = 3.1 \quad (2\text{-}5a)$$

For forced convection, $0.2 < v_a < 4\ m/s$

$$h_{conv} = 8.3 \cdot v_a^{0.6} \quad (2\text{-}5b)$$

$v_a \left(\frac{m}{s}\right)$ - air speed averaged over the height of the body (or at specific location if local heat flux is considered)

https://www.thesun.co.uk/money/15645884/fans-best-deal-savings-heatwave/



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

Radiative Heat Flux: Q_{rad}

- **Radiative heat transfer** between **the clothing outer layer** and **the ambient environment** *can be expressed* introducing *the mean radiant temperature* $\boldsymbol{T_{mrt}}$*:*

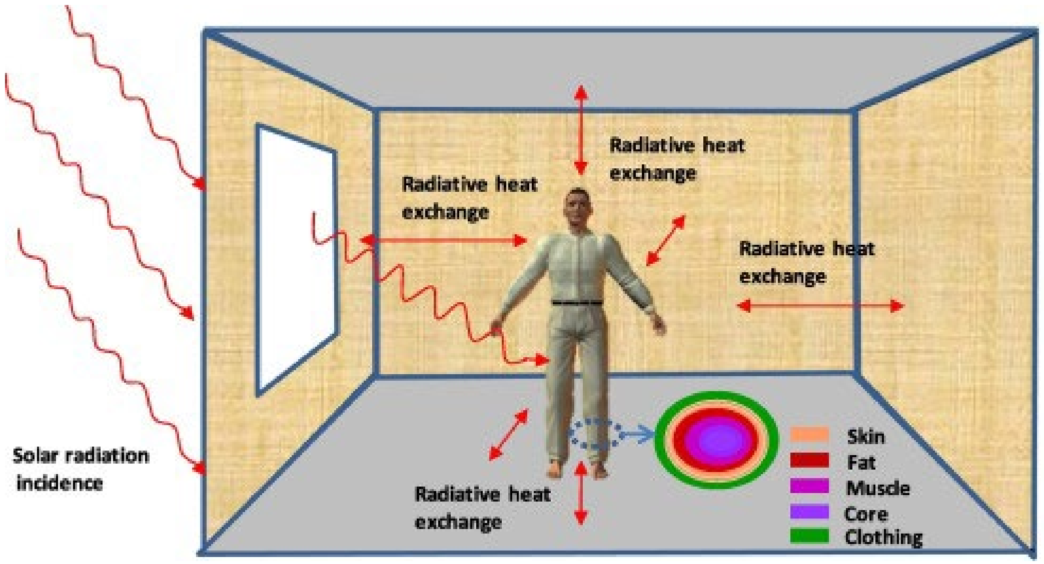
$$\boldsymbol{Q_{rad}} = h_{rad} \cdot f_{cl} \cdot (\boldsymbol{T_{cl}} - \boldsymbol{T_{mrt}}) \quad (2\text{-}6)$$

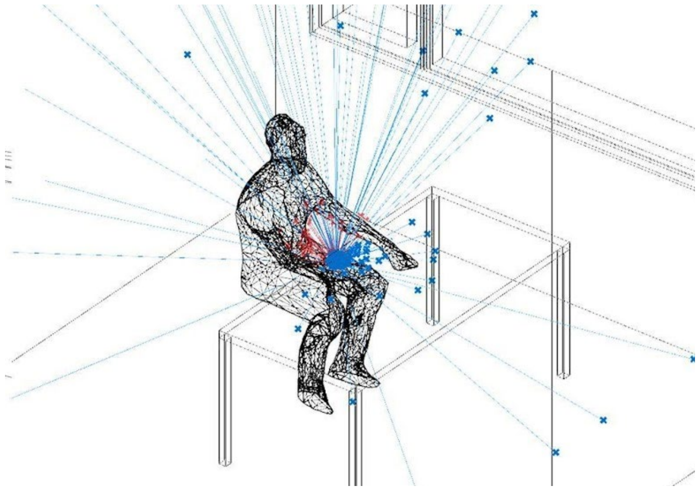
  - Radiative heat transfer coefficient $\boldsymbol{h_{rad}}$ (W/m^2K) :
    (for typical indoor conditions, $h_{rad} = 4.7$)

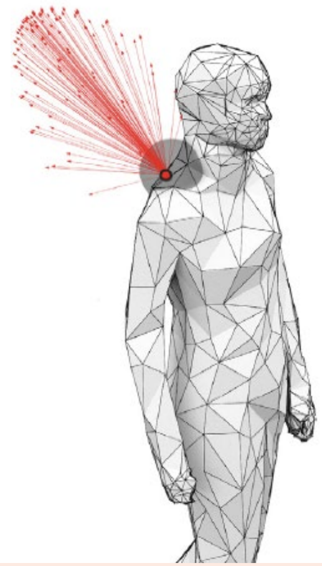
$$\boldsymbol{h_{rad}} = 4 \cdot \boldsymbol{\varepsilon} \cdot \sigma \cdot f_{eff} \cdot \left[273.15 + \frac{\boldsymbol{t_{cl}} + \boldsymbol{t_{mrt}}}{2}\right]^3 \quad (2\text{-}7)$$

  - The effective radiation area factor $\boldsymbol{f_{eff}}$ $(-)$ estimated as **0.72** for sitting person and **0.77** for a standing person (from ISO 7933:2004)

  - Area-weighted emissivity of the clothing enable surface $\boldsymbol{\varepsilon}$ $(-)$ often considered as **0.95-1.0**







Note:
- *lower case* nomenclature for temperature (t_{cl}, t_{mrt}) for values in [°C]
- *upper* case is for the absolute temperatures (T_{sk}, T_{cl}) in [K]

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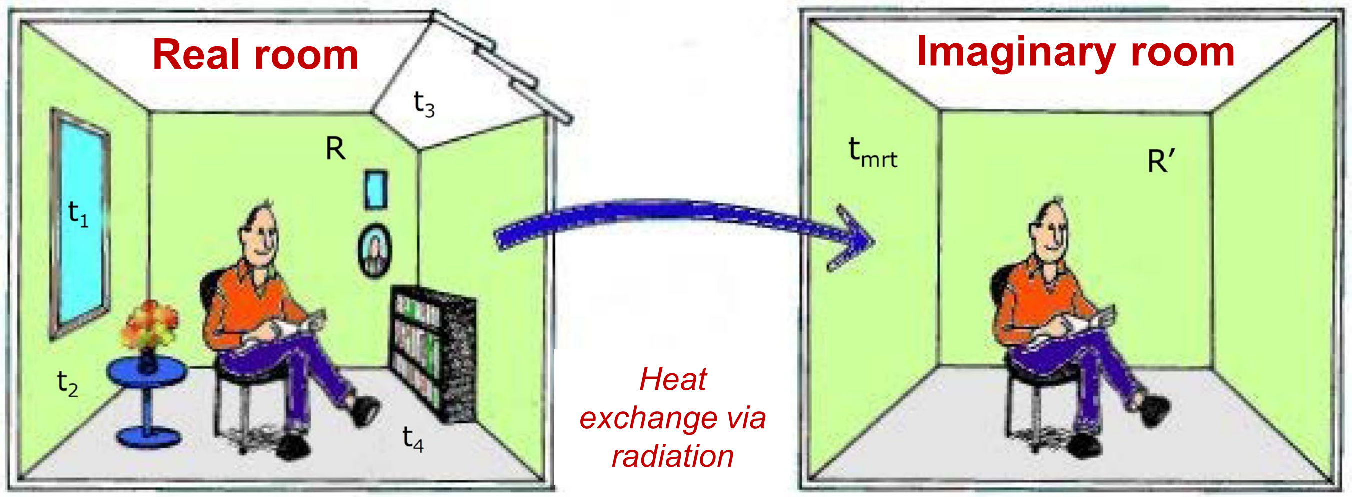
Mean Radiant Temperature: T_{mrt}

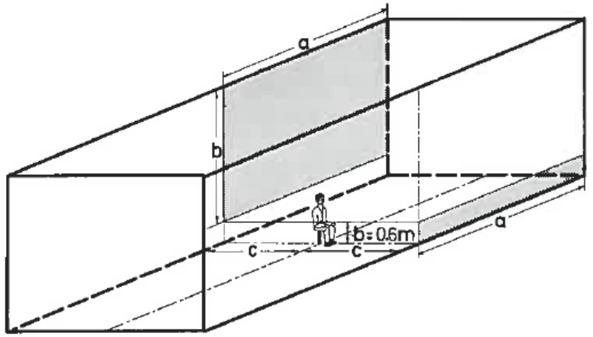
- T_{mrt} is the uniform **surface temperature** of an **imaginary black enclosure** in which an occupant would *exchange the* ***same amount of radiant heat*** as in the ***actual non-uniform space***.
- **MRT** is an abstract parameter introduced *to facilitate* **radiant heat transfer calculations.**



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

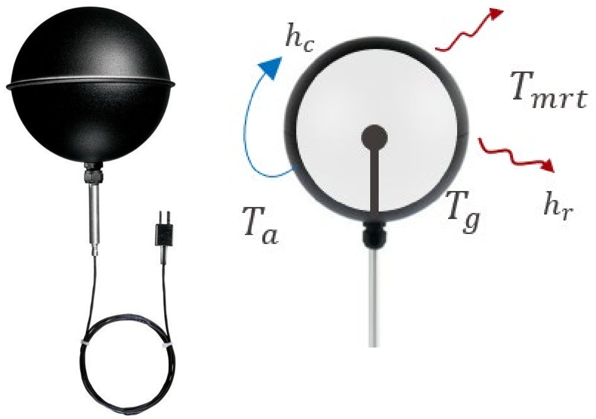
$$Q_{rad} = \sigma \cdot \left(T_p^4 - T_{mrt}^4\right)$$

- **Ways to determine MRT:**
  1. Calculated using **geometrical shape factors**
  2. Estimated from the **globe temperature** measurements
  3. Estimated based on **the plane radiant temperature** measurements in 6 opposite directions
  4. Direct measurements of **radiant heat flux** in 6 opposite directions



$$T_{mrt}^4 = \sum F_{p,i} \cdot T_{s,i}^4 \qquad (3\text{-}5)$$

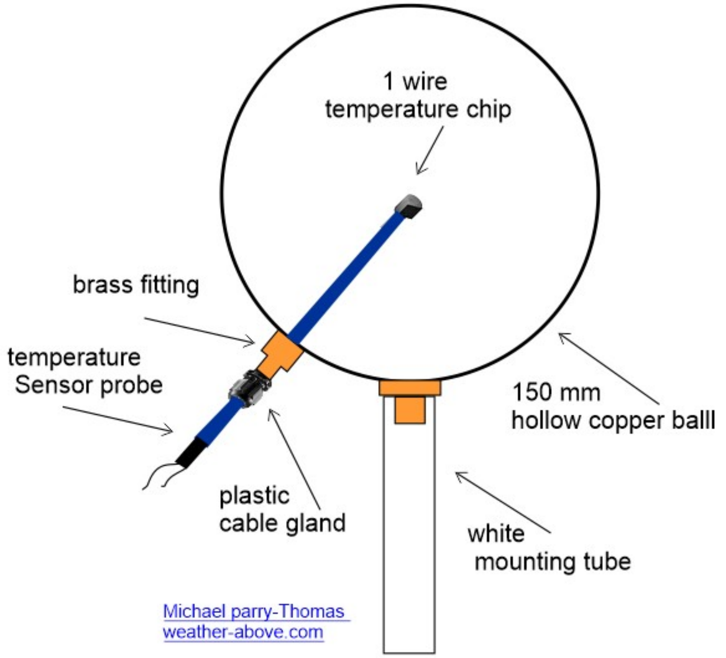
$$\sum F_{p,i} = 1 \qquad (3\text{-}6)$$



$$T_{mrt} = f\,(T_g, T_a, v_a, D, \varepsilon_g, \text{air properties})$$

Globe Temperature: T_g

- 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

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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)*:

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

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

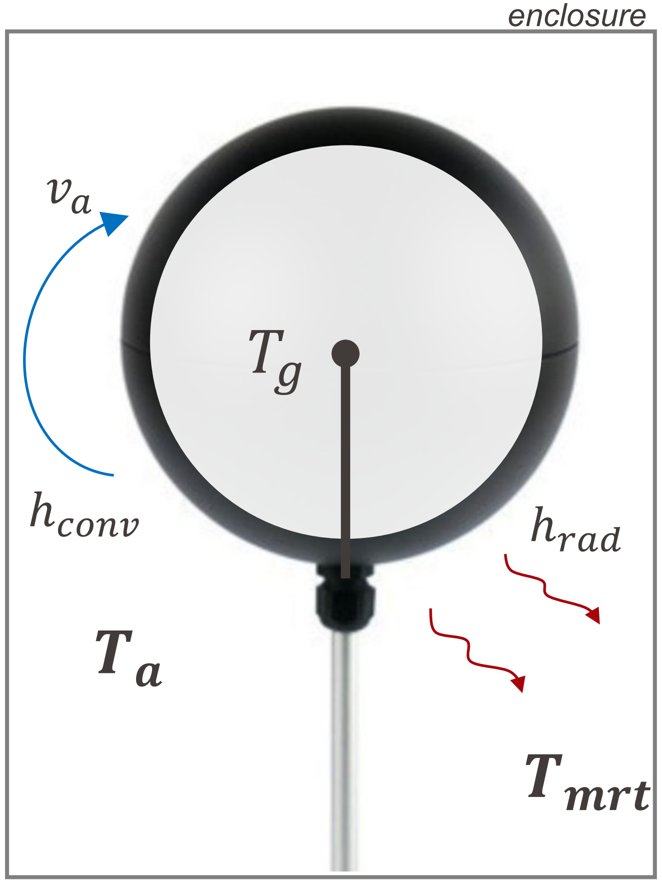
$$Q_{conv} = h_{conv} \cdot \left(T_a - T_g\right) \quad (4\text{-}7)$$

  - **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: $\sigma = 5.67 \cdot 10^{-8}\ W/m^2K^4$

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



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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)*

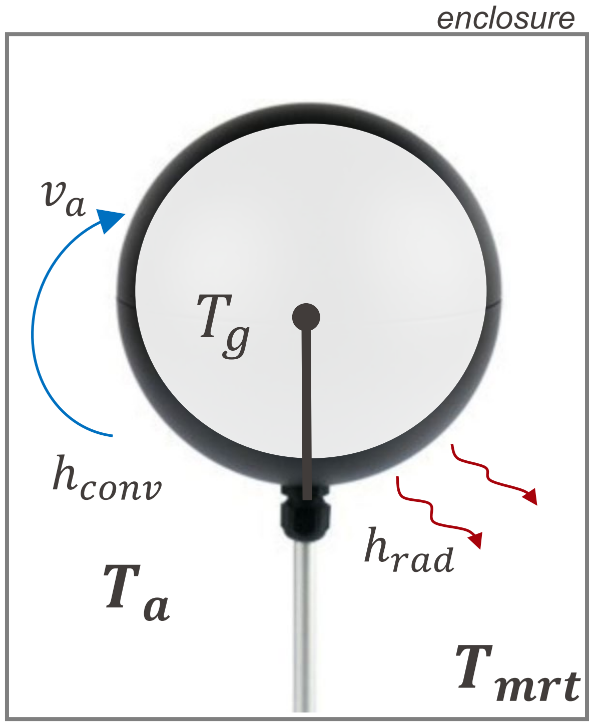
$$h_{conv} = 1.4 \cdot \left(\frac{T_g - T_a}{D}\right)^{1/4} \quad (4\text{-}9)$$

  - ***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 **20°C**)*

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



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 **20°C**)**

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

** If actual air properties are not at **20°C**, thermophysical properties of air corresponding to actual temperature should be used to calculate h_{conv}*

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Operative Temperature: T_{op}

- **Operative temperature** (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*

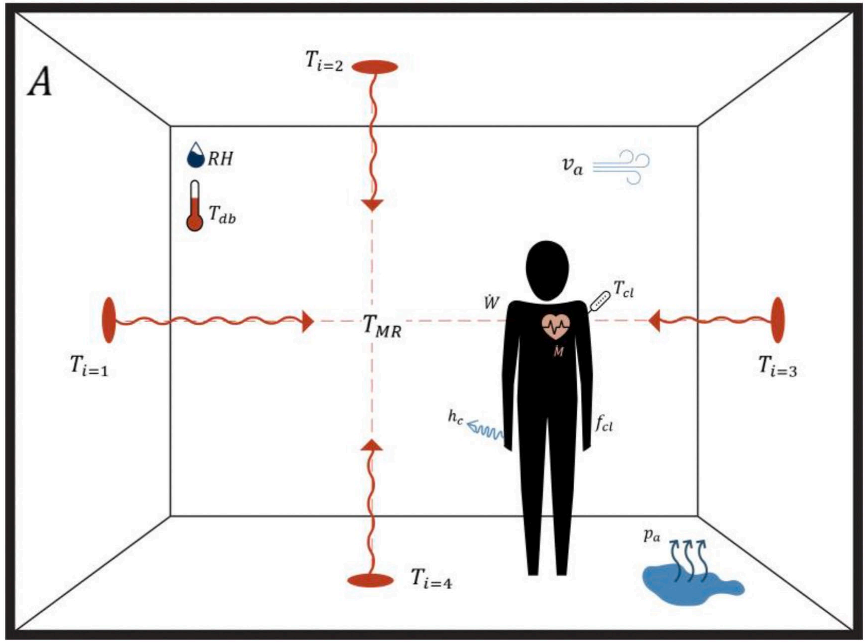
$$T_{op} = \frac{h_c}{h_c + h_r} \cdot T_a + \frac{h_r}{h_c + h_r} \cdot T_{mrt} \quad (2\text{-}8a)$$

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

where a coefficient is $$A = \frac{h_c}{h_c + h_r} = \frac{1}{1 + h_r/h_c} \quad (2\text{-}9)$$

  - *Special case when v_a < 0.2 m/s:*

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



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

Source: ISO 7726, ASHRAE 55-2017

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Sensible Heat Flux: $Q_{rad} + Q_{conv,sk}$

- **Sensible heat fluxes** at the exterior of clothing *can be combined* by *summing heat transfer coefficients* and introducing *the operative temperature* T_{op}

$$Q_{rad} + Q_{conv,sk} = h \cdot f_{cl} \cdot (T_{cl} - T_{op}) \quad (2\text{-}11)$$

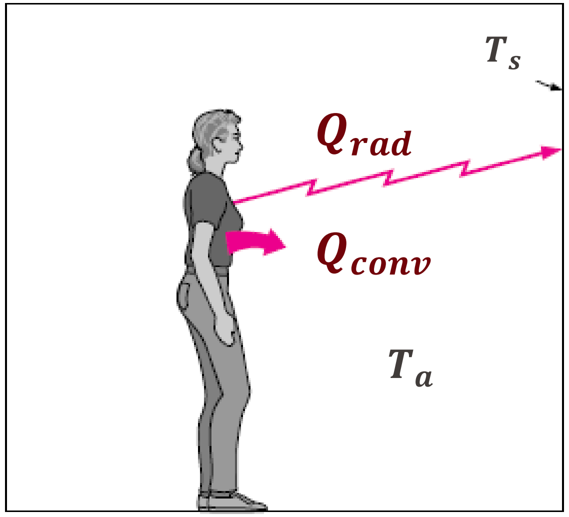
  - combined heat transfer coefficient $h = h_{conv} + h_{rad}$

- **Sensible heat fluxes** at the *exterior* of clothing can be also expressed as transfer of heat through the clothing

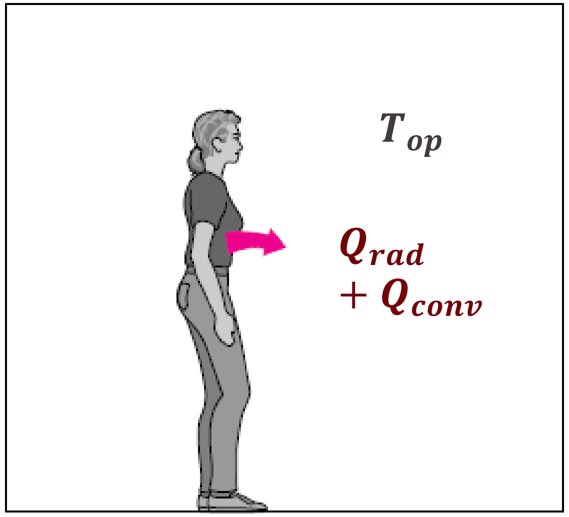
$$Q_{rad} + Q_{conv,sk} = \frac{T_{sk} - T_{cl}}{R_{cl}} \quad (2\text{-}12)$$

- Clothing temeprature not always known, thus, we combine two equations (2-10) and (2-11) to remove T_{cl}:

$$Q_{rad} + Q_{conv,sk} = \frac{T_{sk} - T_{op}}{(R_{cl} + \frac{1}{f_{cl} \cdot h})} \quad (2\text{-}13)$$



(a) Convection and radiation, separate



(b) Convection and radiation, combined

Clothing Temperature: T_{cl}

Note:
- *Lower case* nomenclature (t_{cl}, t_{mrt}) for temperature in [°C]
- *Upper* case (T_{sk}, T_{cl}) is for the absolute temperatures in [K]

- To calculate **clothing temperature** T_{cl} several iterrations are required
- Equations (2-11) or (2-13) and (2-7) should be used to solve for T_{cl} :

1. Guess T_{cl} (between T_{sk} and T_a) and calculate h_{rad} using Eqn. (2-7):

$$h_{rad} = 4 \cdot \varepsilon \cdot \sigma \cdot \frac{A_{cl}}{A_{body}} \cdot \left[273.15 + \frac{t_{cl} + t_{mrt}}{2}\right]^3$$

2. Use calculated h_{rad} and calculate T_{cl} using Eqn. (2-11) or (2-13):

$$Q_{rad} + Q_{conv,sk} = h \cdot f_{cl} \cdot (T_{cl} - T_{op}) = \frac{T_{sk} - T_{cl}}{R_{cl}}$$

$$f_{cl} = \frac{A_{cl}}{A_{body}}$$

$$f_{cl} = 1 + 0.31 \cdot I_{cl} \qquad for\ I_{cl} \leq 0.5$$

$$f_{cl} = 1.05 + 0.645 \cdot I_{cl} \quad for\ I_{cl} > 0.5$$

$$R_{cl} = I_{cl} \cdot 0.155 \frac{m^2K}{W}$$

3. Compare skin temperatures T_{sk} calculated in steps (1) and (2). If they are far apart, repeat the steps (1-2) with a new value of clothing temperature T_{cl}.

4. If after *several iterations* T_{sk} calculated in repeated steps (1) and (2) converged, terminate the iteration. T_{cl} is the value determined in the last iteration T_{cl}.

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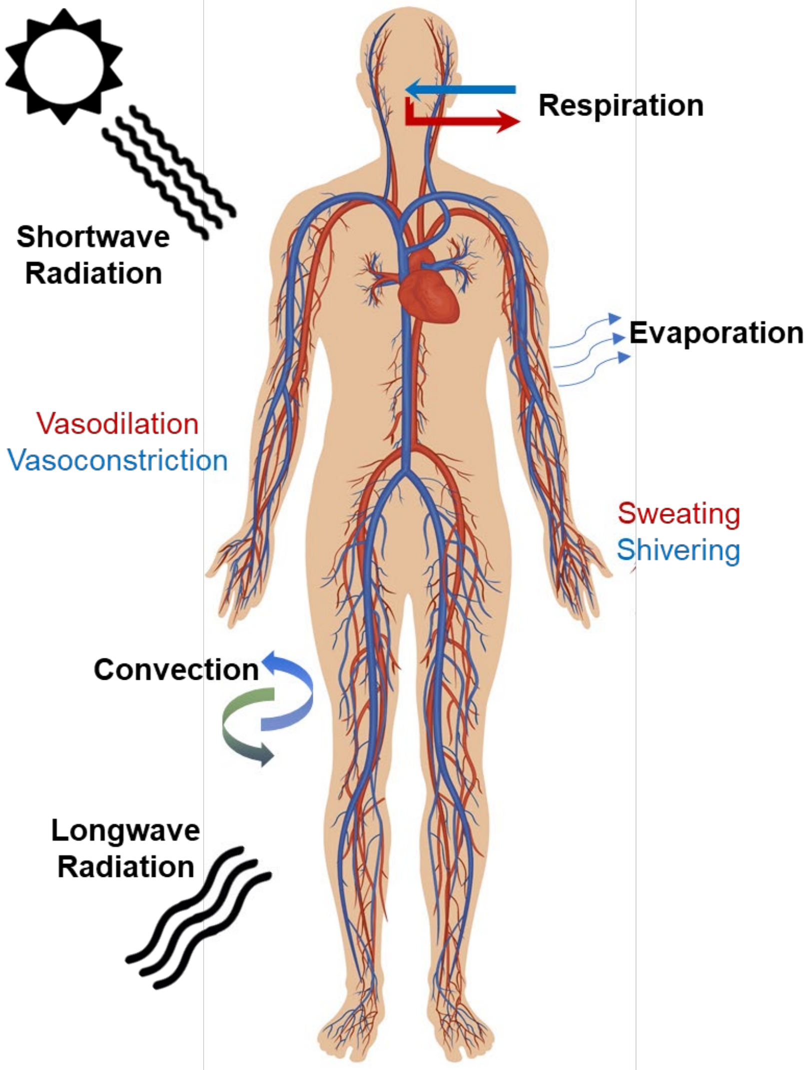

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- **Evaporative heat flux and sweating**

II. Thermal sensation model PMV/PPD

III. Exercise – energy audit

Evaporative Heat Flux: Respiration $Q_{E,rsp}$

- **Latent heat exchange** (Q_E) occurs via **respiration** and via **the skin** (water vapor diffusion).

- **Latent heat flux via respiration $Q_{E,rsp}(W/m^2)$:**
  - Exhaled air is close to saturation ($RH \approx 100\%$) at body's core temperature ($t_{cr} \sim 37^oC$)

$$Q_{E,rsp} = \dot{V} \cdot \rho_{a,in} \cdot (q_{a,out} - q_{a,in}) \cdot L_v / A_{body} \quad (2\text{-}14)$$

- $\dot{V}$ (m^3/s) – breathing rate
- $\rho_{a,in}$ (kg/m^3) – inhaled air density at $t_{a,in}$ and humidity
- $q_{a,out}$ (kg/kg) – specific humidity of exhaled air at $p_{v,sat}$ and body temperature t_b (for t_b, see Eqn. 2-22)
- $q_{a,in}$ (kg/kg) – specific humidity of inhaled air (considering temperature and relative humidity of inhaled air)
- L_v (kJ/kg) – heat of vaporisation of water (e.g., 2418 kJ/kg at 35°C)
- A_{body} (m^2) – body surface area

Breathing rate $\dot{V}$ can be estimated according to the *activity level* or can be determined from *metabolic rate* as the breathing is mainly a function of metabolism:

$$\dot{V}\left(\frac{kg}{h}\right) = 0.006 \cdot M \left(\frac{kcal}{hr}\right) \quad (2\text{-}15)$$

- Simplified $Q_{E,rsp}$ formulation for **average body size** and **normal indoor conditions**:

$$Q_{E,rsp} = 0.0173 \cdot M \cdot (5.87 - p_{v,a}) \quad (2\text{-}16)$$

$p_{v,a}$ in [kPa], M in [W/m²]

Human breathing rates by activity level:

Level of exertion	Resting ($m^3\ h^{-1}$)	Light ($m^3\ h^{-1}$)	Moderate ($m^3\ h^{-1}$)	Heavy ($m^3\ h^{-1}$)
Adult female	0.3	0.5	1.6	2.9
Adult male	0.7	0.8	2.5	4.8
Average adult	0.5	0.6	2.1	3.9
Child 6 years	0.4	0.8	2.0	2.4
Child 10 years	0.4	1.0	3.2	4.2

Source: Oke, Urban Climates, p. 387

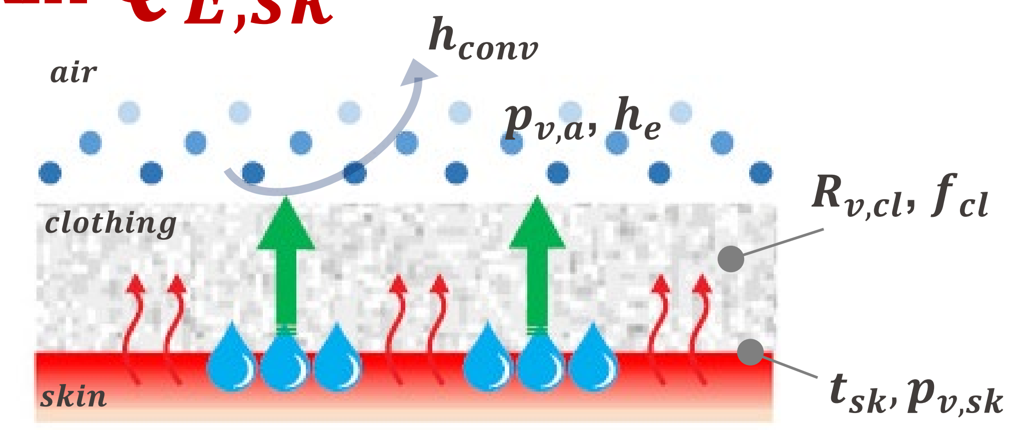
Evaporative Heat Flux: from the skin $Q_{E,sk}$

- **Evaporative heat loss** at the **skin surface** (W/m^2):

$$Q_{E,sk} = \frac{w \cdot (p_{v,skin} - p_{v,a})}{(R_{v,cl} + \frac{1}{f_{cl} \cdot h_e})} \quad (2\text{-}17)$$

- w (-) – skin wettedness (see Eqn. 2-23), varies from **0.06** (natural diffusion of water) to **1** (completely wet skin)
- $p_{v,a}$ (kPa) - water vapour pressure in the ambient air temperature
- $p_{v,skin}$ (kPa) – water vapour pressure at the skin (normally assumed to be saturated water vapour pressure $p_{v,sat}$ at the skin temperature t_{sk})
- $R_{v,cl}$ $(\frac{m^2 \cdot kPa}{W})$ – vapour resistance of clothing (typically 0.015 $\frac{m^2 \cdot kPa}{W}$ for regular clothing)
- f_{cl} (-) – clothing factor
- h_e $(\frac{W}{m^2 \cdot kPa})$ – evaporative heat transfer coefficient, linked with convective heat transfer coefficient h_{conv} (see Eqn. 2-5) via the Lewis ratio LR (for typical conditions, $LR = 16.5\ K/kPa$)

$$h_e = LR \cdot h_{conv} \quad (2\text{-}18)$$



$$w = 0.06 + \frac{Q_{E,rsw}}{Q_{E,max}} \quad (2\text{-}19)$$

Actual regulatory sweat evaporation ($Q_{E,rsw}$)

Maximum evaporation (calculated using Eqn. 2-17 at w=1) ($Q_{E,max}$)

$$Q_{E,rsw} = M_{rsw} \cdot L_v \quad (2\text{-}20)$$

$$M_{rsw} = 4.7 \cdot 10^{-5} \cdot (t_b - 36.18) \cdot e^{(\frac{t_{sk} - 33.7}{10.7})} \quad (2\text{-}21)$$

$$t_b = \alpha \cdot t_{sk} + (1 - \alpha) \cdot t_{cr} \quad (2\text{-}22)$$

- L_v (kJ/kg) - heat of vaporisation of water (2430 kJ/kg at 30°C)
- M_{rsw} (kg/s*m^2) - rate at which sweat is secreted
- t_b , t_{sk}, t_{cr} (°C) – average *body*, *skin*, and *core* temepratures
- α - weighting coefficient (**0.2** for thermal equilibrium while sedentary, **0.1** for vasodilation and **0.33** for vasoconstriction)

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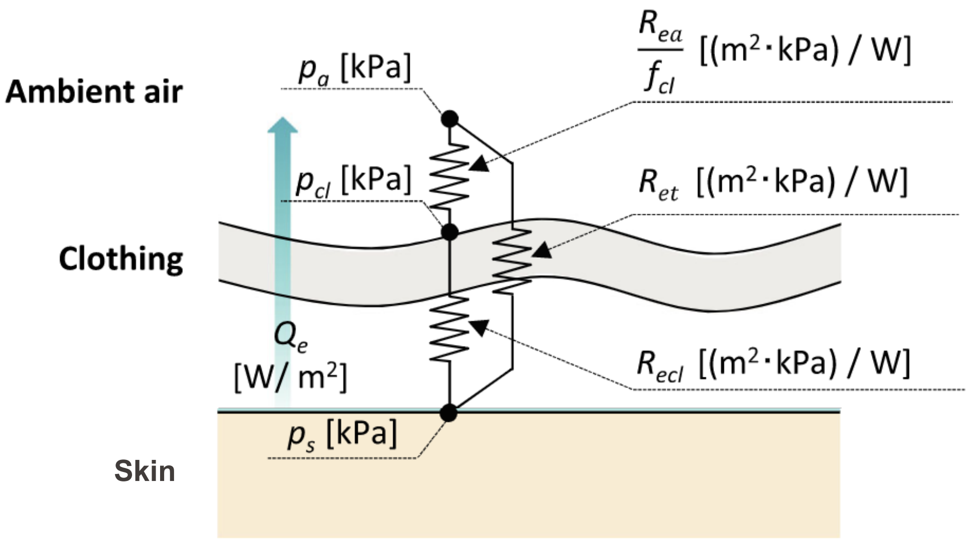
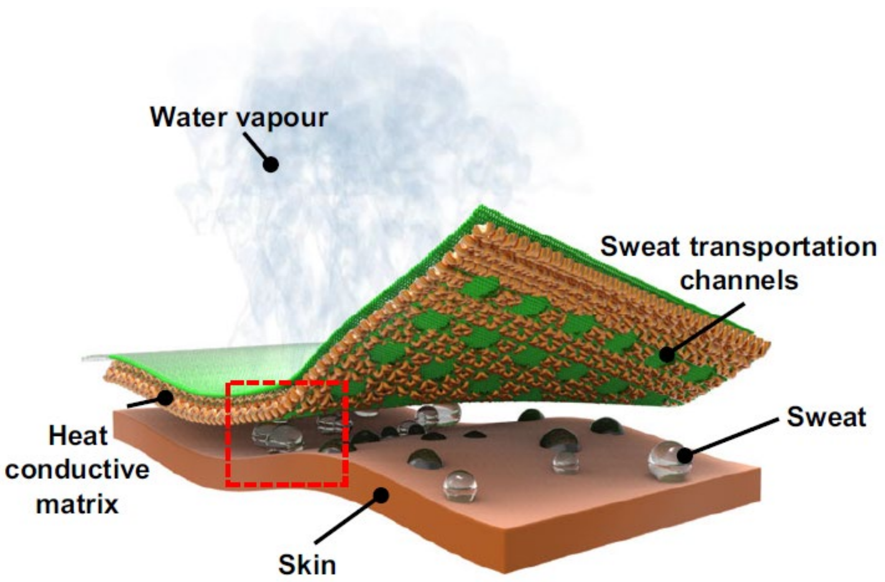
Clothing: Vapor Resistance

- Various types of clothing vary in their **vapor resistance** $R_{v,cl}$ $(\frac{m^2 \cdot Pa}{W})$, in material's reluctance to let water vapor pass through.

$R_{v,cl}$ $(\frac{m^2 \cdot Pa}{W})$	Performance
0–6	Very good or extremely breathable. Comfortable at higher activity rate
6–13	Good or very breathable. Comfortable at moderate activity rate
13–20	Satisfactory or breathable. Uncomfortable at high activity rate
20–30	Unsatisfactory or slightly breathable. Moderate comfort at low activity rate
30+	Unsatisfactory or not breathable. Uncomfortable and short tolerance time



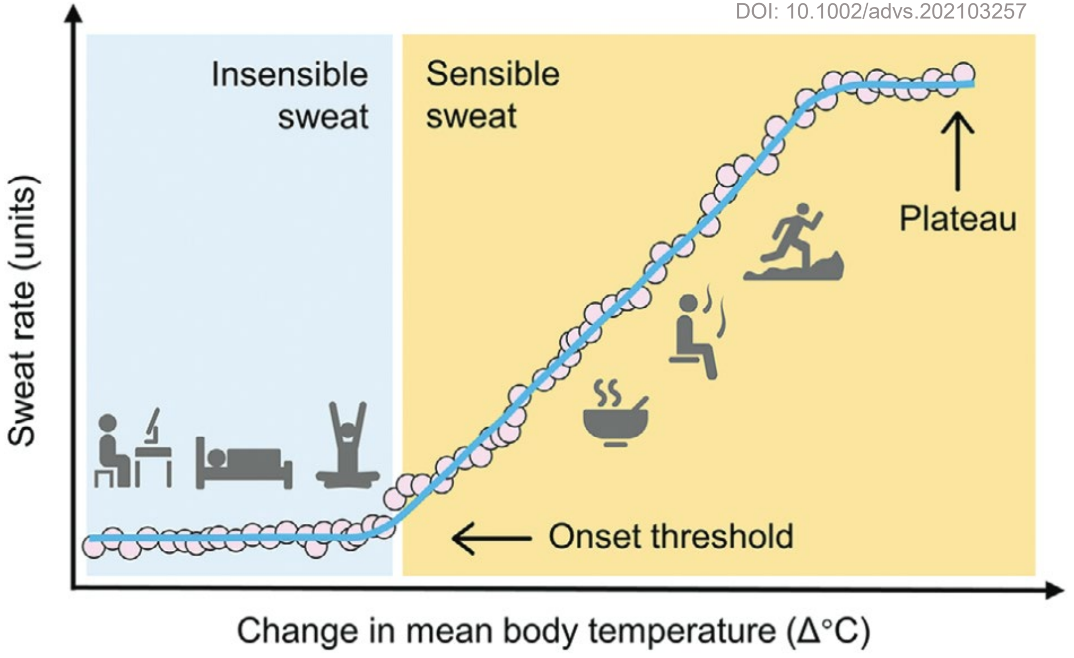
Source: Nomoto et al. (2019) 10.1002/2475-8876.12124

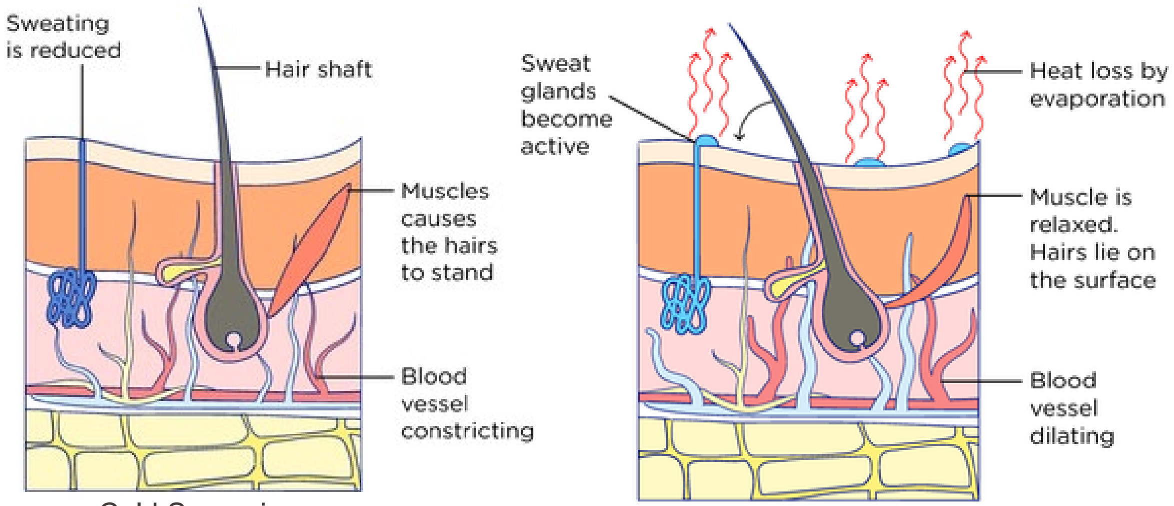


Sweating Mechanism

- Sweating triggers at warm environment, and the sweat rate would depend on the body temperature.
- **Sudorifuc glands** secret sweat which removes heat when water changes state (evaporates).
- The relationship between change in mean body temperature and sweat rate for thermoregulation:
  - **Under the onset threshold** (office work, sleeping, etc.): insensible sweat is the main body sweat loss, the relationship is characterized by an initially relatively flat portion.
  - **Beyond the onset threshold** (eating hot food, sauna, running): sensible sweat emerges and becomes dominant. Ultimately, SSR reaches a maximal level despite mounting mean body temperature.

DOI: 10.1002/advs.202103257





Cold Scenario

Warm Scenario

* At warm environments, **pilorelaxation** (flattening of hair also occurs)

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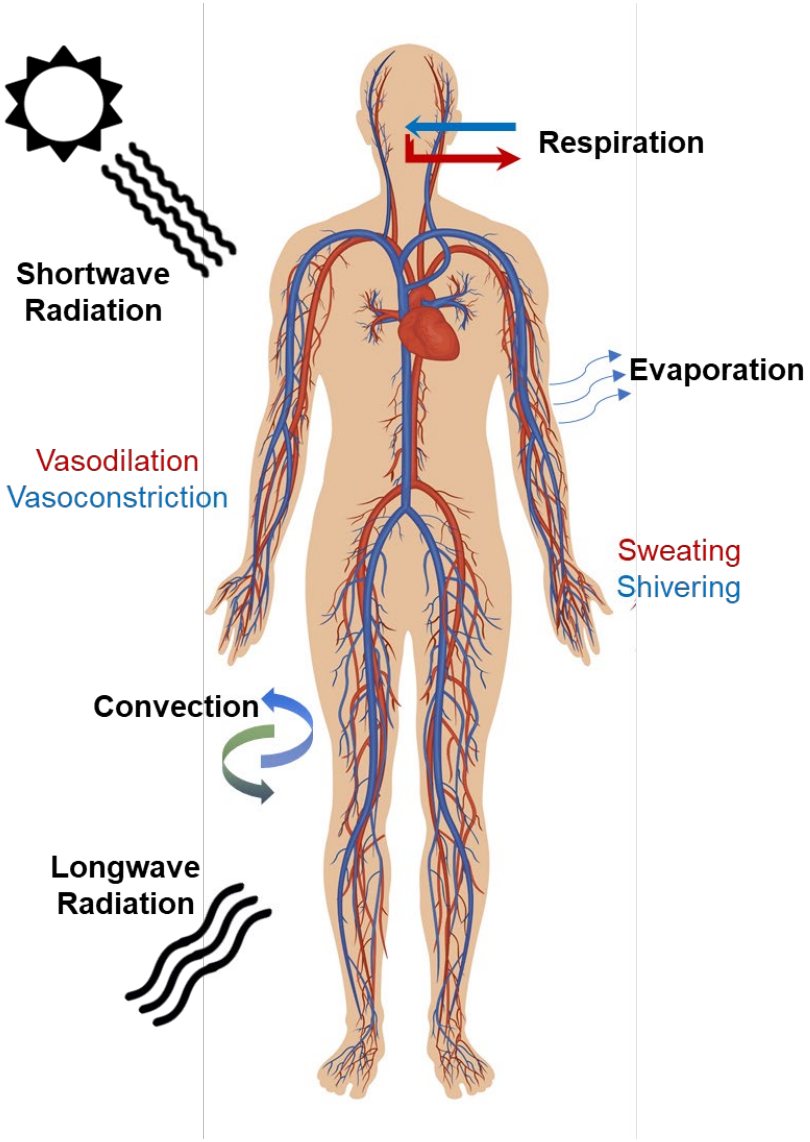

CONTENT:

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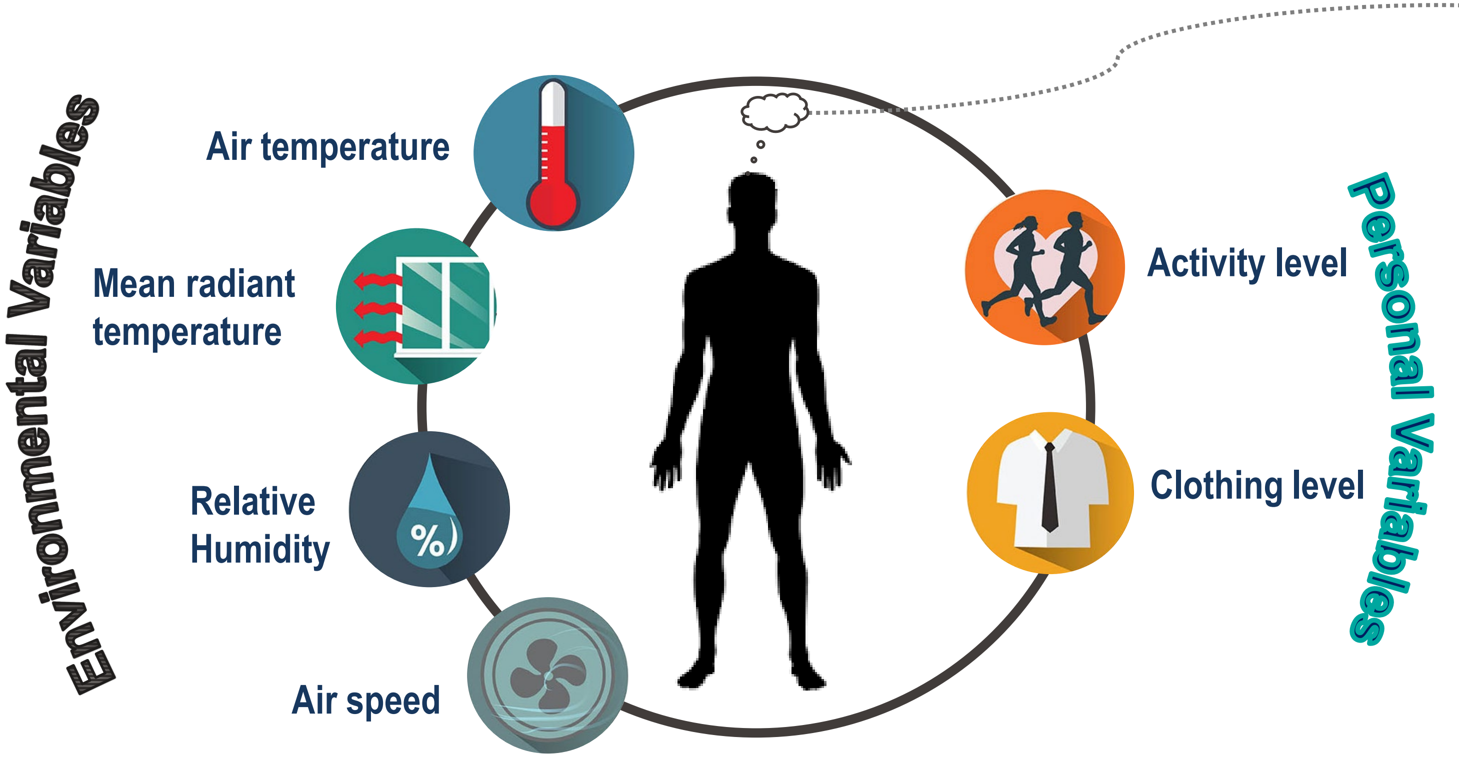
Thermal sensation: PMV/PPD model

- **Predicted Mean Vote (PMV)** – the index predicting **the mean value** of **the overall thermal sensation** (self-reported perceptions) of *a large group* of persons **on a sensation scale**.

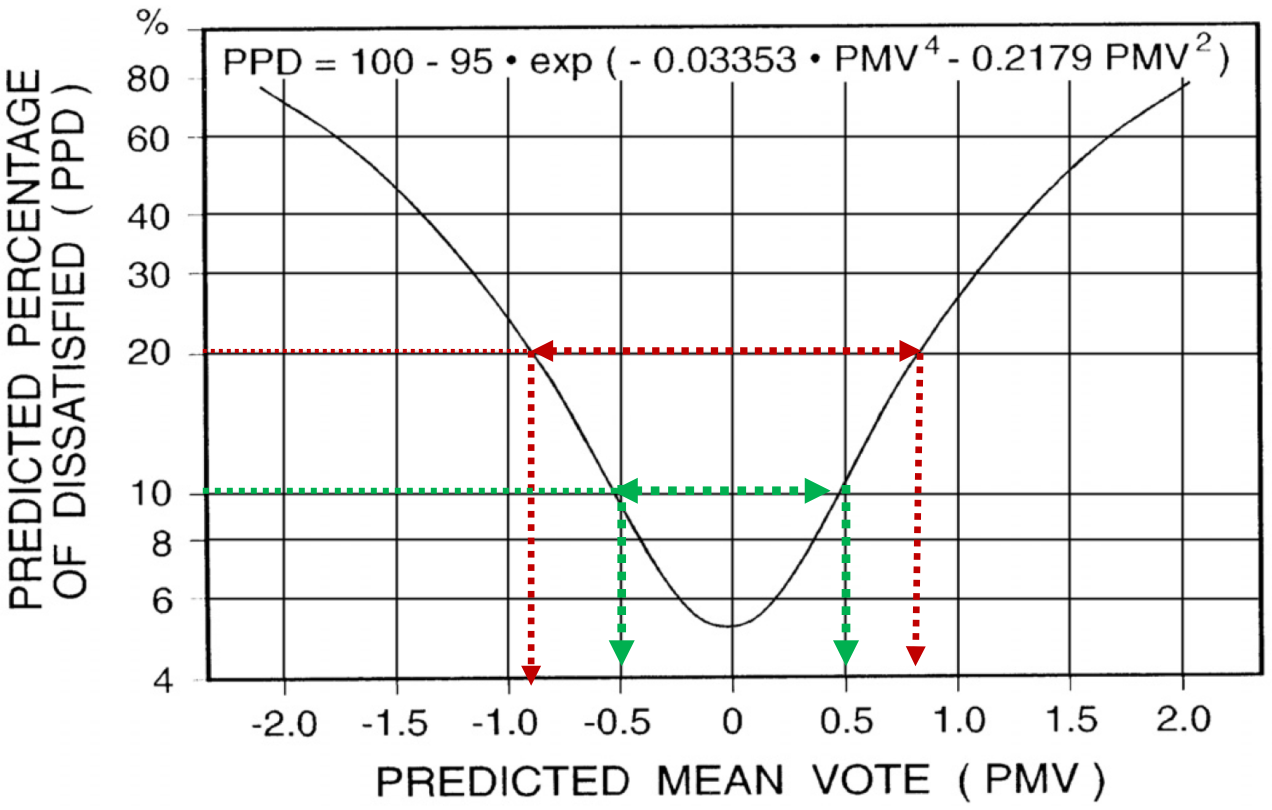


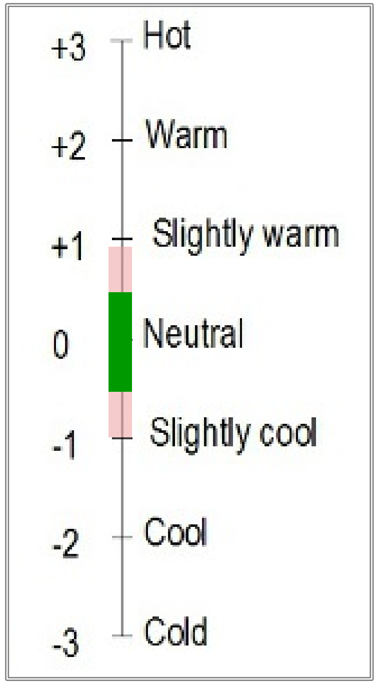
Scale	Thermal Sensation
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

- **Predicted Percent Dissatisfied (PPD)** – the index *derived* from the PMV index, it ***predicts* the percentage** of **thermally dissatisfied occupants** among *a large group of people*

Thermal sensation: PMV/PPD model

- Acceptable thermal conditions: >**10% dissatisfaction (PPD)** for whole-body thermal comfort
- **10% of PPD** => PMV in the range **-0.5 to +0.5**





Source: ASHRAE 55-2017

Thermal sensation: PMV/PPD model

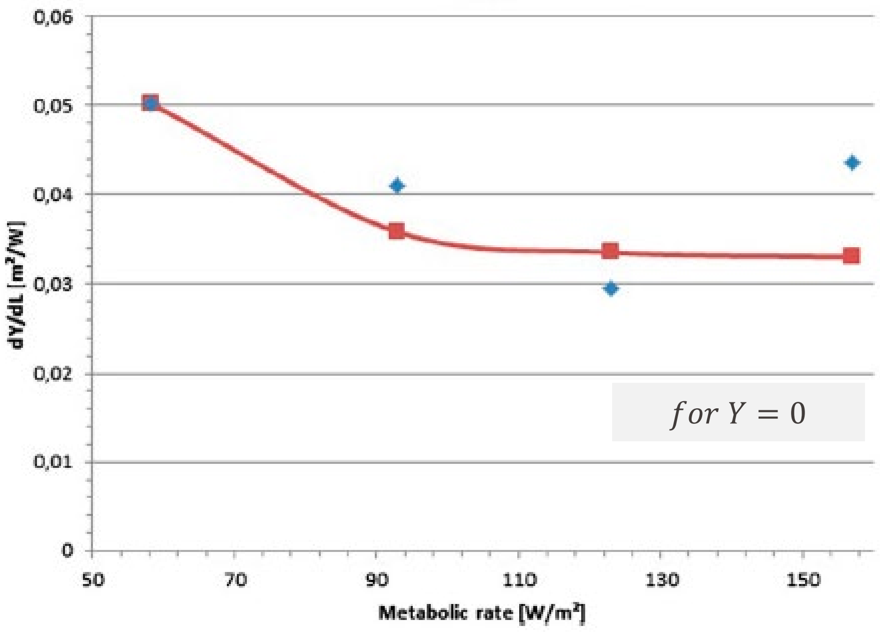
- **Thermal sensation** (**Y**) at a given activity level **is related** to **the physiological strain**.
- **Thermal load of the body** (**L**): **the difference between the internal heat production (H) and the heat loss to the actual environment.**
  - **In the comfort condition**: the thermal load L will be equal to zero
  - **In other environments:** the body adjusts skin temperature and sweat production to regulate heat balance. Thermal load represents *the strain* on these regulatory mechanisms.
  - The more thermal load (strain) on the body, the more uncomfortable it feels

$$Y = f(L, \frac{H}{A_{body}})$$

$$\frac{\delta Y}{\delta L} = 0.352 \cdot e^{-0.042 \cdot M} + 0.032 \quad (2\text{-}23)$$

$$Y = PMV = \left(0.352 \cdot e^{-0.042 \cdot M} + 0.032\right) \cdot L \quad (2\text{-}24)$$

Activity level	Mean vote Y at RH 50%
Sedentary	$Y = -8.471 + 0.331 \cdot t_a$
Low	$Y = -3.643 + 0.175 \cdot t_a$
Medium	$Y = -3.356 + 0.174 \cdot t_a$
High	$Y = -4.158 + 0.265 \cdot t_a$



Thermal sensation: PMV/PPD model

- **Thermal load of the body**:

$$L = (M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] - 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_{mrt} + 273)^4] - f_{cl} \cdot h_{conv} \cdot (t_{cl} - t_a)$$ (2-25)

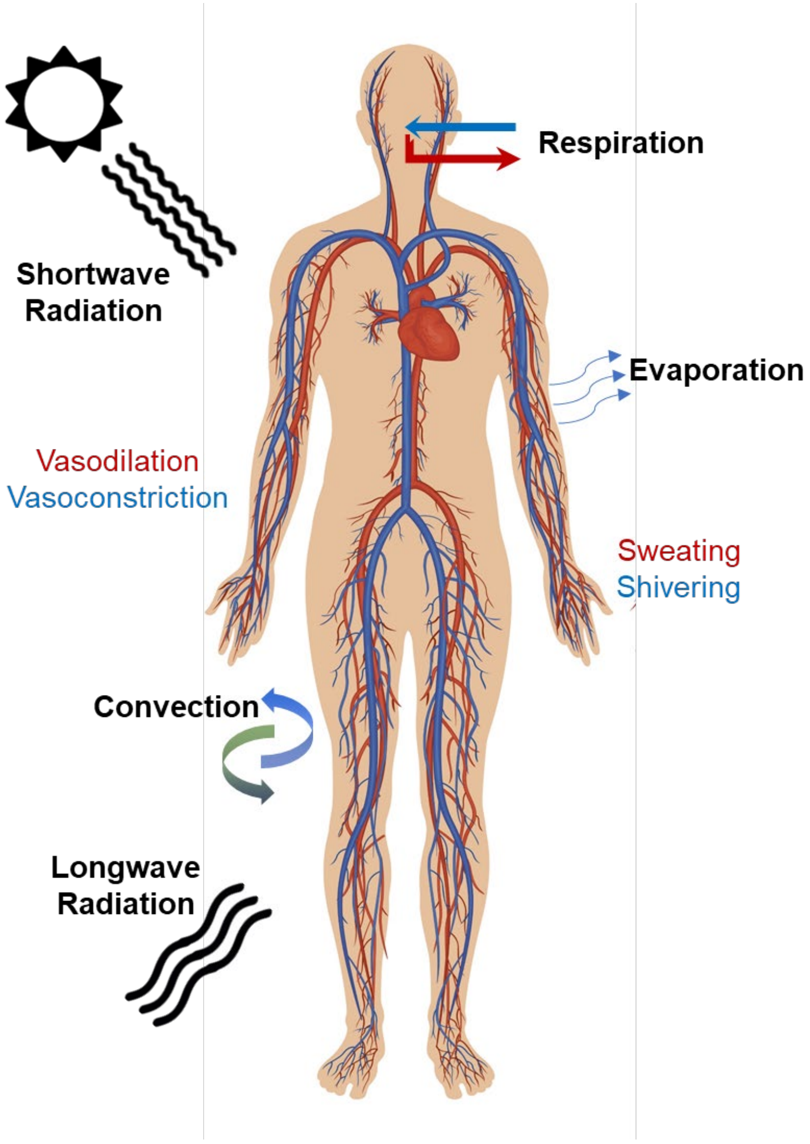
- **Clothing temperature**:

$$t_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_{mrt} + 273)^4] + f_{cl} \cdot h_{conv} \cdot (t_{cl} - t_{air})\}$$ (2-26)

- **Convective heat transfer coefficient**:

$$h_c = \begin{cases} 2.38 \cdot (t_{cl} - t_a)^{0.25} & \text{for } 2.38 \cdot (t_{cl} - t_a)^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & \text{for } 2.38 \cdot (t_{cl} - t_a)^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases}$$ (2-27)

M is the metabolic rate, W/m^2
W is the external work (zero for most indoor activities),
I_{cl} is the thermal resistance of the clothing, $(m^2 \cdot {}^oC)/W$
f_{cl} is the ratio of the clothed surface area to the nude sur
t_a is the air temperature, ^oC
$\bar{t}_r$ is the mean radiant temperature, ^oC
v_{ar} is the air velocity relative to the human body, m/s
p_a is the partial water vapor pressure, Pa
h_c is the convective heat transfer coefficient, $W/(m^2 \cdot {}^oC)$
t_{cl} is the surface temperature of the clothing, ^oC



CONTENT:

I. Human Energy Balance
- Human metabolic rate
- Convective heat flux
- Radiative heat flux
- Temperatures:
  - Mean radiant temperature (T_{mrt})
  - Operative temperature (T_{op})
  - Clothing temperature (T_{cl})
- Evaporative heat flux and sweating

II. Thermal sensation model PMV/PPD

III. Exercise – energy audit

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Human Thermal Balance: Example

- The following data is provided from 2 experiments for a **sitting male** person:
  - **Anthropological data:** 175 cm, 73 kg
  - **Personal data**: metabolic rate (EE), skin temperature t_{sk}
  - **Environmental data**: air temperature t_a, globe temperature t_g, air speed V, relative humidity RH

➢ Case 1: summer clothing (0.4 clo), temperature drift up from **24°C** to **30°C**

➢ Case 2: winter clothing (0.8 clo), temperature drift down from **24°C** to **17°C**

Using the dataset provided, determine and analyze:

1. **Heat transfer from the human body** per ***different mechanisms***
2. Evaluate ***the category of comfort*** per **ISO 17772** standard
3. Evaluate ***the thermal sensation*** using **the PMV index**

Human Thermal Balance: Example

- **Use the following formulation to determine parameters of the humid air:**

  - **Water vapor saturation pressure** $p_{v,sat}$ (Pa) – the pressure at which water vapor is *in thermodynamic equilibrium* with its *condensed state*. At higher pressures ($p > p_{v,sat}$), water would *condense*, and at lower pressures ($p < p_{v,sat}$) it would *evaporate* or *sublimate*.
    - **Relationship** between **saturation water vapor pressure** and **temperature** is related by the Clausius-Clapeyron eqn.
    - Simplified formula for air temperature $\boldsymbol{t_a}$ > 0°C:

$$\boldsymbol{p_{v,sat}} = 611 \cdot e^{\frac{17.08 \cdot \boldsymbol{t_a}}{234.18 + \boldsymbol{t_a}}} \quad (Pa)$$

  - **Partial pressure of water vapor** p_v (Pa): the pressure that would be exerted *by water vapor* if it occupied the same volume as the moist air on its own

$$\boldsymbol{p_v} = RH \cdot p_{v,sat}$$

  - **Specific humidity** $\boldsymbol{q}$ $(\frac{kg}{kg})$: the mass ratio between the mass of water vapor and the mass of moist air (does not change with the change of temperature and pressure)

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

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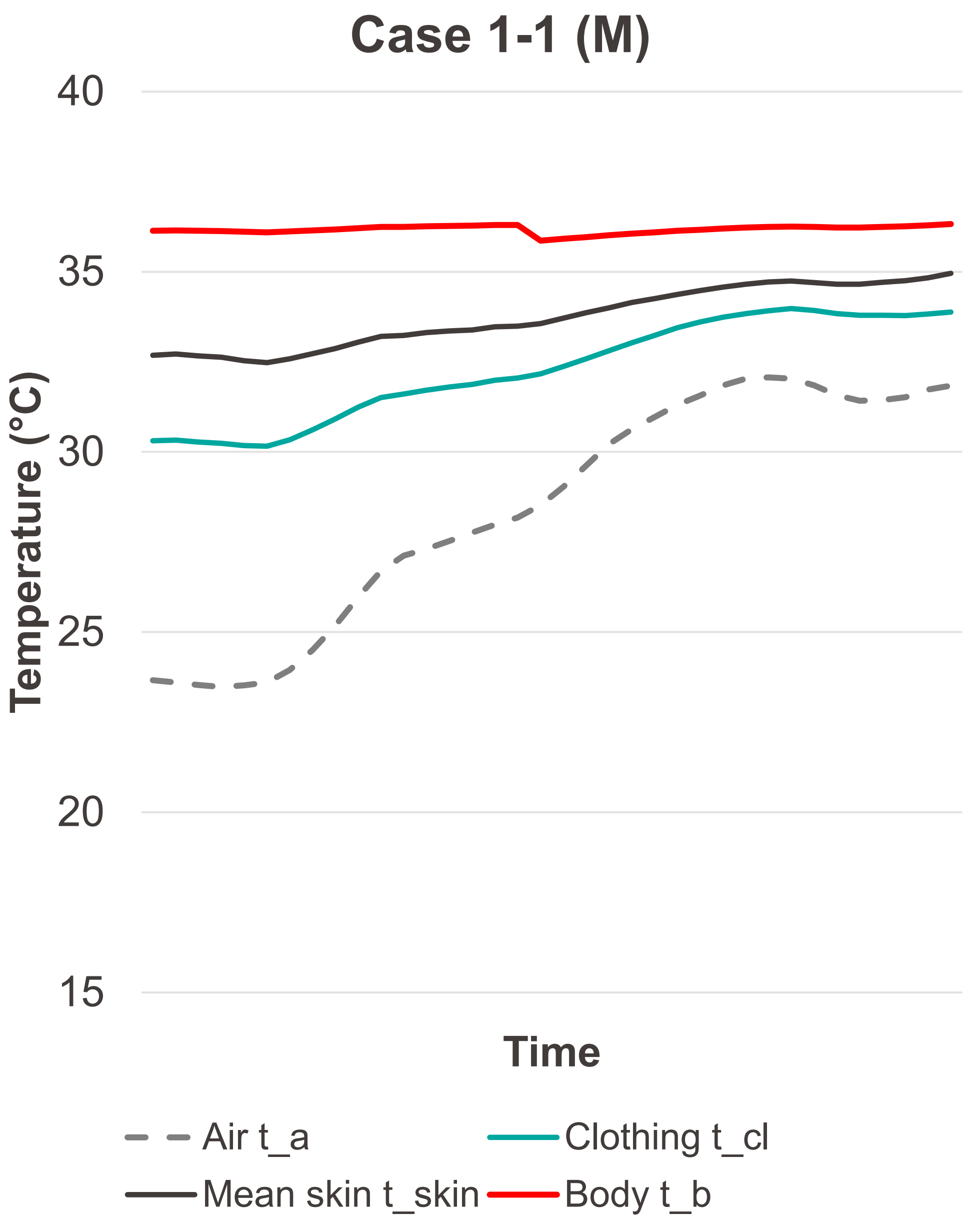
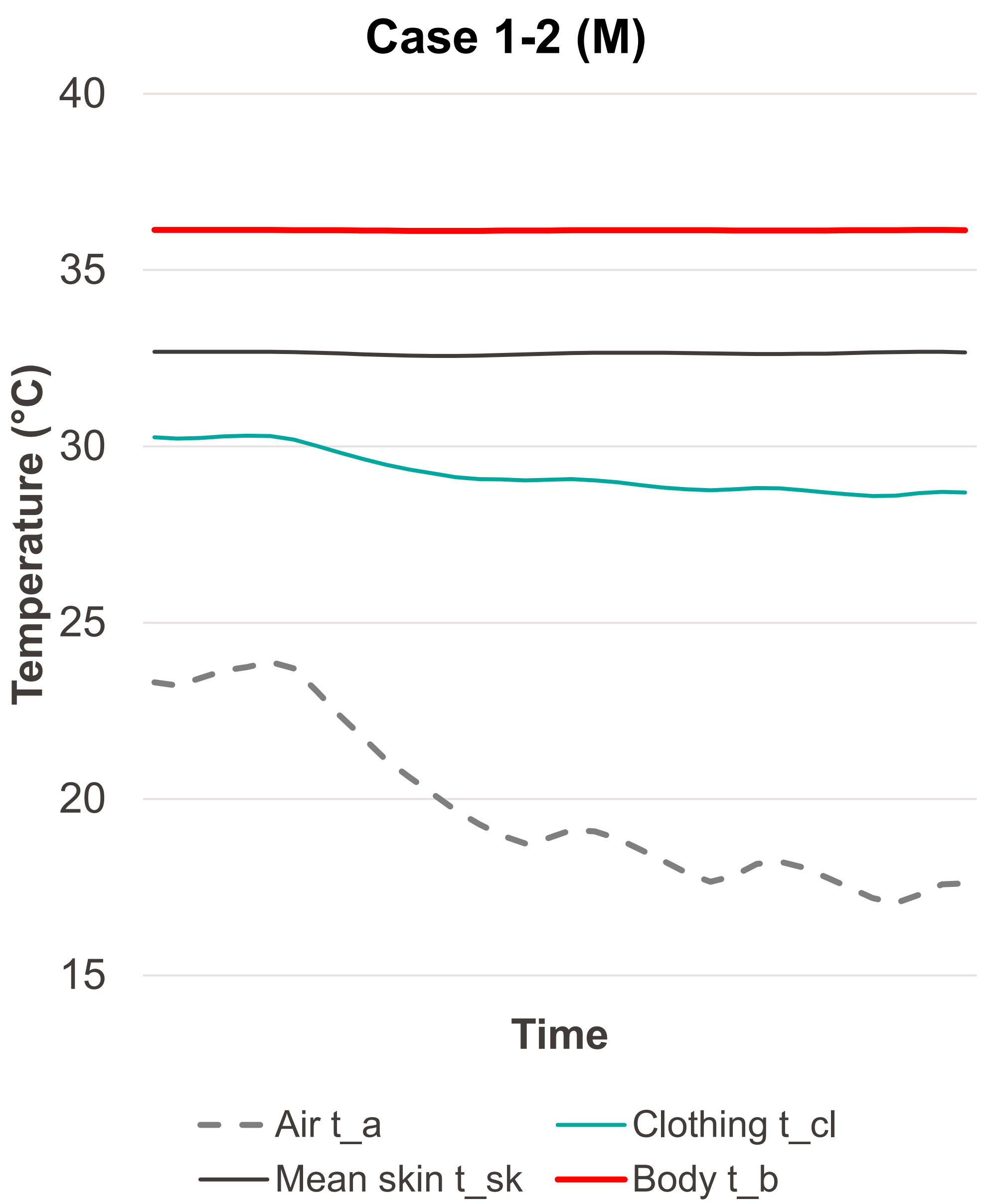
Example: Cases 1-1 (drift up) and 1-2 (drift down)





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DISCUSSION

- **Discuss the data provided and the result:**
  1. **Heat transfer** from **the human body** per ***different mechanisms***
  2. Combine (1) discussion with ***the category of comfort*** per **ISO 17772**
  3. Combine (1) discussion with ***the thermal sensation*** using **the PMV index**
  4. List assumptions in (1) that simplify the analysis and calculations

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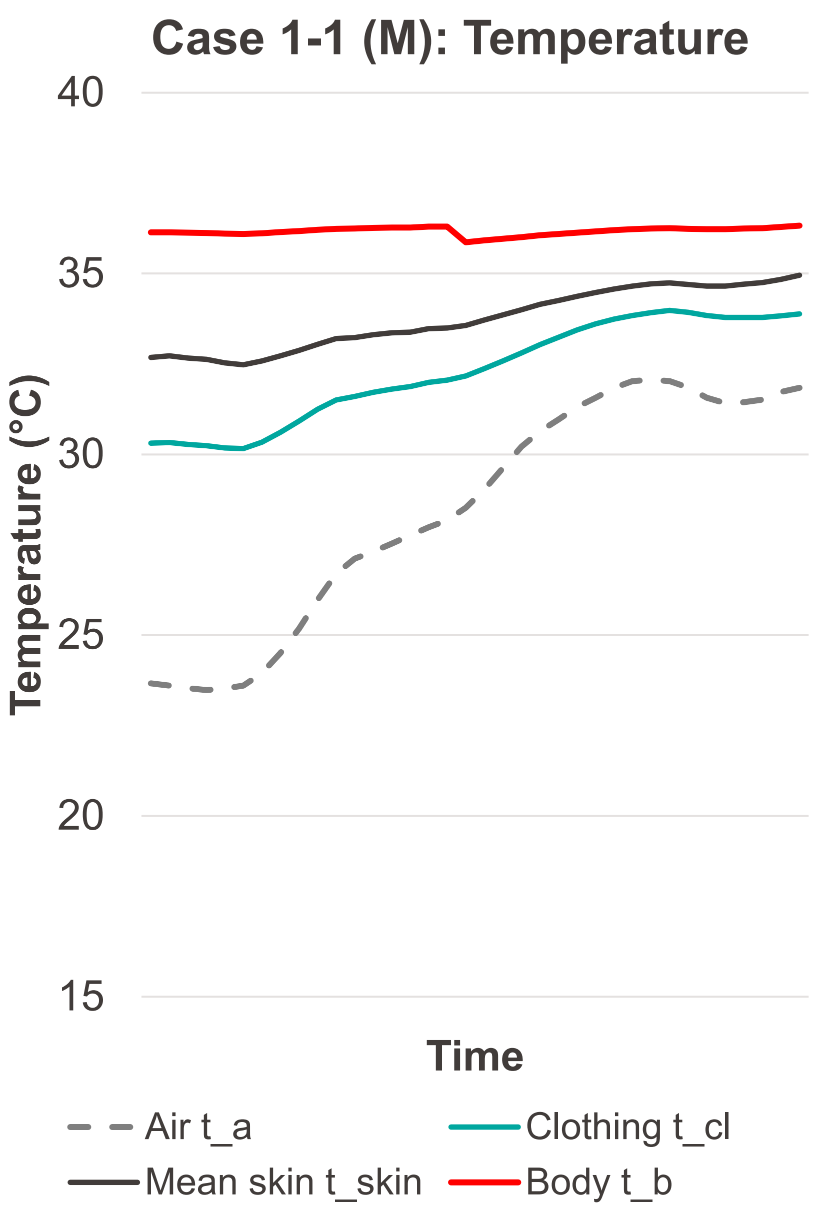
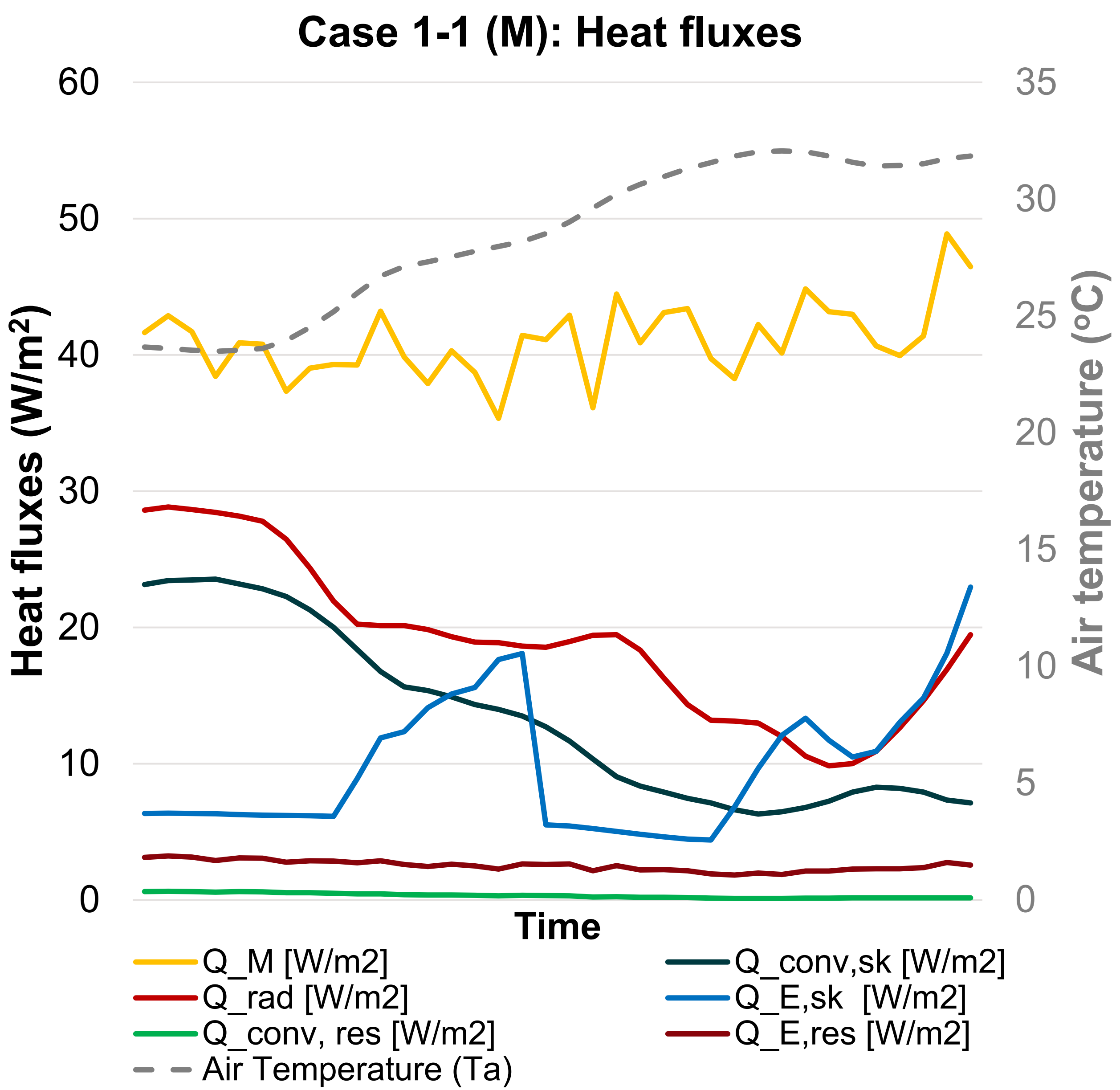
Example results: Cases 1-1 (drift up)





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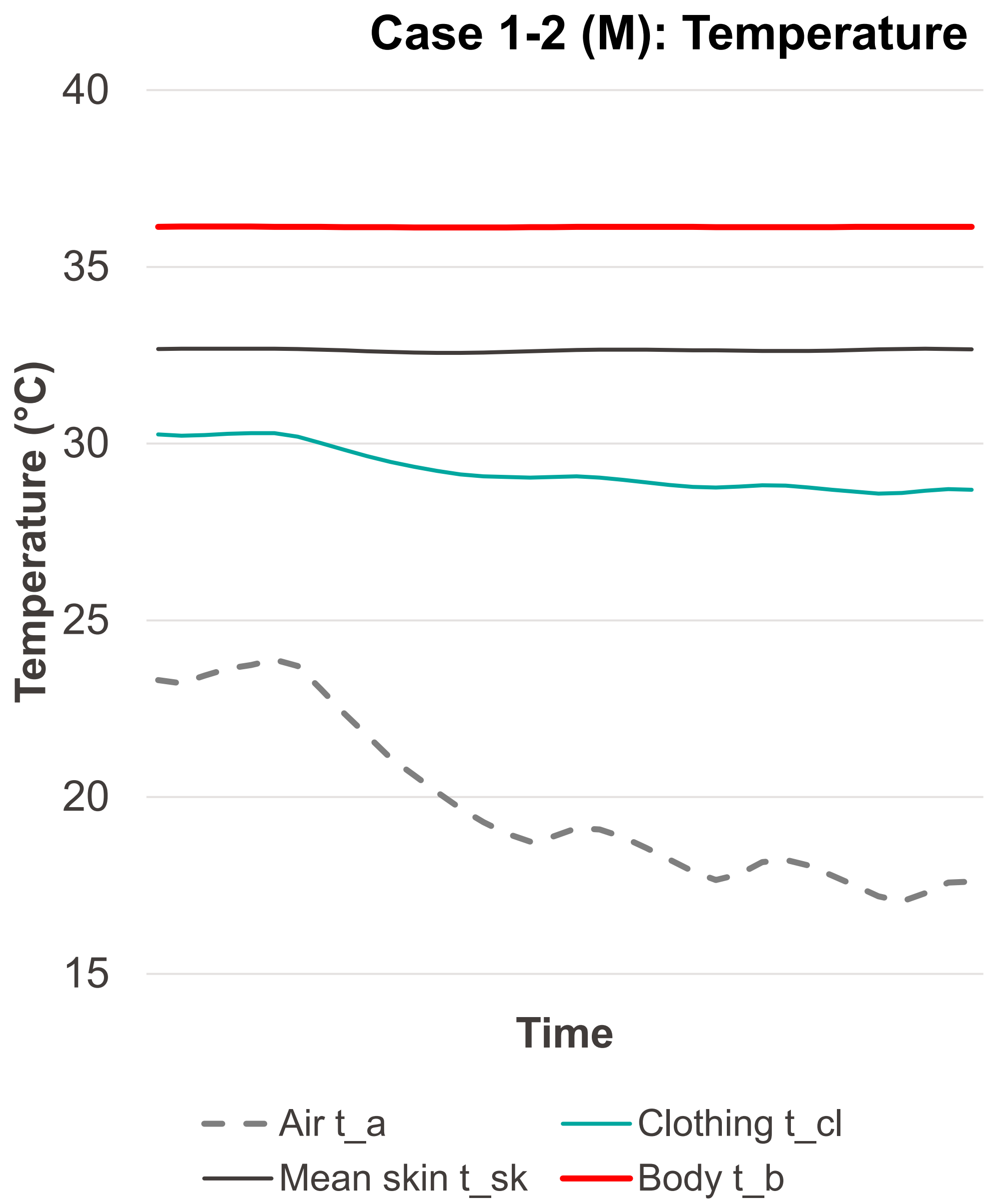
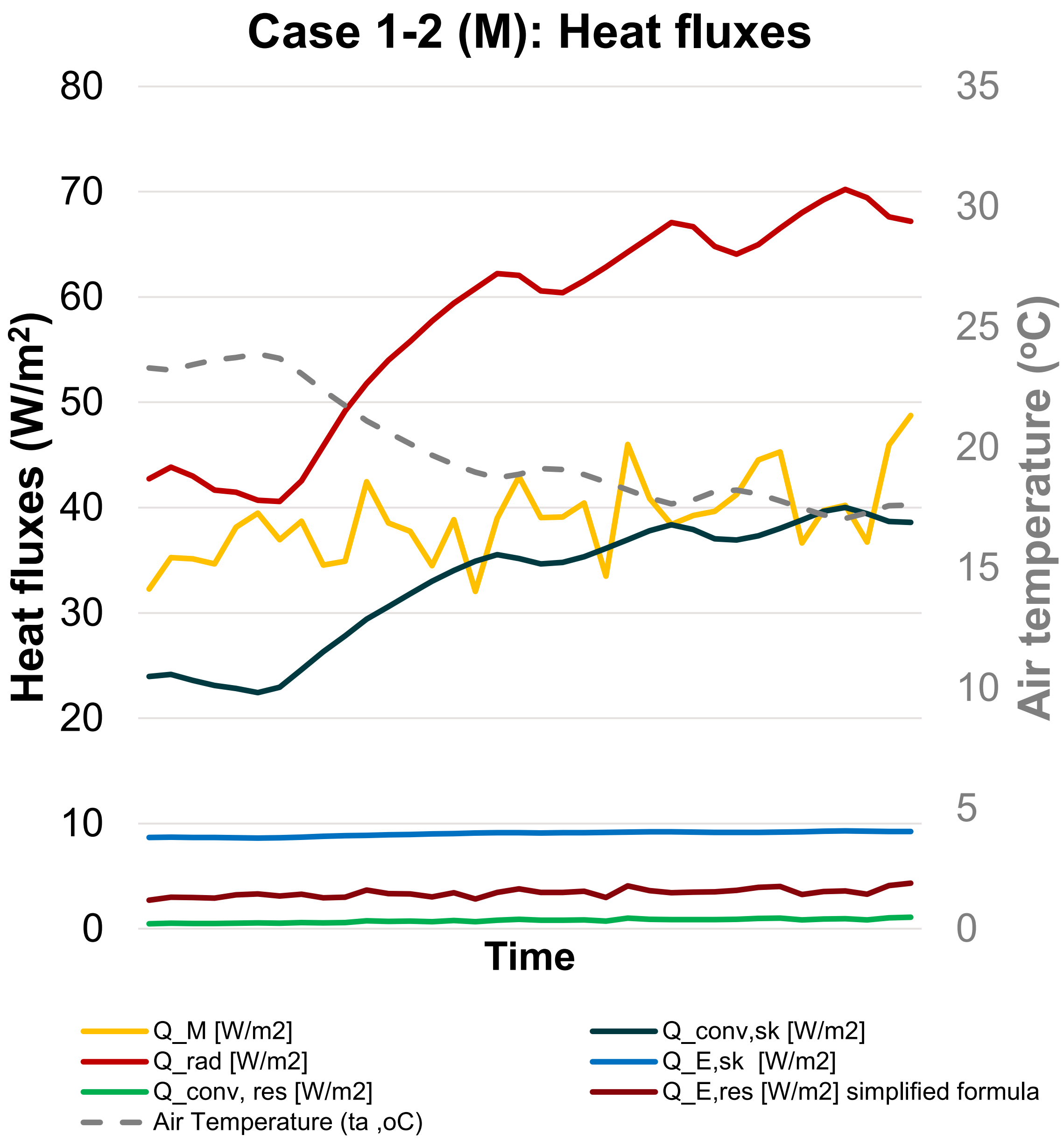
Example results: Case 1-2 (drift down)





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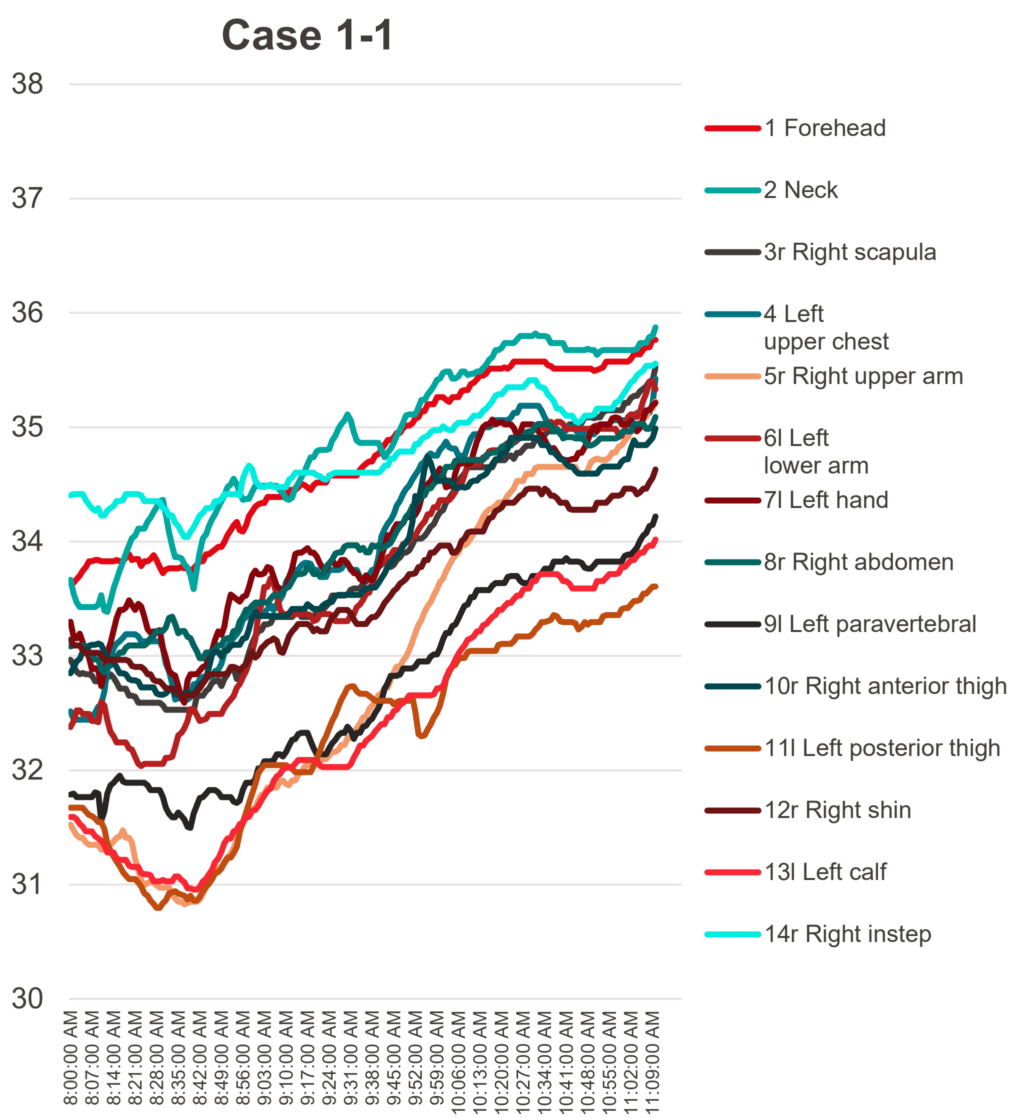
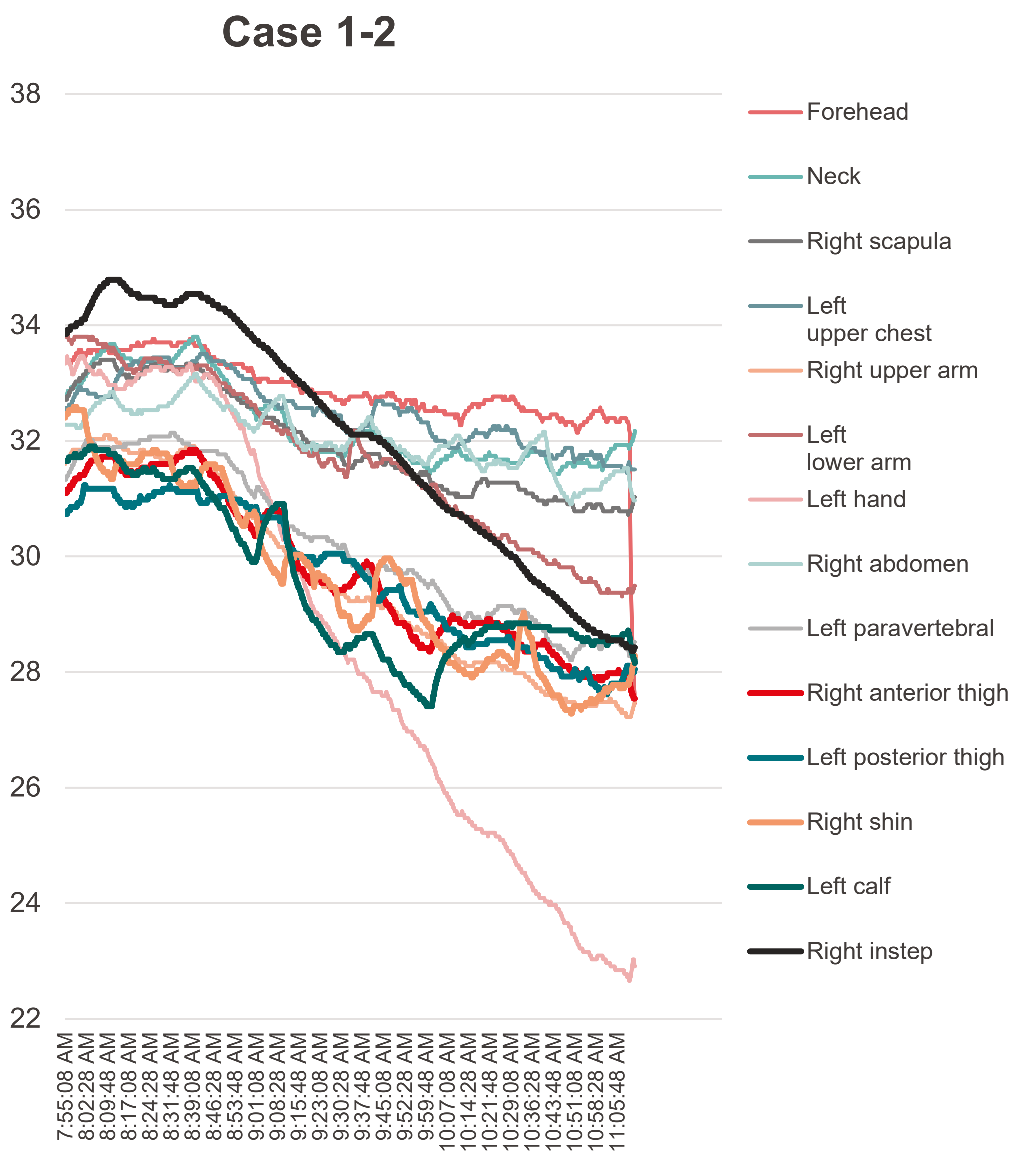
Local Skin Temperatures: Drift UP & Drift DOWN





Mean Skin Temperature: ISO 9886:2004

- For the determination of **the mean skin temperature** from ***local temperatures measured*** at ***different body locations***, three weighting schemes, with 4, 8 or 14 measuring points, are used.
- *In warm or hot conditions*, the weighting scheme using 4 points can be chosen, except in the case of a highly asymmetrical radiation.

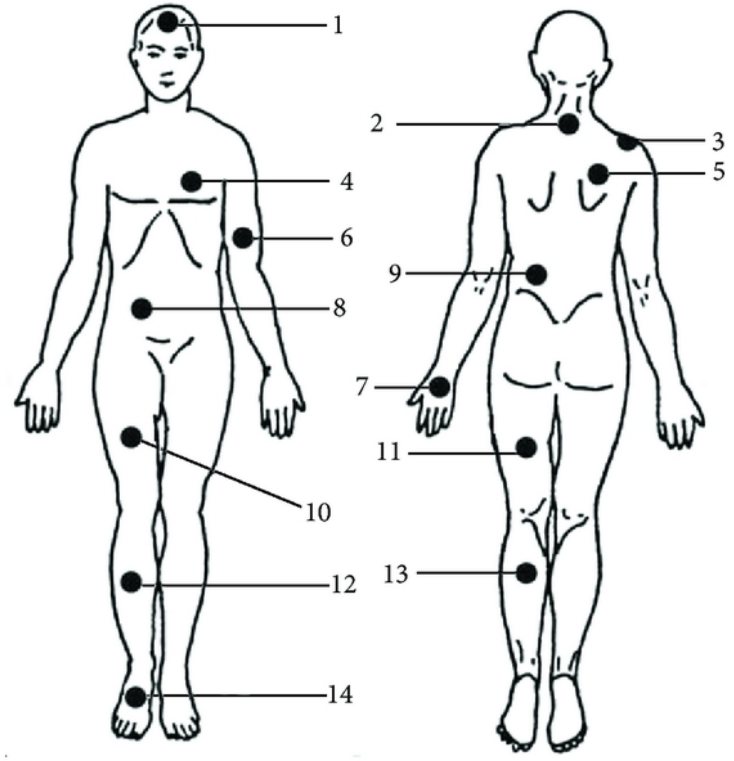


Table B.1 — Measuring sites and weighting coefficients

	Sites	4 points	8 points	14 points
1	forehead		0,07	1/14
2	neck	0,28		1/14
3	right scapula	0,28	0,175	1/14
4	left upper chest		0,175	1/14
5	right arm in upper location		0,07	1/14
9	left arm in lower location		0,07	1/14
7	left hand	0,16	0,05	1/14
8	right abdomen			1/14
9	left paravertebral			1/14
10	right anterior thigh		0,19	1/14
11	left posterior thigh			1/14
12	right shin	0,28		1/14
13	left calf		0,2	1/14
14	right instep			1/14

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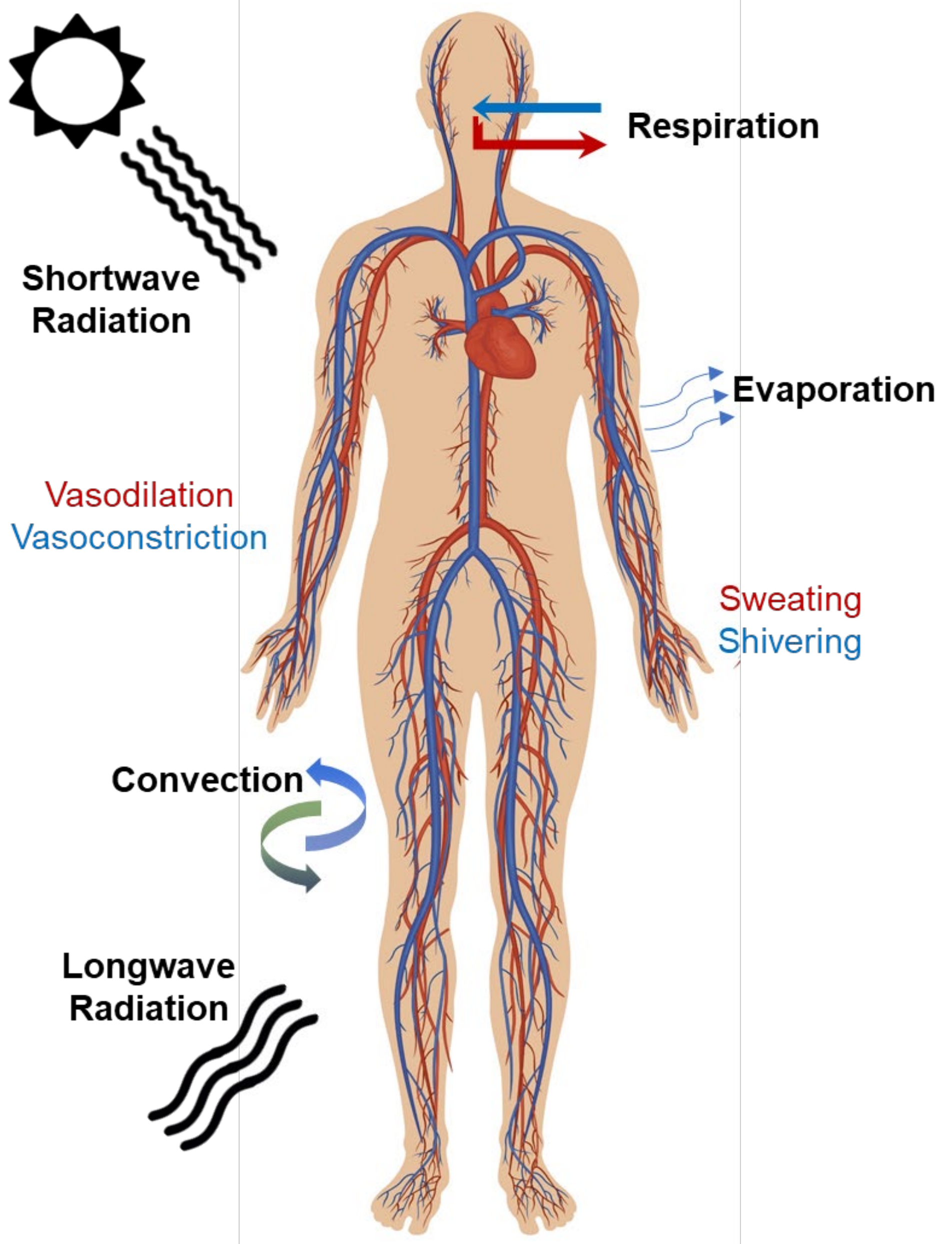

Thank you for your attention!

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