Inhabitants and buildings

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1. Introduction

Dwellings should provide comfortable indoor living conditions. This is achieved by providing a good air quality, i.e. by controlling CO_2 and moisture. They are not pollutants but markers: high CO_2 concentration reveals bad smells and accumulation of other pollutants (see hereafter). Moisture can cause mould growth.

- $PM_{2.5}$/PM_{10} — cooking, candles, smoking, infiltration from outdoors.
- NO_2 — gas stoves/heaters without adequate ventilation.
- CO — faulty heaters, garages; acute poisoning risk.
- Formaldehyde and other VOCs — furniture/pressed wood, paints, adhesives, air fresheners.
- Ozone (indoors) — certain "ionizing" purifiers; reacts on surfaces to form irritants.
- Radon (^{222}Rn) — soil gas ingress; lung-cancer risk (especially with smoking).
- Biological agents — mould spores, dust mites, pet dander, pollen; trigger asthma/allergies.
- Environmental tobacco smoke (ETS) — mixture of PM, PAHs, VOCs, CO; high health burden.

Dwellings should also maintain a comfortable thermal comfort considering clothes, activity, air speed,etc.

2. Human respiration

- Respiration influences the CO_2 and water vapor in the air.
- Respiration is a chemical process dictated by the following equation:

$$C_6H_{12}O_6 + 6 \times 0_2 \rightarrow 6 \times CO_2 + 6 \times H_2O + \text{energy}$$

  where $C_6H_{12}O_6$ is glucose, O_2 is oxygen, CO_2 is carbon dioxide and H_2O is water vapor.

- one glucose molecule reacts with 6 molecules of oxygen to produce 6 molecules of carbon dioxide, 6 molecules of water vapor and energy.*

It shows that 1 molecule of O_2 is transformed into 1 molecule of CO_2 and 1 molecule of H_2O (vapor).

- This is why the breath fogs up a mirror (with the water vapor)
- You can see your breath in cold weather due to condensation

Regarding comfort, high humidity levels are not good because it causes discomfort and can lead to mold growth.

Nominal values for normal human adult breathing at sea-level

Condition	Rate (Breaths/min)	Tidal Volume (L/breath)	Minute Ventilation (L/min)
Nominal At-Rest	12	0.5	6
Normal Activity	16	1	16
Moderate Exercise	20	2	40
Stress Test	35	3	140
Maximum PFT*	NA	4.5	NA

*standard pulmonary function test (PFT)

3 Indoor CO_2

3.1 Production of CO_2

In terms of concentration, the exhaled air from breaths is at 38000ppm of CO_2 and 100% of relative humidity at 37°C. At rest, for n persons, the volume of air exhaled per second is:

$$Q_{breath[m^3/s]} = n\frac{Q_{breath[l/min]}}{60000}$$

Therefore, the CO_2 production is equal to Q_{breath} in m^3/s multiply by 38000ppm:

$$\Pi_{CO_2} = n \times 38000ppm \times Q_{breath[m^3/s]} = 0.64nQ_{breath[l/min]}$$

At normal activity, production is about $10 \times n\ ppm.m^3/s$.

At moderate exercise, production is about $13 \times n\ ppm.m^3/s$.

At stress exercise, production of CO_2 is about $22 \times n\ ppm.m^3/s$.

3.2 Impact of CO_2 on human

C_{CO_2}	effect on human
400-1000ppm	comfortable
1700ppm	considered as significant confinement
6000ppm	cause headache after 30min exposure
30000ppm	cause increase of breath rate and beat rate
100000ppm	cause vomiting
>200000ppm	black-out and death

3.3 ICONE, a containment indicator

ICONE (*Indicateur de Confinement*) is a French indicator used to measure the confinement level (i.e. exposure time to high concentration of CO_2) in a room.

Note: even if CO_2 is not a pollutant at low concentration, it reveals bad smells and at higher levels, it causes headache.

Let k be an instant of a regularly sampled time dataset $(0, T_s, 2T_s, \ldots, (n-1)T_s)$.

- Let O_k be the number of occupants in a zone.
- Let C_k be the CO2 concentration in the zone at time k.

- Let $level(C_k, O_k) \in \{-1, 0, 1, 2\}$ such as:
  - $O_k = 0 \rightarrow level(C_k, O_k) = -1$ (no exposure)
  - $O_k > 0$ and $C_k < 1000ppm \rightarrow level(C_k, O_k) = 0$ (normal exposure)
  - $O_k > 0$ and 1000ppm< $C_k < 1700ppm \rightarrow level(C_k, O_k) = 1$ (medium exposure)
  - $O_k > 0$ and $C_k > 1700ppm \rightarrow level(C_k, O_k) = 2$ (high exposure)

Let's define the frequency of a level=L_i as the ratio of the number of occurences of level= L_i over the number of occurences of level ≥ 0:

$$f_i = \frac{\mid \{k/\text{level}(C_k, O_k) = L_i\} \mid}{\mid \{k/\text{level}(C_k, O_k) \geq 0\} \mid}$$

Because of an admitted logarithmic relationship between stimuli and olfactive sensation, the ICONE indicator of containment (confinement in French) is defined by:

$$\text{ICONE} = 8.3 log_{10}(1 + f_1 + 3 f_2)$$

The following scale is admitted:

ICONE	level of containment
0	no containment
1	low containment
2	average containment
3	high containment
4	very high containment
5	extreme containment

Suppose we consider a room with ventilation.

The production of CO_2 and H_2O are denoted respectively Π_{CO_2} and Π_{H_2O}.

The variation of CO_2 (and resp. H_2O) in a room (volume V, ventilation Q) is given by:

$$V\frac{dC_{CO_2,in}}{dt} = Q_{m^3/s}\left(C_{CO_2,out} - C_{CO_2,in}\right) + \Pi_{CO_2}$$

or,

$$\frac{dC_{CO_2,in}}{dt} = \frac{Q_{vol/h}}{3600}\left(C_{CO_2,out} - C_{CO_2,in}\right) + \frac{\Pi_{CO_2}}{V}$$

The steady state $\left(\frac{dC_{CO_2,in}}{dt} = 0\right)$ leads to:

$$Q_{vol/h} = \frac{3600\Pi_{CO_2}}{V\left(C_{CO_2,in} - C_{CO_2,out}\right)}$$

4. Indoor moisture

4.1 Reminder

Let's recall the basic ideal gas law reflecting the state of a gas, air and water vapor for us:

$$PV = nRT$$

where P is the pressure in Pascal, V is the volume in m^3, n is the number of moles, R is the ideal gas constant in J/mol.K and T is the temperature in Kelvin (273.15 + temperature in Celsius).

Suppose the ideal gas is composed of n_i moles (1 mol~$6.022\ 10^{23}$ molecules) of component i.

- When we have a mixture of gasses, each component follows the same ideal gas law.
- The total number of moles is $n = \sum_i n_i$

The molar fraction ζ_i, which is homogeneous at a concentration, is defined by: $\zeta_i = \frac{n_i}{n}$ where n_i is the number of moles of the component i and n is the total number of moles. We have $\sum_i \zeta_i = 1$.

Molar masses of common gases

gas	molar mass (g/mol)
argon (Ar)	39.94
carbon dioxide (CO2)	44.01
carbon monoxide (CO)	28.01
hydrogen (H2)	2.02
nitrogen (N2)	28.02
oxygen (O2)	32
dry air	28,97
water (H2O)	18.015

4.2 Dry air composition and wet air

The density of dry air at 20°C: 1204g/m^3 (41.4 mol/m^3) at standard atmospheric pressure: $P_{atm} = 101325$Pa

The dry air composition in mole/volume fractions ζ_i and mass fraction μ_i:

- nitrogen: ζ_{N_2} = 78.08%, μ_{N_2}=75.52% (=$\frac{0.7808 \times 28.02}{28.97}$)
- oxygen: ζ_{O_2} = 20.95%, μ_{O_2} = 23.14% (=$\frac{0.2095 \times 32}{28.97}$)
- argon: ζ_{Ar} = 0.93%, μ_{Ar} = 1.28% (=$\frac{0.0093 \times 39.94}{28.97}$)
- carbon dioxide: ζ_{CO_2} = 0.04%, μ_{CO_2} = 0.04% (=$\frac{0.0004 \times 44.01}{28.97}$)

plus other traces less than $\zeta_i < 0.01$ each

Besides that, wet air can contain up to 4% of the volume of water vapor.

4.3 Absolute and relative humidity

From dry to wet air: Consider 1 m³ of air containing both dry air and water vapor.

- Dry air: density $\rho_{\text{dry air}}$ ≈ 1200 g/m³, molar mass $M_{\text{dry air}}$ = 28.97 g/mol
  - Number of moles of dry air: $n_{\text{dry air}} = \frac{\rho_{\text{dry air}}}{M_{\text{dry air}}}$ in mol/m³
- Water vapor: absolute humidity AH_V (g/m^3), molar mass M_{H_2O} = 18.015 g/mol
  - Number of moles of water: n_{H_2O} = $\frac{AH_V}{M_{H_2O}}$ in mol/m³

The dry air mole fraction in wet air is:

$$\zeta_{\text{dry/wet air}} = \frac{n_{\text{dry air}}}{n_{\text{dry air}} + n_{H_2O}} = \frac{1}{1 + \frac{\text{AH}_V \cdot M_{\text{dry air}}}{\rho_{\text{dry air}} \cdot M_{H_2O}}} = \frac{1}{1 + \text{AH}_V/746} \rightarrow \zeta_{\text{H2O}} = \frac{\text{AH}_V}{746 + \text{AH}_V} \approx \frac{\text{AH}_V}{746}$$

Because $\text{AH}_V\ [\text{g/m}^3\ ] \approx 1200 \times \text{AH}_M\ [\text{g/kg}]$ (dry air density ≈ 1200 g/m³), or equivalently $\text{AH}_V\ [\text{g/m}^3\ ] \approx 1000 \times \text{AH}_M\ [\text{kg/kg}]$, we have also:

$$\zeta_{\text{dry/wet air}} = \frac{1}{1 + 1608\text{AH}_{M[g/kg]}} \rightarrow \zeta_{\text{H2O}} = \frac{1608\text{AH}_{M[g/kg]}}{1 + 1608\text{AH}_{M[g/kg]}} \approx 1608\text{AH}_{M[g/kg]}$$

ζ are concentrations, so they are always less than 1.

The relative humidity (RH) between 0 and 1, is defined by:

$$\mathrm{RH} = \frac{P_{H_2O}(T)}{\hat{P}_{H_2O}(T)}$$

where $P_{H_2O}(T)$ and $\hat{P}_{H_2O}(T)$ are the vapor pressure and the saturation vapor pressure at temperature T.

$\hat{P}_{H_2O}$ is given in Pascal (and T in Celsius) by the Magnus formula:

$$\hat{P}_{H_2O} = 611.2 e^{\frac{17.67T}{243.12+T}}$$

Noticing the number of moles of water vapor per m^3 is given by $n/V = AH_v/M_{H2O}$, the vapor pressure can be inferred from the ideal gas law:

$$P_{H_2O} = \frac{nRT_K}{V} = AH_V \frac{RT_K}{M_{H_2O}} = \frac{273.15+T}{2.167} \times AH$$

We've got the relationship between $AH_V[g/m^3]$ and $RH(\%) \in [0,1]$ (T in $^\circ C$):

$$\boxed{\mathrm{RH} = \frac{273.15+T}{1324.5 e^{\frac{17.67T}{243.12+T}}} \mathrm{AH}_{V[g/m^3]} \leftrightarrow \mathrm{AH}_{V[g/m^3]} = \frac{1324.5 e^{\frac{17.67T}{243.12+T}}}{273.15+T} \mathrm{RH}}$$

Let's convert now the relative humidity in g/m^3 to absolute humidity in g/kg.

We have:

$$\text{AH}_{V[g/m^3]} = \frac{m_{H2O}}{V_{\text{wet air}}}$$

and

$$\text{AH}_{M[g/kg]} = \frac{\rho_{H2O}}{m_{\text{dry air}}} = \frac{\text{AH}_{V[g/m^3]}}{\rho_{\text{dry air}}} = \frac{\text{AH}_{V[g/m^3]} R(273.15+T)}{M_{\text{dry air}} p_{atm}}$$

With R=8.61J/mol.K, T=20°C, P_{atm}=101325Pa and $M_{H_2O} = 18.015 g/mol$, we get:

$$\boxed{\text{AH}_{M[g/kg]} = \frac{R(273.15+T)}{M_{\text{dry air}} p_{atm}} \text{AH}_{V[g/m^3]} = 0.83 \text{AH}_{V[g/m^3]}}$$

4.4 Production of water vapor by breath

The exhaled air is at 100% of relative humidity at 37°C. Because RH=1, we have for the exhaled air:

$$\mathrm{AH}_V = \frac{273.15 + 37}{1324.5 e^{\frac{17.67*37}{243.12+37}}} = 44.07[g/m^3]$$

Therefore, the exhaled mass of water vapor is:

$$\dot{m}_{H_2O} = 44.07 g/m^3 \times n \times \frac{Q_{breath\ l/min}}{60000} = 44.07 n \frac{Q_{breath\ l/min}}{60000} [g/s]$$

We pass from mass to moles using molar mass:

$$\dot{n}_{H_2O} = \frac{\dot{m}_{H_2O}}{M_{H_2O}}\ [\mathrm{mol/s}]$$

To pass from moles to volume, we use the ideal gas law ($PV = nRT$). For a flow rate of moles per second producing a volume flow:

$$\dot{V}_{H_2O} = \frac{n_{moles} \times R \times T}{P_{atm}} = \frac{\dot{m}_{H_2O} \times R \times T}{M_{H_2O} \times P_{atm}}\ [\mathrm{m^3/s}]$$

To pass from volume fraction to ppm, we use the Dalton's law. The molar fraction equals the volume fraction.
If we produce $\dot{V}_{H_2O}$ m³/s of water vapor at standard conditions, this is equivalent to producing that volume with a concentration of 1 i.e. 100% or 1,000,000 ppm.
Therefore, the ppm·m³/s production is:

$$\Pi_{H_2O} = \dot{V}_{H_2O} \times 10^6 [\text{ppm}\cdot\text{m}^3/\text{s}]$$

It yields to:

$$\Pi_{H_2O}\ [\text{ppm}\cdot\text{m}^3\ /\text{s}] = \dot{m}_{H_2O} \times 10^6 \times \frac{RT}{M_{H_2O}P_{atm}} = 44.07 \times n \times \frac{Q_{breath[l/min]}}{60000} \times 10^6 \times \frac{R(273.15+T)}{M_{H_2O}P_{atm}}$$

where R=8.61J/mol.K, T=20°C, P_{atm}=101325Pa and $M_{H_2O} = 18.015 g/mol$

It comes:

$$\boxed{\Pi_{H_2O}\ [\text{ppm}\cdot\text{m}^3\ /\text{s}] = 0.98 n Q_{breath[l/min]} \text{ in } ppm \cdot m^3\ /s}$$

4.5 H_2O and ventilation

For moisture, the equation for ventilation is given by :

$$\frac{dC_{H_2O,in}}{dt} = \frac{Q_{vol/h}}{3600}(C_{H_2O,out} - C_{H_2O,in}) + \frac{\Pi_{H_2O}}{V}$$

where concentration are in ppm (particles per millions): see next slide to see the conversion from absolute humidity to ppm.

steady state leads to:

$$Q_{vol/h} = \frac{3600\Pi_{H_2O}}{V\left(C_{H_2O,in} - C_{H_2O,out}\right)}$$

where Π_{H_2O} in $ppm/m^3.\,s$

4.6 Conversion from absolute humidity to ppm

Assumption: n_{H2O} is small comparing to $n_{\text{dry air}}$ and therefore, that the mass of water vapor m_{H2O} is small comparing to the mass of dry air $m_{\text{dry air}}$ i.e. $m_{\text{wet air}} \approx m_{\text{dry air}}$.

We can develop the absolute humidity as:

$$AH_{M[kg/kg]} = \frac{m_{H2O}}{m_{\text{dry air}}} \rightarrow AH_{M[g/kg]} = 10^3 \frac{m_{H2O}}{m_{\text{dry air}}}$$

The concentration of water vapor in ppm is given by:

$$C_{H2O[ppm]} = 10^6 \times \frac{n_{H2O}}{n_{H2O}+n_{\text{dry air}}} \approx 10^6 \times \frac{n_{H2O}}{n_{\text{dry air}}} = 10^6 \times \frac{\frac{m_{H2O}}{M_{H2O}}}{\frac{m_{\text{dry air}}}{M_{\text{dry air}}}} = 10^3 \frac{M_{\text{dry air}}}{M_{H2O}} AH_{M[g/kg]}$$

It comes:

$$\boxed{C_{H20[ppm]} = 1608 AH_{M[g/kg]}}$$

4.7 Impact of moisture on the human body

HR minimum	HR maximum	Description
70%	80%	dust mites thrive at high relative humidity. To limit their growth and allergens
60%	70%	mould risk strongly increases, especially on cold surfaces where condensation can appear
50%	60%	acceptable range with discomfort
40%	50%	relative humidity (RH) is the optimal range for living spaces
30%	40%	acceptable range with discomfort
30%	35%	getting too dry: symptoms like dry skin, irritation, nosebleeds, electrostatic discharge, wood movement begin for many occupants
15%	25%	problematic dryness: frequent irritation, nosebleeds, electrostatic discharge, wood movement begin for many occupants
0%	15%	extreme dryness: significant discomfort; sensitive materials at risk

Note that 100% of humidity means the air is fully saturated in vapor and dew starts to appear. It depends on the air temperature (see Givoni chart in the nexts slides).

Ideal relative humidity for different rooms:

Moisture is not only produced by human respiration but also by other sources:

- Showers: 1–2 kg per event (without extraction)
- Cooking/boiling: 0.2–1 kg per meal
- Laundry drying indoors / aquariums / many plants: often dominant sources
- Ingress: rising damp/capillarity, rain leaks, plumbing pinholes, wet basements

Room	Ideal Relative Humidity (%)	Recommended Humidity Levels
Living Room	40-50%	Comfortable for most people; prevents static electricity and damage to furniture
Bedroom	30-50%	Improves sleep quality; prevents dry skin and respiratory problems
Kitchen	40-50%	Prevents mould and mildew growth due to cooking steam
Bathroom	40-60%	Common high humidity from showers; manage to avoid mould
Basement	30-50%	Prevents dampness, mould, and mildew
Home Office	30-50%	Comfortable for working; protects electronics from moisture damage

5. Modeling thermal comfort

5.1 Moisture impact on thermal comfort

Human body regulates its interior temperature by adjusting its perspiration that take advantage of latent heat:

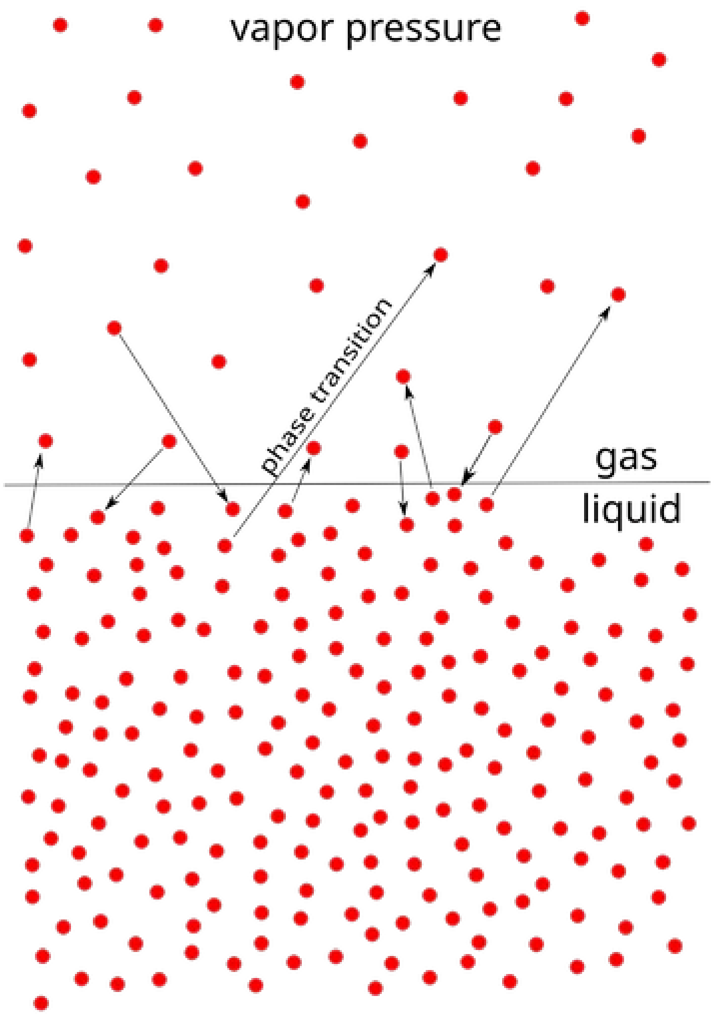
- steam from breath (see respiration formula)
- sweat through skin (evaporation is endothermic, meaning that it takes energy from the body).

We have:

$$P_{\text{absorbed}} = \tau L_{\text{water}}$$

where:

- P_{absorbed} is the absorbed power in Watt
- L_{water} is the latent heat of water vaporization (2.45×10^6 J/kg)
- τ is the rate of transpiration in kg/s



5.2 Example

Let's consider a rate of sweating of 0.5 l/day (from 0.1 to 8l/day).

During a day, the power absorbed can range from 2W to 227W.

If the relative humidity is 100% and ambient temperature is over 35°C:

- your body needs to cool down
- you need to transpire and release the heat, but the air is already saturated in vapor
- since you cannot transpire, your body cannot cool down
- the death can occur within few hours

Note: this is one of the issue of the climate change at equatorial regions.

5.3 Impact of clothes on the human body

The power produced by the body at rest is given by:

$$P_{rest} = \frac{31^{\circ}C - T_{\text{ambient}}}{0.155 R_{clo}} S_{\text{skin}} \text{ [W]}$$

with T_{ambient} in °C, R_{clo} in clo.

One clo is the amount of insulation that allows a person at rest to maintain thermal equilibrium in an environment at 21°C in a normally ventilated room with 0.1 m/s air movement:

$$1 \text{ clo} = 0.155 \text{ K}{\cdot}\text{m}^2/\text{W}$$

clothes description	Icl (clo)
Walking shorts, short-sleeved shirt	0.36
Trousers, short-sleeved shirt	0.57
Trousers, long-sleeved shirt	0.61
Same as above, plus suit jacket	0.96
Same as above, plus vest and T-shirt	0.96
Trousers, long-sleeved shirt, long-sleeved sweater, T-shirt	1.01
Same as above, plus suit jacket and long underwear bottoms	1.30

clothes description	Icl (clo)
Sweat pants, sweat shirt	0.74
Long-sleeved pajama top, long pajama trousers, short 3/4 sleeved robe, slippers (no socks)	0.96
Knee-length skirt, short-sleeved shirt, panty hose, sandals	0.54
Knee-length skirt, long-sleeved shirt, full slip, panty hose	0.67
Knee-length skirt, long-sleeved shirt, half slip, panty hose, long-sleeved sweater	1.10

clothes description	Icl (clo)
Knee-length skirt, long-sleeved shirt, half slip, panty hose, suit jacket	1.04
Ankle-length skirt, long-sleeved shirt, suit jacket, panty hose	1.10
Long-sleeved coveralls, T-shirt	0.72
Overalls, long-sleeved shirt, T-shirt	0.89
Insulated coveralls, long-sleeved thermal underwear, long underwear bottoms	1.37

The internal temperature of the human body is also impacted by the sensitive heat exchange with the environment. It therefore depends on:

- the surface of the body i.e. the skin surface:

$$S_{skin} \approx 0.202 m^{0.425} h^{0.725}$$

where m represents the weight in kg and h in meters.

- the produced work:

$$P_{\text{body}} = P_{\text{met}} P_{\text{rest}}$$

where P_{met} is the metabolic rate in W/m^2 and P_{rest} is the rest power in W/m^2.

	W/m^2	met*
Resting		
Sleeping	40	0.7
Reclining	45	0.8
Seated, quiet	60	1.0
Standing, relaxed	70	1.2
Walking (on level surface)		
3.2 km/h (0.9 m/s)	115	2.0
4.3 km/h (1.2 m/s)	150	2.6
6.4 km/h (1.8 m/s)	220	3.8
Office Activities		
Reading, seated	55	1.0
Writing	60	1.0
Typing	65	1.1
Filing, seated	70	1.2
Filing, standing	80	1.4
Walking about	100	1.7
Lifting/packing	120	2.1

One considers that the energy produced by human body is spread as:

- 24% with perspiration (removed by ventilation)
- 35% with convection (skin-air exchanges, important part of metabolism)
- 35% with radiation (body radiates power in the infrared range, important part of metabolism)
- 6% with food (which has a different temperature)
- 1% with conduction (feet)

5.4 Models for modeling the thermal comfort

There are two main categories of models for analysis of thermal comfort:

- static/steady-state models
  - Psychrometric analysis (Givoni chart)
  - Predictive mean vote (PMV)
- adaptive models
  - ASHRAE 55
  - ISO 15251/ISO 17772-1

Static models:

- assume fixed comfort conditions
- dont consider occupants' behavior/adaptation
- don't consider comfort expectations for seasonal changes

Adaptive models:

- consider that humans can adapt to the environment
- consider that humans have comfort expectations for seasonal changes
- can adjust their clothing/activity

5.4.1 Comfort assessment with the psychrometric (or Givoni) chart

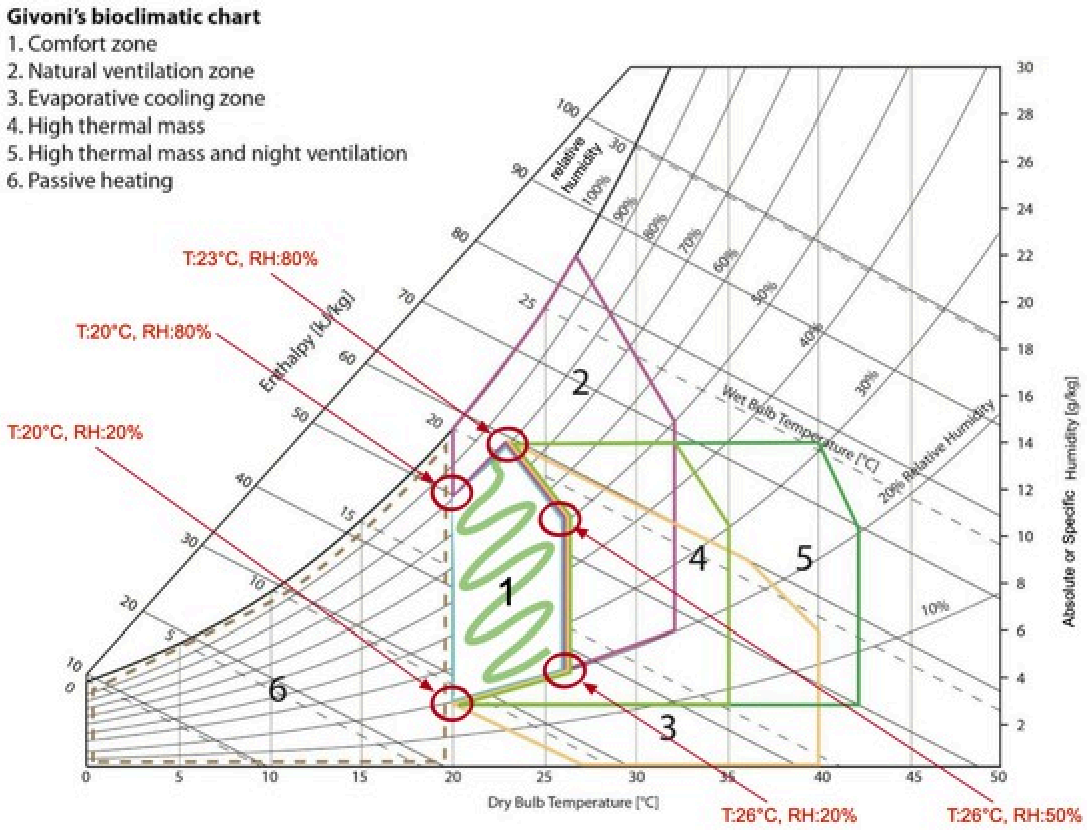
- The psychrometric chart is a graphical representation of the thermodynamic properties of moist air.
- It is used to analyze the behavior of air in relation to its temperature, humidity, and other thermodynamic properties.
- One of the major applications of the Psychrometric Chart is in air conditioning, and we find that most humans feel comfortable about when the temperature is between 20°C and 27°C, and the relative humidity is between 20% and 80%.
- The psychrometric analysis is applicable for indoor and outdoor environment.

On the psychrometric chart, the air is represented by a point whose coordinates are:

- the "dry bulb" temperature in °C (regular temperature)
- the absolute humidity in g/kg dry air

The relative humidity is represented by the dashed lines on the chart.

The absolute humidity is the mass of water vapor per unit mass of dry air.



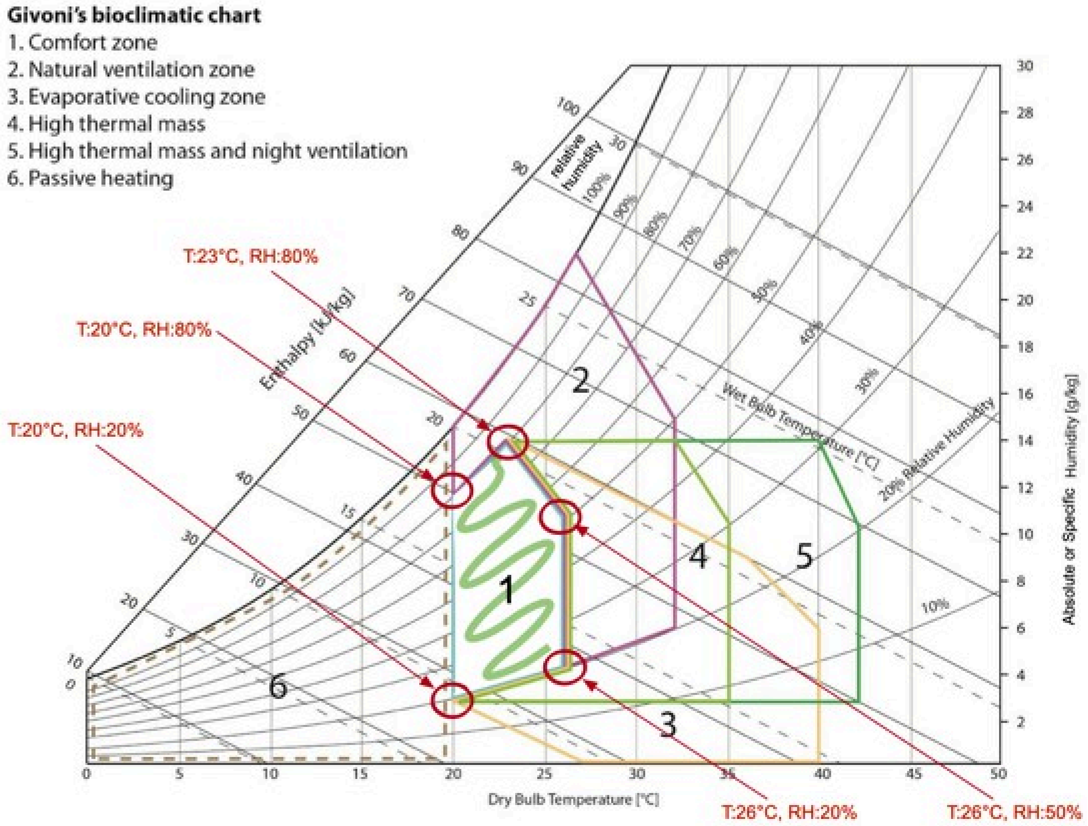
Bioclimatic zones based on the Giovanni diagram.

The dry-bulb temperature is simply the ordinary air temperature, measured by a standard thermometer exposed to the air but shielded from radiation and moisture. It is what we typically call "the air temperature" in weather forecasts or on thermostats. It reflects how warm the air feels if humidity is not considered.

The wet-bulb temperature is the lowest temperature that can be reached by evaporative cooling of a water-wetted surface exposed to air. It is measured by covering a thermometer bulb with a wet wick (cloth) and ventilating it: as water evaporates from the wick, it removes heat from the thermometer. The evaporation rate depends on air humidity and air movement. The thermometer stabilizes at the wet-bulb temperature.

Impact of phenomena:

- heating moves you to the right of the chart
  - the absolute humidity stays the same
  - the relative humidity decreases
- cooling moves you to the left of the chart
  - the absolute humidity stays the same
  - the relative humidity increases
- humidification moves you up of the chart
  - the dry bulb temperature stays the same
  - the absolute humidity increases
- dehumidification moves you down of the chart
  - the dry bulb temperature stays the same
  - the absolute humidity decreases



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5.4.2 Comfort assessment with the predictive mean vote

The PMV is a scientific method developed by Fanger in 1982 to quantify thermal comfort. It takes into account several key factors that influence how comfortable a person feels in an indoor environment:

- Air Temperature (T_{air}): The temperature of the surrounding air
- Radiant Temperature: The temperature of surrounding surfaces that radiate heat
- Relative Air Velocity: How fast the air is moving around the person
- Clothing: The thermal insulation provided by what the person is wearing
  Base Metabolism: The heat generated by the person's body at rest
- it does not take into account the human work
- for indoor environment only

Discomfort is considered as the metabolic heat flow L required to maintain the comfortable skin temperature and the latent energy corresponding to comfortable sweat.

The comfortable skin temperature during comfort is given by:

$$T_{\text{skin}} = 35.7 - 0.0276M$$

where M is the metabolic rate per skin surface in W/m^2 and the comfortable sweat secretion for comfort:

$$P_{\text{sweat}} = 0.42(M - 58)$$

In order to characterize the relationship between the thermal sensation and the metabolic heat flow L, lots of people have been asked to assess their level of comfort under different conditions accordingly to the next table. The resulting relationship is given by:

$$\text{PMV} = 3.155(0.303e^{-0.144M+0.028})L$$

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

Finally, the predicted mean vote is the average response of a large number of people. Given the subjective nature of comfort, there will actually be a distribution of satisfaction among a large group of people.

The next figure shows an empirical relationship between the percentage of people dissatisfied (PPD) with a thermal environment as a function of the PMV:

$$\mathrm{PPD} = 1 - 0.95e^{-0.03353\mathrm{PMV}^4 - 0.2179\mathrm{PMV}^2}$$

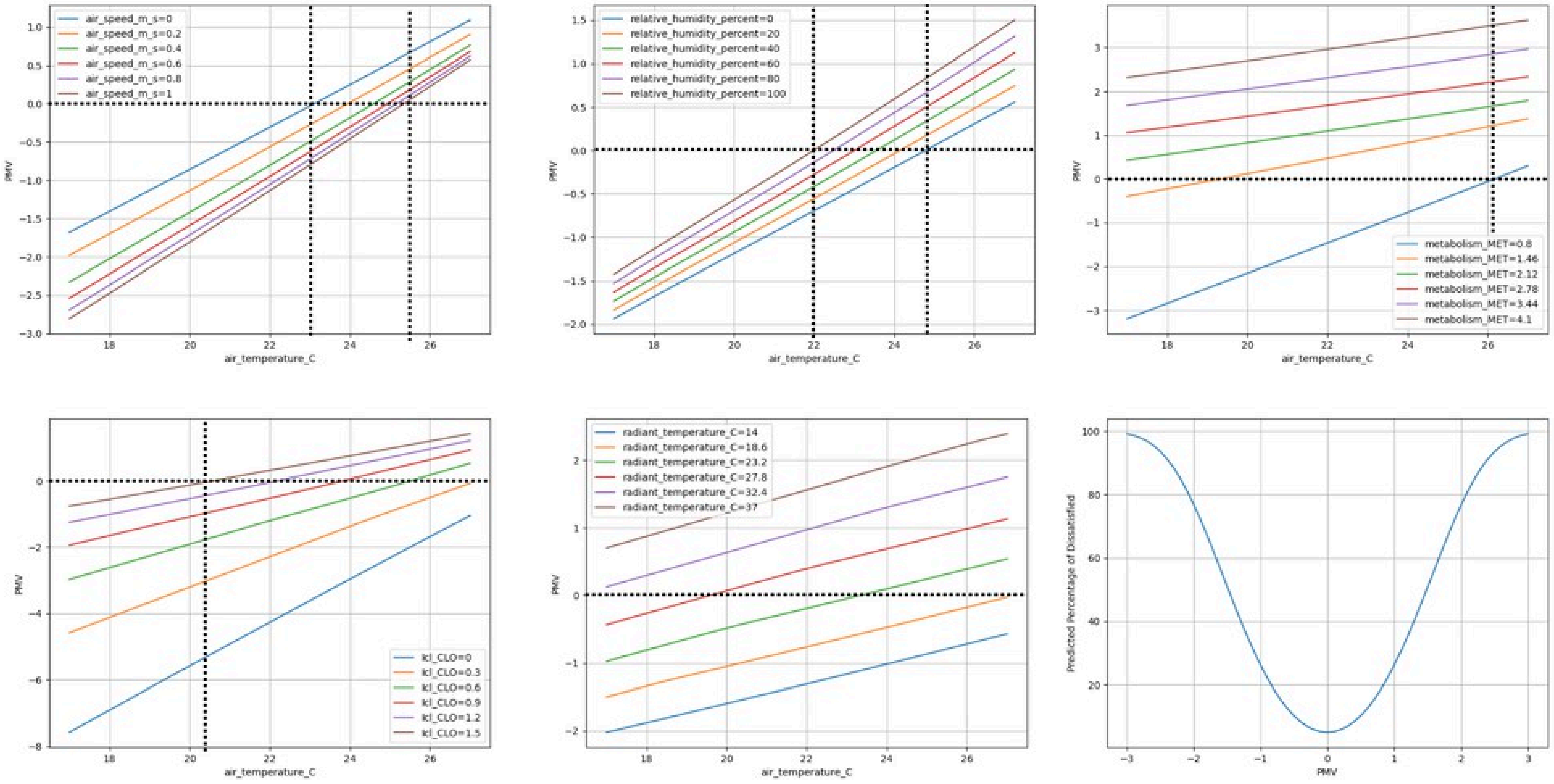
An example of implementation of PMV/PPD computation is available at `batem/core/comfort.py`

Let's consider a room at 21°C with 50% relative humidity, 0.1 m/s air speed.

There is one person in the room with clothing of 1 clo and 1 MET metabolism.

The resulting PMV is -0.6, indicating a slightly cool sensation, but still in an acceptable confort range.

input data	output data
air_temperature_C: 21	PMV: -0.6
relative_humidity_percent: 50	P_metabolism_W_m2: 58.15
radiant_temperature_C: 21	P_perspiration_sweat_W_m2 12.45
Icl_CLO: 1	P_perspiration_diffusion_W_ 0
metabolism_MET: 1	P_breath_latent_W_m2: 4.57
air_speed_km_h: 0.1	P_breath_sensitive_W_m2: 1
	P_rad_W_m2: 21.5624
	P_conv_W_m2: 17.8693
	Tclothes_C: 26.4247
	Pvapor_Pa: 376.071


air_speed_m_s=0
air_speed_m_s=0.2
air_speed_m_s=0.4
air_speed_m_s=0.6
air_speed_m_s=0.8
air_speed_m_s=1
PMV
air_temperature_C
relative_humidity_percent=0
relative_humidity_percent=20
relative_humidity_percent=40
relative_humidity_percent=60
relative_humidity_percent=80
relative_humidity_percent=100
PMV
air_temperature_C
metabolism_MET=0.8
metabolism_MET=1.46
metabolism_MET=2.12
metabolism_MET=2.78
metabolism_MET=3.44
metabolism_MET=4.1
PMV
air_temperature_C
Icl_CLO=0
Icl_CLO=0.3
Icl_CLO=0.6
Icl_CLO=0.9
Icl_CLO=1.2
Icl_CLO=1.5
PMV
air_temperature_C
radiant_temperature_C=14
radiant_temperature_C=18.6
radiant_temperature_C=23.2
radiant_temperature_C=27.8
radiant_temperature_C=32.4
radiant_temperature_C=37
PMV
air_temperature_C
Predicted Percentage of Dissatisfied
PMV

Disadvantage of the PMV

The PMV provides a very strict definition of what is thermal comfort but it does not take into account that people are not passive. They can:

- adapt physiologically to warmer or colder temperatures by gradually becoming accustomed to these conditions (at home, 21°C during winter does not lead to the same feeling that 21°C during summer even with the same clothes)
- adapt their expectations of thermal comfort because of capabilities to adjust their environment (opening/closing windows,...).

5.4.3 Adaptive comfort models

The aim of these models is to provide a more flexible definition of thermal comfort.

- The adaptive comfort model differs from traditional models such as the PMV in that it allows a wider range of acceptable indoor temperatures, depending on outdoor temperatures.
- This model is particularly applicable to naturally ventilated buildings, where occupants have more control over their environment, unlike air-conditioned buildings where thermal conditions are often rigid and controlled by heating and cooling systems.

For example, according to the standards established by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), the acceptable indoor temperature in a naturally ventilated building can vary between 18°C and 30°C, depending on outside temperatures.

There are different models for adaptive comfort but all of them rely on a 7-day to 30-day outdoor temperature average of the past, a linear relation giving the indoor comfort temperature and a level of tolerance around this comfort temperature.

For instance, ASHRAE 55 Standard proposes the model:

$$T_{\text{comfort}} = 0.31T_{out,moy} + 17.8$$

if $T_{out,moy} \in [10^{\circ}C, 35.5^{\circ}C]$

where $T_{out,moy}$ is the average outdoor temperature over the past 7-30 days.

The EN 15251/ISO 17772-1 standard proposes the model:

$$T_{\text{comfort}} = 0.33T_{out,moy} + 18.8$$

with the following tolerances:

- Catégorie I : $T_{\text{comfort}} \pm 2^{\circ}C$
- Catégorie II : $T_{\text{comfort}} \pm 3^{\circ}C$
- Catégorie III : $T_{\text{comfort}} \pm 4^{\circ}C$

5.5 Hot days and the indoor operative temperature

Reference hot day:

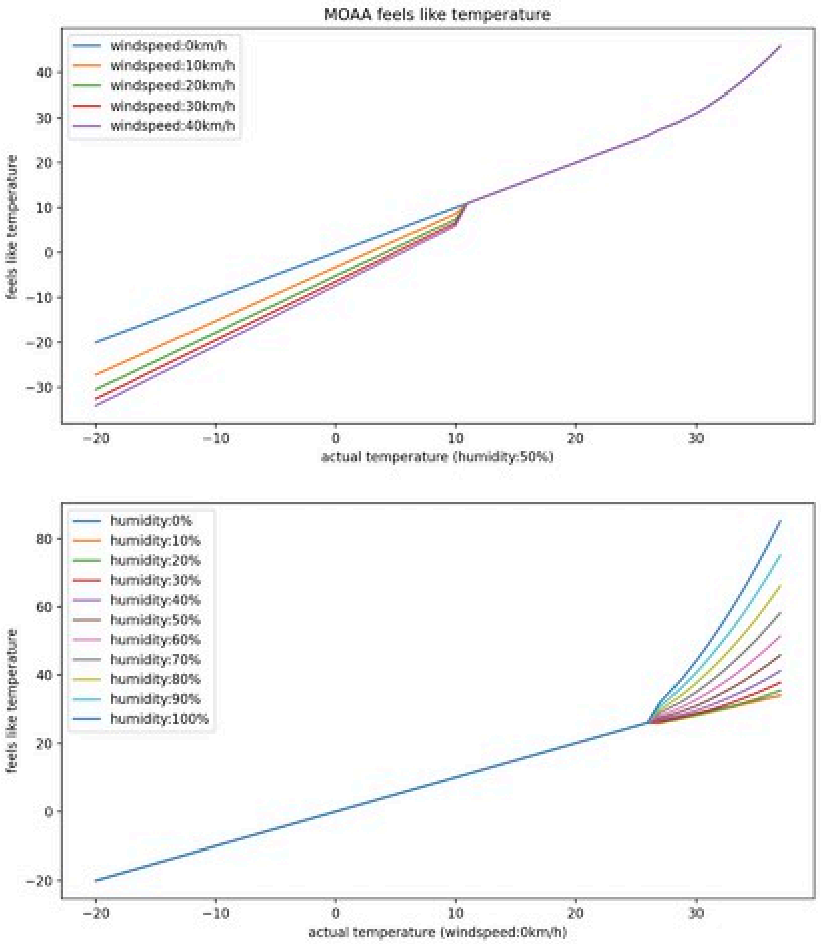
- The indoor operative temperature of the reference hot day is conventionally the coldest of the five hottest days of a year.

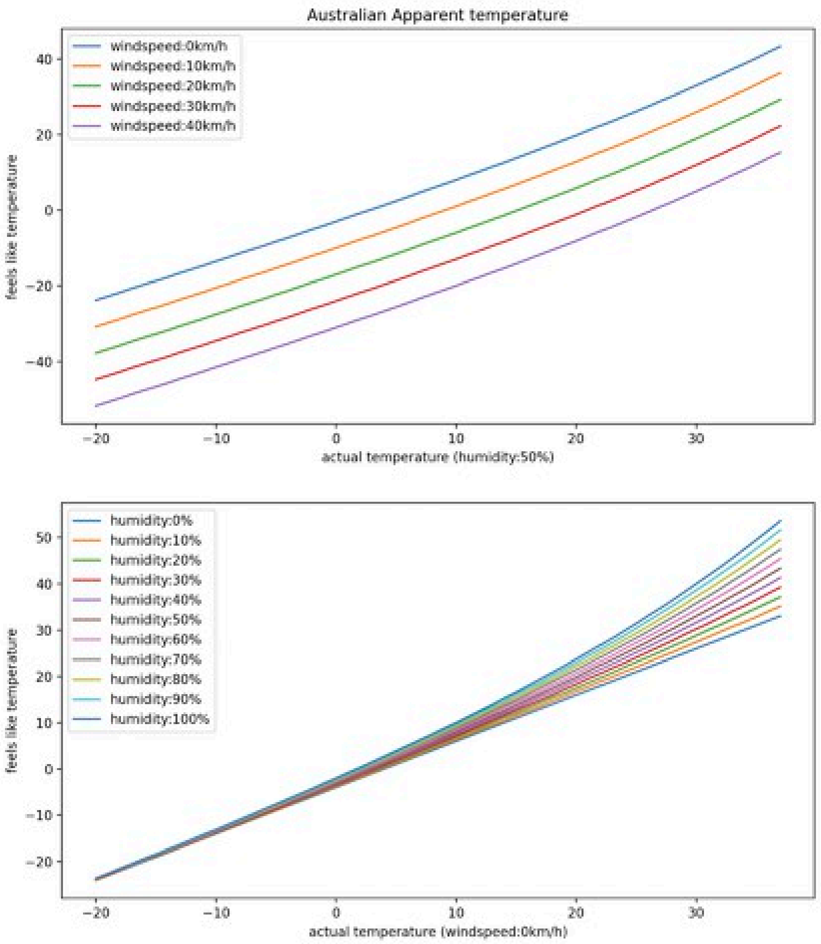
The indoor operative temperature (TIC - Temperature Intérieure Conventionnelle) is the average of the air temperature and the mean radiant temperature from the walls.

$$T_{\mathrm{ic}} = 0.5T_{\mathrm{air}} + 0.5T_{\mathrm{rad}}$$

This coefficient represents the hourly value of the operating temperature during the period of occupation.

5.6 Outdoor apparent temperature (température ressentie)





6. Home services

6.1 Other home services?

The system of services also includes home services like:

- cleaning dishes or clothes service
- service for conserving food
- ...

Services collect energy from the environment or from the grid

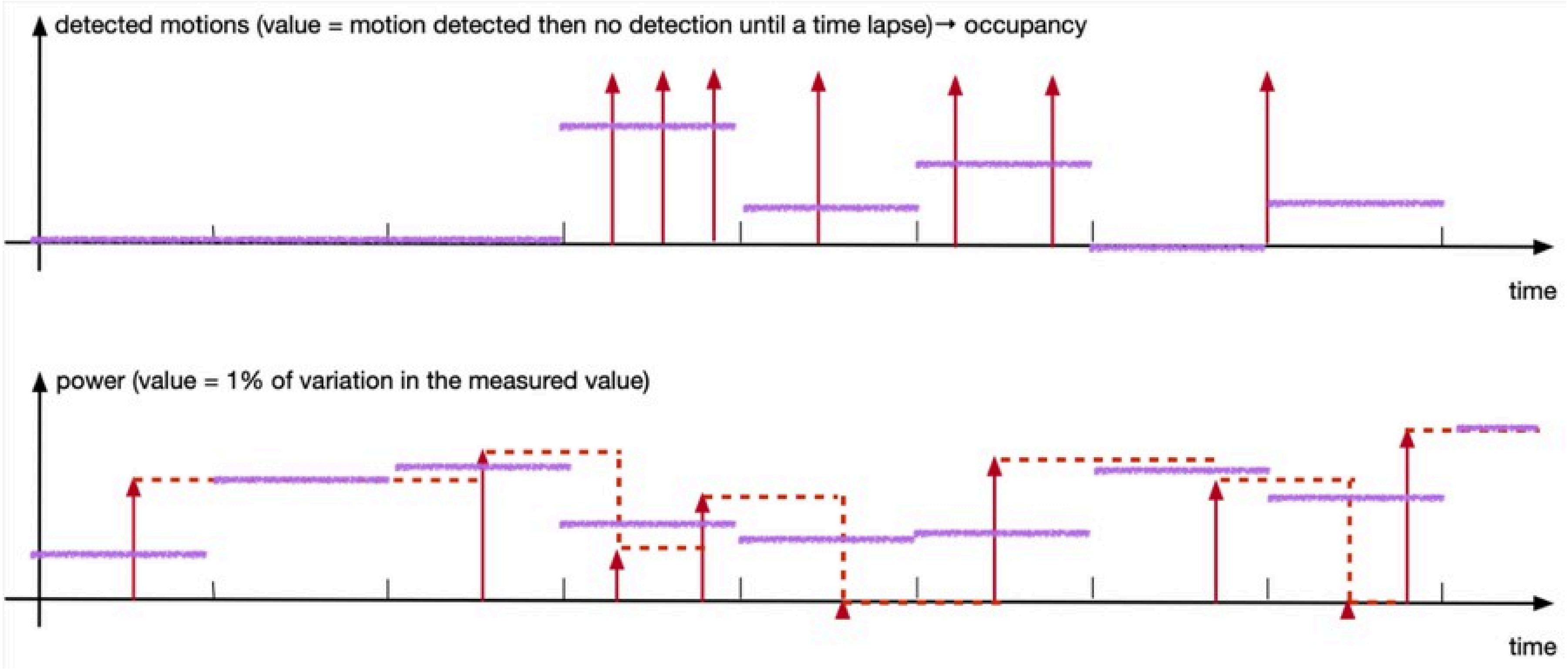
6.2 Efficiency (efficacité) and sufficiency ($\approx$ sobriété)

- Efficiency deals with services: it's the ratio between the quality of a service divided by a needed energy. Improving the efficiency is a matter of product design: for instance, a building envelope or a HVAC system.
- Sufficiency with how people use the services. For instance, the temperature set-point they set, how they use a washing machine,...

6.3 Handling measurement data

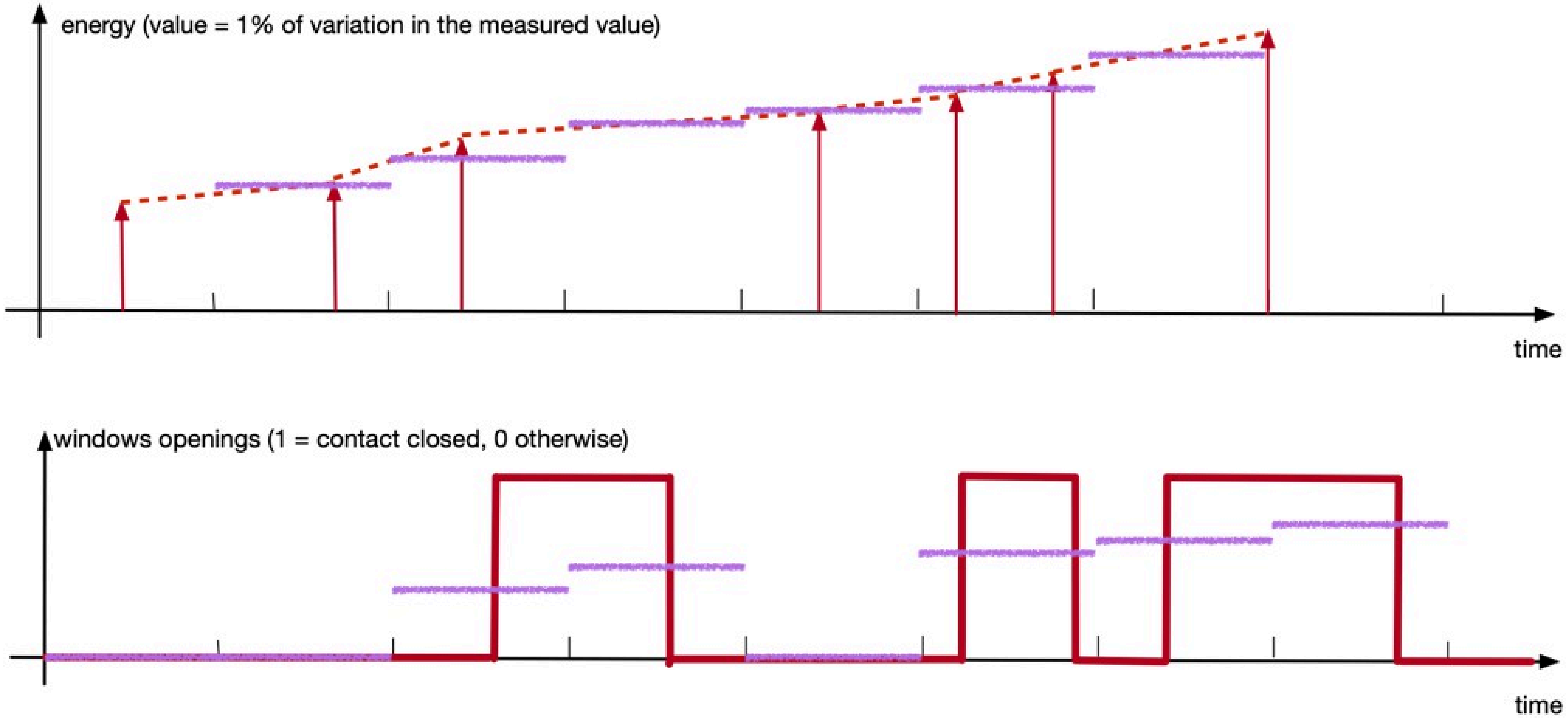
- Most sensors do not provide data regularly sampled. It is all the more true with self-powered and low consumption sensors using radio communication where each data sent has an energy cost.
- A sensor usually sends a data when a significant change has been detected (x% depending on the sensitivity) and a minimum time lap has passed.
- The way of getting usable sampled data depends on the type of measured variable. In the next, the red arrows stand for received measurement data, and horizontal lines illustrate the resulting sampled values.

Regarding motion detectors, one have to count the number of detected motion per sample time. For power, we have to compute the average power per sample time.



Energy data are processed in the same way than power whereas for a contact sensor, one has to compute the ratio of time it remains in the "detection" state.

A contact sensor used with a door or a window leads to values between 0 and 1: 0 means always closed during the considered time period (1 hour here to match the weather data precision), 1 means always opened and x, x means it has been opened x% of the time period.


energy (value = 1% of variation in the measured value)
time
windows openings (1 = contact closed, 0 otherwise)
time

Self-check questionnaire

12 questions — inhabitants, air quality, and comfort

Choose the best answer each time.

(In class: discuss in pairs; answers on the following slides.)

Q1 — Indoor air quality framing

According to the introduction, indoor CO_2 and moisture are mainly treated as:

- A. Markers of ventilation/air quality (CO_2 also signals confinement and other pollutants), not classical “pollutants” at usual indoor levels
- B. The only regulated toxic gases in all dwellings with zero health effect below 1 ppm
- C. Unrelated to human respiration or building ventilation
- D. Fixed properties of the building envelope that never change with occupancy

Q2 — Human respiration (stoichiometry)

From the respiration equation on the slides, for each O_2 molecule consumed at rest you get approximately:

- A. One CO_2 and one H_2O (vapour), plus energy
- B. Only CO_2, with no water vapour
- C. Only water vapour, with no CO_2
- D. Six CO_2 molecules per O_2 molecule

Q3 — CO_2 comfort levels

Which pairing matches the impact table in the lecture?

- A. 400–1000 ppm → comfortable; ~1700 ppm → significant confinement
- B. 400–1000 ppm → immediate blackout; 1700 ppm → outdoor background only
- C. Any level below 50 000 ppm is always comfortable
- D. 1700 ppm is the outdoor pre-industrial reference only

Q4 — ICONE indicator

ICONE (*Indicateur de Confinement*) on the slides is used to:

- A. Quantify exposure time to elevated indoor CO_2 (levels 0/1/2 above 1000 and 1700 ppm when occupied), then combine frequencies in a logarithmic formula
- B. Measure outdoor $PM_{2.5}$ only
- C. Replace the psychrometric chart
- D. Give thermal comfort in clo units

Q5 — Relative humidity

Relative humidity RH is defined on the slides as:

- A. $\mathrm{RH} = P_{H_2O}(T)/\hat{P}_{H_2O}(T)$ (actual vapour pressure over saturation vapour pressure at the same T)
- B. Mass of dry air divided by mass of water vapour
- C. Always equal to absolute humidity in g/m^3 without conversion
- D. The CO_2 concentration divided by 1 000 000

Q6 — Ideal gas (moist air)

For moist-air calculations, the slides use the ideal gas law:

- A. $PV = nRT$
- B. $P = \rho g h$ only, with no temperature
- C. $E = mc^2$ for water vapour mass
- D. RH = constant for all temperatures

Q7 — Moisture and ventilation

At steady state, the lecture relates required ventilation flow $Q_{vol/h}$ to indoor moisture mainly through:

- A. Production rate Π_{H_2O}, room volume V, and the difference $C_{H_2O,in} - C_{H_2O,out}$
- B. Solar zenith angle and albedo only
- C. PMV and PPD exclusively
- D. The number of clo worn by occupants only

Q8 — Sweating and high humidity

When relative humidity is 100% and ambient temperature exceeds ~35°C, the slides explain that:

- A. Evaporative cooling is strongly limited; the body may fail to lose heat by transpiration → serious heat-risk
- B. Sweating becomes more effective because air is saturated
- C. Latent heat of vaporization is zero
- D. RH has no effect on thermal regulation

Q9 — Clothing insulation (clo)

One clo is defined on the slides as:

- A. $1\ \mathrm{clo} = 0.155\ \mathrm{K} \cdot \mathrm{m}^2/\mathrm{W}$ of thermal insulation
- B. $1\ \mathrm{clo} = 1\ \mathrm{kWh}/\mathrm{m}^2$
- C. The CO_2 production in ppm·m^3/s per person
- D. The ICONE containment level

Q10 — Comfort models

Which statement matches the two main categories on the slides?

- A. Static/steady-state models (e.g. psychrometric chart, PMV) vs adaptive models (e.g. ASHRAE 55, ISO 15251) that allow seasonal and behavioural adaptation
- B. Only PMV exists; adaptive models are deprecated
- C. Psychrometric charts apply only to combustion gases in engines
- D. Adaptive models ignore outdoor temperature history entirely

Q11 — PMV limitation

A key limitation of PMV stressed in the lecture is that it:

- A. Treats occupants as relatively passive and does not fully account for adaptive actions (clothing, behaviour, expectations)
- B. Cannot use air temperature
- C. Applies only to outdoor “feels like” temperature
- D. Requires ICONE = 0

Q12 — Efficiency vs sufficiency

On the home services slides, efficiency and sufficiency differ because:

- A. Efficiency = service quality per energy (product/system design); sufficiency = how people use services (set-points, habits, etc.)
- B. They are identical French and English synonyms
- C. Sufficiency is only about sensor sampling; efficiency is only about CO_2
- D. Efficiency concerns occupant behaviour; sufficiency concerns wall U-value only

Answer key (1/2)

Q	Answer	Short rationale
1	A	CO_2 and moisture as ventilation/quality markers.
2	A	Respiration: O_2 → CO_2 + H_2O (vapour) + energy.
3	A	400–1000 ppm comfortable; ~1700 ppm confinement.
4	A	ICONE: CO_2 exposure levels + log formula.
5	A	RH = actual / saturation vapour pressure.
6	A	Ideal gas law $PV = nRT$.

Answer key (2/2)

Q	Answer	Short rationale
7	A	Steady-state ventilation vs $\Pi_{H_2O}, V, \Delta C$.
8	A	Saturated air limits evaporation → heat stress risk.
9	A	$1\ \mathrm{clo} = 0.155\ \mathrm{K \cdot m^2/W}$.
10	A	Static (PMV, psychrometric) vs adaptive models.
11	A	PMV: passive occupant assumption vs adaptation.
12	A	Efficiency (design) vs sufficiency (use).

Open and solve workshop03_human.ipynb