PERFORMANCES

The aims of models related to buildings and heating systems are:

- to verify the ability of the equipments to provide a given *level of comfort* to the building occupants
- to yield a complete *heat balance* of the building and of its system in order to further propose different energy saving strategies and to evaluate their financial and environmental impacts.

1.1. Comfort

1.1.1 Air quality requirements

Air quality requirement is generally translated as minimum fresh air flow rate. A 30 m³/h.occ minimum value is required as a standard for workers protection.

Standard values are also established per square meter of floor area as function of room occupancy:

- residential : 3.6 m³/h.m²
- individual office : 2.9 m³/h.m²
- shared office : 2.5 m³/h.m²
- meeting room : 8.6 m³/h.m²
- conference room : 23 m³/h.m²
- restaurant : 11.5 m³/h.m²
- classroom: 8.6 m³/h.m²
- kindergarten: 10.1 m³/h.m²

A fast way to verify air quality is to compute hour by hour the cumulated deficits of air flow rate.

A more accurate way to estimate air quality is to follow CO_2 as a tracer gas knowing the CO_2 flow rate from occupants, if contamination is mainly due to occupants. The balance of ventilation CO_2 flow rates is written as:

$$dM\backslash dtau_{CO2,in} = \dot{M}_{CO2,vent,su,room} - \dot{M}_{CO2,vent,ex,room} + \dot{M}_{CO2,occ}$$

$$\dot{M}_{CO2,vent,su,room} = \frac{MM_{CO2}}{MM_a} \cdot (\dot{M}_{a,ex,supplyduct} \cdot X_{CO2,ex,supplyduct} + \dot{M}_{a,infiltr} \cdot X_{CO2,out})$$

$$\dot{M}_{CO2,vent,ex,room} = \frac{MM_{CO2}}{MM_a} \cdot (\dot{M}_{a,su,returnduct} + \dot{M}_{a,exfiltr}) \cdot X_{CO2,ex,room}$$

The CO_2 flow rate produced by occupants can be deduced from their metabolism:

$$\dot{M}_{CO2,peroccupant} = 1.05 \times 10^{-7} \cdot \dot{E}_m$$

Internal CO_2 production is expressed in *kg/s* and occupant metabolism $\dot{E}_m$ in *W*.
$\dot{E}_m = 100\,W$ at rest.

A room air balance performs the integration from an initial concentration in order to follow the room CO_2 indoor concentration:

$$\Delta M_{CO2,in} = \int_{\tau_1}^{\tau_2} (\, dMdtau_{CO2,in} \,)\, d\tau$$

$$\Delta M_{CO2,in} = \frac{V_{in}}{v_a} \cdot \frac{MM_{CO2}}{MM_a} \cdot (\, X_{CO2,in} - X_{CO2,in,init} \,)$$

Molar masses of CO2 and air are:

$MM_{CO2} = 44$ [kg/kmol] $MM_a = 29$ [kg/kmol]

Considering one occupant produces *1.05.* 10^{-5} kg_{CO2}/s at rest and receives *30 m³/h* fresh air at *300 ppm* CO_2 concentration, the room CO_2 concentration stabilizes at *992 ppm*, which means a difference of *692 ppm* between indoor and outdoor air. Belgian standard NBN EN 13779 defines four categories of indoor air qualities with corresponding levels of indoor CO_2 concentrations compared to outdoor concentration (ref. [37]):

Table 1.1: Indoor air quality classes as function of ppm CO_2 concentration (NBN EN 13779 - Tables 8 and 9)

Category	Description	Difference of *ppm* CO_2 concentration between indoor and outdoor air	
		Range	Default value
IDA1	Excellent indoor air quality	≤ 400	350
IDA2	Medium indoor air quality	400 – 600	500
IDA3	Moderate indoor air quality	600 – 1000	800
IDA4	Low indoor air quality	> 1000	1200

1.1.2 Predicted Mean Vote

The Predicted Mean Vote Method (PMV) is correlated to the *thermal load* versus *thermal insulation* imposed to the human body (ref. [41]):

$$\dot{L} = \dot{Q}_m - \dot{Q}_a \quad (1.1)$$

$\dot{L}$: Thermal imbalance of the human body *W*
$\dot{Q}_m$: Fraction of metabolism not converted in work and that should be dissipated as heat *W*
$\dot{Q}_a$: Heat flow dissipated to ambiance in comfort conditions through breathing process and skin superficial heat exchange *W*

The heat flows $\dot{Q}_m$ and $\dot{Q}_a$ can be estimated through the following expressions:

$$\dot{Q}_m = (1-\eta).\dot{E}_m \qquad \dot{Q}_a = \dot{H}_R + \dot{H}_{persp} + \dot{H}_{sweat} + \dot{Q}_{cl} + \dot{Q}_{rad} + \dot{Q}_{conv} \quad (1.2)$$

$\dot{E}_m$: Metabolism *W*
η: Mechanical efficiency
$\dot{H}_R$: Enthalpy taken away by the breathing air *W*
$\dot{H}_{persp}$: Perspiration i.e. steam diffusion through skin *W*
$\dot{H}_{sweat}$: Sweating steam diffusion *W*
$\dot{Q}_{cl}$: Heat flow through clothing *W*
$\dot{Q}_{rad}$: Radiation heat exchange with ambiance *W*
$\dot{Q}_{conv}$: Convection heat exchange with ambiance *W*

The Predicted Mean Vote Method (PMV) is computed as:

$$PMV = C.\frac{L^{\cdot}}{A_{sk}} \qquad \text{with} \qquad C = 0.303.\exp\left(-0.037.\frac{\dot{E}_m}{A_{sk}}\right) + 0.0275 \tag{1.3}$$

A_{sk}: Skin area *m²*
C: Occupant *susceptibility*

A Predicted Percentage of Dissatisfied (PPD) can be deduced assuming a Gaussian distribution of individual votes (V) around the PMV with a standard deviation σ=1. Discomfort is defined as |V| ≥2.

$$PPD = 100 - 95.\exp(-0.2179.|PMV|^2 - 0.03353.|PMV|^4)$$

The Predicted Mean Vote criterion involves a complete description of air parameters including temperature, relative humidity and air speed.

1.1.3 Discomfort degree-days

Another comfort criteria is provided by computing discomfort degree-days. Those are obtained by adding the hour by hour degree days of discomfort, the computation being performed only during the time periods where comfort is required:

$$discomfort_{dd,heat} = \frac{\int_{\tau_{initial}}^{\tau_{final}} (f_{comfort,profile} \cdot \mathbf{Max}(t_{set,occ} - t_{in}, 0))\, d\tau}{3600} \tag{1.4}$$

$f_{comfort,\ profile}$: Factor equal to *1* when comfort is required, and to *0* when it isn't
$t_{set,occ}$: Set point temperature during occupancy period *°C*
t_{in}: Indoor temperature *°C*
τ Time expressed in *s*

Discomfort degree-hours can be evaluated only for heating (1.4) and similarly for cooling. As an order of magnitude, in Belgium, air conditioning is considered as necessary to achieve summer comfort in residential buildings if cooling degree-hours exceed 17500 K.h/year (ref. [43], Annexe1 "Méthode de détermination du niveau de consommation d'énergie primaire des bâtiments résidentiels",§8.2, p 27722).

Discomfort degree-days only involve air temperature as parameter; they don't account for air humidity and air speed.

1.1.4 Air humidity requirements

Air humidity requirement is generally translated as a relative humidity ranging from 40 to 60%. The balance of air humidity flow rates can be written similarly to that of ventilation CO_2 flow rates:

$$dM\backslash dtau_{w,in} = \dot{M}_{w,vent,su,room} - \dot{M}_{w,vent,ex,room} + \dot{M}_{w,occ}$$

$$\dot{M}_{w,vent,su,room} = \dot{M}_{a,ex,supply\,duct} \cdot W_{ex,supply\,duct} + \dot{M}_{w,infiltr} + \dot{M}_{a,infiltr} \cdot W_{out}$$

$$\dot{M}_{w,vent,ex,room} = (\dot{M}_{a,su,returnduct} + \dot{M}_{a,exfiltr}) \cdot W_{ex,room}$$

The water flow rate produced by occupants can be deduced from their metabolism:

$$\dot{M}_{w,peroccupant} = \dot{M}_{w,0} + 0.44 \cdot \left[\frac{\dot{E}_m - \dot{E}_{m,0}}{2.5 \times 10^6} \right]$$

Occupant water production is expressed in *kg/s* and occupant metabolism in *W*.
$\dot{E}_{m,0} = 100\,W \quad \dot{M}_{w,0} = 8.10^{-6}\,kg/s$ at rest.

A room air balance performs the integration from an initial concentration in order to follow the room indoor water mass:

$$\Delta M_{w,in} = \int_{\tau_1}^{\tau_2} (dM\backslash dtau_{w,in}) \; d\tau$$

$$\Delta M_{w,in} = F_{w,in} \cdot V_{in} \cdot \rho_a \cdot (W_{in} - W_{in,1})$$

$F_{w,in}$ is a fictitious surcharge of indoor moisture capacity, with a default value $F_{w,in}$ =5, taking into account the lack of homogeneity if indoor moisture in a room.

Indoor relative humidity can be deduced directly:

$$p_{w,in} = p_{atm} \cdot \left[\frac{W_{in}}{0.622 + W_{in}} \right]$$

$$p_{w,s,in} = \mathbf{exp} \left[17.438 \cdot \left(\frac{t_{a,in}}{239.78 + t_{a,in}} \right) + 6.4147 \right]$$

$$RH_{in} = \frac{p_{w,in}}{p_{w,s,in}}$$

A comfort index related to humidity level requirement could be simply built by adding the number of hours when the relative humidity is exceeds 60 % or is lower than 40 %.

1.2. Energy Consumptions, CO_2 emissions and Cost

1.2.1 Net Energy Demand and Net Energy Consumption

The Energy Demand of a building is currently distinguished from the Energy Consumption incurred by its system. The ratio of those quantities yields the system efficiency or the coefficient of performance, depending on the production system:

$$\eta = \frac{Energy\ Demand}{Energy\ Consumption} \qquad COP = \frac{Energy\ Demand}{Energy\ Consumption} \qquad (1.5)$$

1.2.2 Primary Energy Consumption and CO_2 emissions

The energy consumptions of a building are translated into *primary energy consumptions*, by adding the supplementary energy necessary to produce and transport the energy provided to the building. The following factors are used to perform that conversion:

Table 1.2: Conversion factor for primary energy consumption estimation (ref [43], chapter 11, Art. 11, p 2768).

Energy	**Conversion factor**
Fossil fuel	1
Electricity	2.5
Cogeneration electricity	1.8
Biomass	1

The energy consumptions of a building can also be translated in terms of carbon dioxide emission through the following coefficients:

Table 1.3: CO_2 coefficient for estimation of carbon dioxide emission (ref [45])

Energy	**CO_2 coefficient**
Natural gas	0.056 *kg/MJ*
Electricity	0.198
Fuel oil	0.073
Propane	0.062
Butane	0.062
Liquified Petroleum Gas	0.062
Coal	0.093
Wood	0

1.2.3 Energy Cost

Energy cost is related to energy consumption.

Table 1.4: Energy consumption costs (February 2007, Ref [44])

Electricity	Rate : 0.12 *€/kWh*	Fee: 58.00 *€/an*
Natural gas	Rate : 0.05 *€/kWh*	Fee: 126.24 *€/an*
Fuel	Rate : 0.52 *€/l*	
Propane	Rate : 0.47 *€/l*	
Butane	Rate : 1.36 *€/kg*	
Liquified Petroleum Gas	Rate : 0.40 *€/l*	
Coal	Rate : 0.32 *€/kg*	
Wood billets	Rate : 50 *€/stere*	
Wood pellets	Rate : 0.22 *€/kg*	

For electricity, energy cost is an average value including low electricity rate that occurs on week-ends and from 10 PM till 7 AM for ordinary days. The cost of energy consumption should be added to the cost of peak power requirement, both depending on the time of the day, high rate occurring during the day time and low rate during the night time and week-ends.