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"Physical Principles Involved in Natural Cooling"

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Introduction

The purpose of explaining the physical principles involved in natural cooling in the 75 minutes of this lecture, is not a realistic one, unless we agree that we are only taking a glance and remembering that we have studied and worked some time ago. Also, that we want to remember these principles because we are interested in bioclimatic architecture and we want to summarize the physical principles involved, quoting some references for further study. I also wish to remember something that was discussed in the last Workshop in 1987 (1): that, like as physicists and thermal scientists - who make the models - are not necessarily involved with the conception of design (but it should be better if they know a lot about it), architects do not necessarily need to know the mathematical procedure to develop the computational aid, but they ought to know as deep as possible the physical principles involved, in order that their intuition in doing the design, guides them to deal with an environmental design that would, then, be improved and assisted by the computational aids.

Physics Involved in Natural Cooling

We call Natural Cooling the group of building techniques we work with in hot countries that make use of local climate characteristics, to reach an acceptable thermal comfort inside a building. Roughly, there are five main ways to do it (*)

- Prevention of heat and solar energy to enter into the building during the day time
- Usage of evaporative cooling
- Increasing the heat losses from the building to the external environment during the night
- Absorbing thermal energy with materials that have a lower temperature than the human body temperature
- Improving the heat losses from the human body

As it is well-known, in order to predict the thermal behaviour of a building where natural cooling techniques were employed - as the calculation is rather complicated - we make use of computational aids. The computational aids simulate the building response to a given set of climatical data, giving us the thermal behaviour of our building design.

The computational program makes use of hear transfer formulae, physical parameters of building materials, mathematical techniques and climate data. In this lecture we will revise the physics involved in it.

(*) I propose this division in five items for the sake of simplicity. Those interested in a more deeper and wider analysis should consult references 2,3,4 and 5.

Heat transfer

Before we start working with a specific way to obtain cooling, we should take a glance (and rememeber) (*) some topics of heat transfer that is, thermal conduction, convection, radiation and evaporation.

Conduction

Some techniques require hindering the heat going on or out of the building. That could be done by insulation of the walls, windows, roof (or ceiling) and/or floor. In the simplest case where we can consider only one material, the heat transferred is calculated by the following formula

$$\dot{Q} = \frac{kA}{e}(T_1 - T_2) = h_k A (T_1 - T_2) = \frac{T_1 - T_2}{R_k} \qquad (1)$$

where

- Q = rate of heat trasferred, $Js^{-1} = W$
- A = area of heat exchange, m^2
- T_1 = hot surface temperature, K
- T_2 = cold surface temperature, K
- e = distance between T_1 surface and T_2 surface, m
- k = thermal conductivity, $W\, m^{-1}\, K^{-1}$
- h_k = coefficient of heat transferred by conduction, $W\, m^{-2}\, K^{-1}$
- R_k = thermal resistance, by conduction, KW^{-1}

Table I gives some examples of the thermal conductivity and other characteristics of usual building materials.

(*) There are many excellent books on heat transfer. See for example ref. 6,7 and 8.

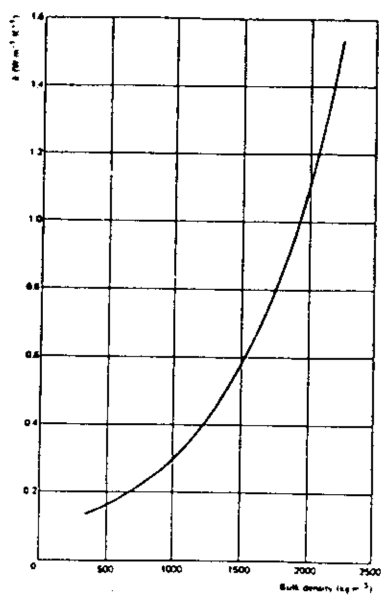
Table I - Example of Thermal Properties of Building Materials* at 20-30°C

	Density Kg m^{-3}	Thermal conductivity $Wm^{-1}K^{-1}$
Copper	8795	385
Steel	7850	47.6
Aluminium	2675	211
Glass	2515	1.05
Concrete **	2400	1.6
Brick	2000	1.32
Asbestos cement, sheet	1900	0.32
Water (20 ° C)	977	0.596
Ice (-1° C)	918	2.26
Gypsum plaster (dry)	881	0.17
Pine (15% wet)	570	0.14
Mineralwood	32	0.0346
Polyurethane foam	24	0.0346
Polystyrene	16	0.0245
Air (at 20 ° C)	1.204	0.026

* For more complete tables consult ref. 9,10, 11 and 12

** Thermal conductivity varies with density. See fig. 1 below taken from ref. 10

Fig. 1 -
Relationship between bulk density and thermal conductivity for concrete (Ref. 10)



Remember that there is a close similarity between thermal and electrical circuits; so, in a wall composed of several materials, single thermal resistences are added if they are in series and their inverses, are added if they are in parallel. Note that the heat transfer coefficients are the inverse of resistences. From Table I we also notice that air, when static and dry, is one of the best insulaters. So, small cavities, that is, small spaces filled with air with a low moisture content, are good insulators. Their thermal conductivity depends on its size and the water vapor content, and in many cases, on the contribution of convection and radiation. The overall thermal resistance will be treated together with the other heat transmission modes.

Thermal bridges, that is, ways of low resistance through which heat can be conducted, are important and must be avoided. Sometimes, there is no sense in putting a double sheet of glass in a window if it has an unprotected aluminium frame. Furthermore, attention should be given to the fact that steel included in the structure could constitute a thermal bridge.

Convection

Air layers in contact with the building surfaces introduce an additional resistance to heat transfer. Differences in air temperature will result in density differences that will move the air, extracting heat from some surfaces and adding it in others, producing heat exchange by convection. Therefore the formulas used in this subject are more complex because, besides fluid conductivity, they use fluid movement, that is, fluid mechanics. Main equation is

$$\dot{Q} = h_c A(T_1 - T_2) = \frac{T_1 - T_2}{R_c} \qquad (2)$$

where

h_c = heat transfer coefficient, by convection, $Wm^{-2}K^{-1}$

R_c = thermal resistance by convection, KW^{-1}

the other symbols having the same meaning as in equation 1.

We are using the symbol h again, but differently from conductivity, it is not nearly as constant as it was above. h_c depends on the temperatures of the air and the surfaces involved, surface characteristics, shape, relative position of the surfaces and also the

Simple relationships can only be found using the dimensionless parameters Nu, Re, Gr and Pr defined as:

$$Nu = \frac{h_c D}{k} \tag{3}$$

$$Re = \frac{\rho v D}{\mu} \tag{4}$$

$$Gr = \frac{g\beta(T_w - T_\infty) D^3}{\nu^2} \tag{5}$$

$$Pr = \frac{\mu C_p}{k} \tag{6}$$

where the new symbols are

Nu = Nusselt number

Re = Reynolds number

Gr = Grashoff number

Pr = Prandtl number

D = characteristic linear dimension, m

ρ = fluid density, kg m^{-3}

v = fluid velocity, m s^{-1}

μ = absolute viscosity, Pa s

g = gravity acceleration, m s^{-2}

β = volumetric expansion coefficient (for ideal gases = T^{-1}), K^{-1}

T_w = wall temperature, K

T_∞ = mean fluid temperature, K

ν = kinematic viscosity, m^2 s^{-1}

c_p = specific heat, J kg^{-1} K^{-1}

The equations relating the above parameters have the form of

$$Nu = C(Re)^n(Pr)^m \tag{7}$$

for forced convection
- mainly external heat exchange

or

$$Nu = C'(Gr)^{n'}(Pr)^{m'}$$ for natural convection - mainly internal heat exchange (8)

However, as Pr is almost constant for the temperature interval we are considering here, the equations become

$$h_c = \frac{k}{D} C_1' \left(\frac{\rho v D}{\mu}\right)^n \quad \text{for forced convection} \qquad (9)$$

and

$$h_c = \frac{k}{D} C_2' \left[\frac{(T_f - T_\infty)D^3}{\nu^2}\right]^{n'} \quad \text{for natural convection} \qquad (10)$$

where C'_1 and C'_2 are constants which can be deduced from equations 3 to 8. For a less ambitious mathematical model, if we do not mind having less precision - and for the temperature range we are working at - we may use for an external surface (from ref. 10),

$$h_c(\text{forced}) = 5.7 + 4.1\ v \qquad (11)$$

for $v < 5ms^{-1}$, and

$$h_c(\text{forced}) = 7.3(v)^{0.78} \qquad (12)$$

for $v > 5ms^{-1}$, where v is the wind velocity in ms^{-1} and h_c in $W\ m^{-2}K^{-1}$.

Values of h_c, for surfaces with simpler geometries, for particular cases, are quoted in several books (6)(13)(14). In Table II we reproduce values for h_c for natural convection between two parallel planes and forced convection on external surfaces of a building.

Table II - Values of h_c in W $m^{-2}K^{-1}$ (Ref. 15)

Flow	directions	h_c
Natural between two parallel planes	upwards	4.3
	downwards	1.5
	horizontally	3.0
	wind speed , m s^{-1}	
Forced on roofs	1.0	9.9
	3.0	18.1
	9.0	42.7
Forced on walls	0.7	8.7
	2.0	14.0
	6.0	30.4

As in the case of conduction, convection resistances are not presented alone, but in combination with conduction and radiation. After treating with radiation, we will discuss some examples where they work together.

3) Radiation

Here the simplest case is the black body, defined as a body whose surface absorbs all the incident radiation falling on it. The main equations that describe its emission are

Planck's law $$E_{\lambda_b} = \frac{C_1}{\lambda^5(e^{C_2/\lambda T}-1)} \quad (13)$$

Wien's law $$\lambda_{max} = \frac{C_3}{T} \quad (14)$$

Stefan-Boltzmann's law $$E_b = A\int_0^\infty E_\lambda d\lambda = A\,\sigma T^4 \quad (15)$$

where C_1,C_2, C_3 and σ are constants

$C_1 = 3.7405 \times 10^{-16}$ W m^2
$C_2 = 0.0143879$ mK
$C_3 = 0.028978$ mK
$\sigma = 5.669 \times 10^{-8}$ Wm^{-2} K^{-4} (Stefan - Boltzmann's constant)
λ = wavelength of the electromagnetic emission, m
$E_{\lambda b}$ = rate of energy emitted by the black body with λ wavelength, W m^{-1}
λ_{max} = value of λ where the maximum of the electromagnetic spectrum is produced, m
E_b = rate of energy emitted by a black body in all the spectrum, W

Emission of other bodies other than black ones, are related to the former by

$$E_\lambda = \varepsilon_\lambda E_{\lambda b} \ , \qquad (16)$$

where ε_λ is the emittance of this body at λ.

Absorptance of surfaces is characterized by α_λ and can be defined as

$$A_\lambda = \alpha_\lambda I_\lambda \ , \qquad (17)$$

where A_λ is the absorbed energy (at λ) and I_λ is the incident energy on the surface.

Absorptance and emittance for the same surface are related by the Kirchoff's law

$$\alpha_\lambda = \varepsilon_\lambda \ . \qquad (18)$$

It is important to note that, in general,

$$\alpha_{\lambda_1} \neq \varepsilon_{\lambda_2} \quad \text{if } \lambda_1 \neq \lambda_2 \ . \qquad (19)$$

Grey bodies (they have several colours) are defined by

$$\varepsilon_\lambda = \varepsilon = \text{constant (not depending on } \lambda) \qquad (20)$$

and

$$\varepsilon = \alpha \ \text{ for the total spectrum.} \qquad (21)$$

The majority of building surfaces are not grey (that is, ε_λ is depending on λ). However, except a few cases (selective surfaces), they can be considered with constant values throughout the visible and the infrared spectrum. Therefore, if a contrary indication is not is given, building surfaces irradiate energy described by

$$\dot{Q} = A\varepsilon\sigma T^4. \qquad (22)$$

Note that there are differences for the interval of the spectrum we are working with, therefore:

$\alpha_{sol} = \varepsilon_{sol}$ in the solar spectrum, for external walls

$\alpha_{vis} = \varepsilon_{vis}$ in the visible spectrum, for internal reflexions

$\alpha_{IR} = \varepsilon_{IR}$ for infrared spectrum, for body exchanges with building surfaces.

Emittance in the infrared (at usual building temperature) and absorptance for the solar radiation of some building materials are given in Table III.

Table III. Emittance and absorptance for surfaces of some building materials (Ref. 10)

	ε (infrared)	α (solar)
Aluminium	0.05	0.2
Glass (3 mm sheet)	0.94	0.08 (60° incidence)
Concrete	0.9	0.65
Brick (red)	0.9	0.55 - 0.7
Brick (dark)	0.9	0.65
Asbestos cement (sheets)	0.9	0.6
Asphalt	0.95	0.9
Paint-white	0.9	0.3
Paint-black	0.9	0.9
Slate	0.9	0.9
Tiles	0.9	0.4 - 0.8
Whitewashed roof	0.9	0.3 - 0.5

So far, we have only considered the radiation of a single body. As we are interested in the energy exchange of two or more bodies, the formulas will become complicated taking into account the emittance and absorptance of the surfaces involved, and the fraction of energy emitted by one surface reaching the other, the so-called view factor (or configuration factor or form factor).

In the actual radiative exchange in a building, there are several surfaces with different emission properties (walls, ceiling, doors, windows, etc.) For two surfaces , i and j, assumed to be opaque, grey, uniform and diffuse, the net exchange of radiant energy will be given by

$$Q_{ij} = A_i \varepsilon_i F_{ij} \; T_i^4 - A_j \varepsilon_j F_{ij} T_j^4 \tag{23}$$

where F_{ij} is the view factor, that is, the fraction of the energy emitted by i that reaches the surface j. The view factors involve geometrical calculations - double integration on the two surfaces - and there is a wide range of existing literature (for example see ref. 16 and 17), giving these values in the form of tables or graphics, that cover all the simple cases we may find in buildings. For example, inthe case of two grey finite parallel planes of areas and emittance A_1, ε_1 and A_2, ε_2, equation 23 reads

$$\dot{Q}_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_2} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}} \tag{24}$$

or, for example, if A_1 is the ceiling and A_2 the floor, in a parallelepiped like room, $A_1 = A_2 = A$

$$\dot{Q}_{12} = \frac{A\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2}} \tag{25}$$

where ε_1 is the emittance of the ceiling, ε_2 the emittance of the floor and F_{12} is a number that depends on the length, width and height of the room. As an example we give the graphics in fig. 2 for this case, and a graphic in fig. 3 for two orthogonal planes (like a corner between two adjacent walls or a wall with a ceiling or floor).

In an actual case where the surface i is involved by N different surfaces, the net radiation energy going to this surface is given by

$$\dot{Q}_i = \sum_{j=i}^{N} \varepsilon_i \varepsilon_j A_i \tilde{F}_{ij} (T_i^4 - T_j^4) \tag{26}$$

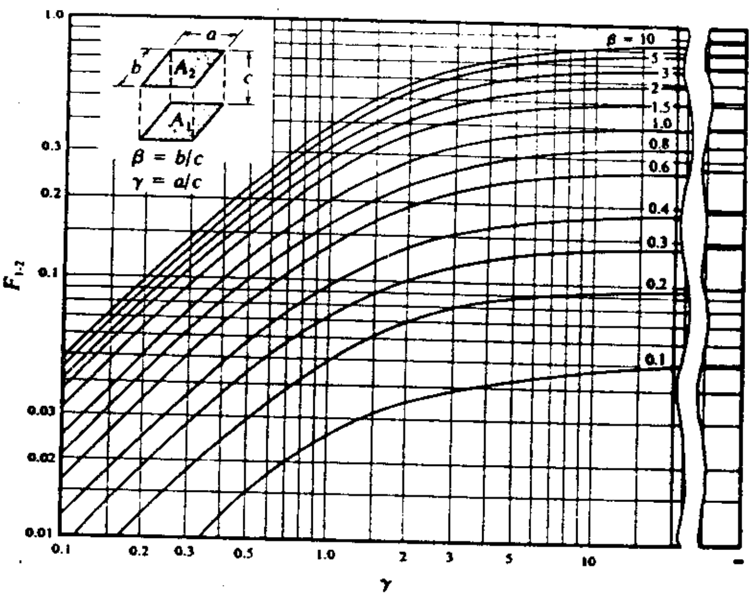


Fig. 2 - Two identical, parallel, directly opposed flat plates (adapted from Ref. 18)

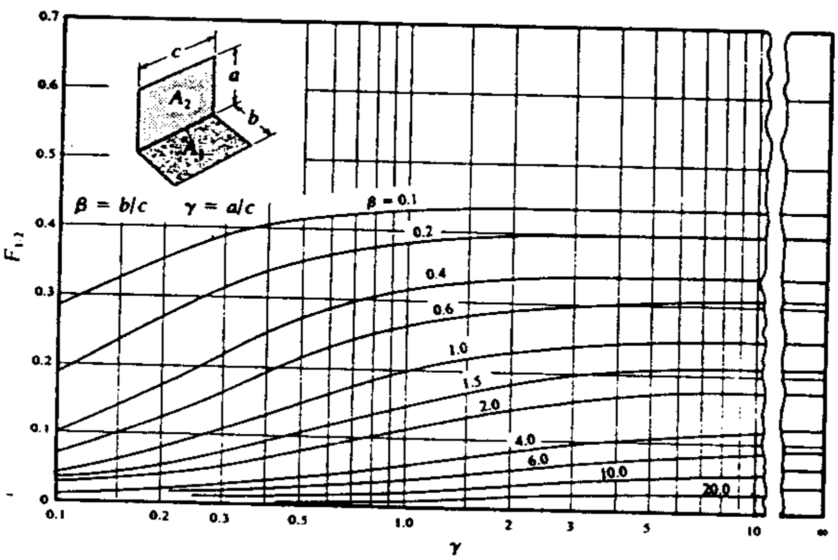


Fig. 3 - Two perpendicular flat plates with a common edge (Adapted from Ref. 18)

where F_{ij} is the total exchange factor (elements of a matrix), being a function of the view factors F_{ij} , the surfaces A_i and A_j and the emissivities ε_i and ε_j, including multiple reflexions. Methods to calculate F_{ij} are given in advanced radiation texts and most of them need heavy computing (see discussion, for example, in ref. 19).

The case of radiative exchange between external surfaces of the building and the sky is easier, because the form factors are very simple. Nevertheless, an additional complexity is introduced in defining the sky temperature, that is, the temperature of the ideal surface with which the external building surface is exchanging radiation. Several formulas were proposed, combining the external ambient temperature, the humidity, and/or the fraction of the sky covered by clouds (see references 20 and 21).

The net flux of energy reaching or leaving a surface, could be expressed as

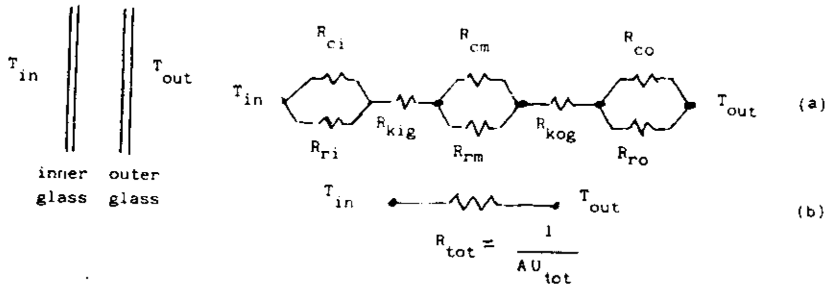
$$\dot{Q}_{r_1} = A_1 h_{r_1} (T_1 - T_o) = \frac{T_1 - T_o}{R_r} \qquad (27)$$

transferring all the complexity to the heat exchange factor, radiative, or to the thermal radiative resistance - note that now they depend on the third power of all absolute temperatures involved and all the surface emissivities. T_o is the mean radiant temperature of all radiating surfaces.

Combined effects

Equation (27) allows us to deal with radiation in the same way we did with conduction and convection. Therefore we can replace every participating surface by a node, with an associate temperature representing the thermal exchange by a resistance (conductive, convention, or radiative one), making a network representative of the entire thermal phenomenon. In Fig. 4 and 5 as examples we present the thermal circuit for a window, and for a small building. (*)

(*) As we can see in Fig. 4B, the whole circuit can be replaced by a single resistance linking the two principal nodes. Its inverse is AU = 1/R, where A is the heat transfer area and U is called the thermal transmittance or the overall heat transfer coefficient. The U-value of a building is a useful quantity to characterize its thermal behaviour.



$$R_{tot} = \frac{1}{\frac{1}{R_{ci}} + \frac{1}{R_{ri}}} + R_{kig} + \frac{1}{\frac{1}{R_{cm}} + \frac{1}{R_{rm}}} + R_{kog} + \frac{1}{\frac{1}{R_{co}} + \frac{1}{R_{ro}}}$$

Fig. 4 - Thermal circuit for a double glass window

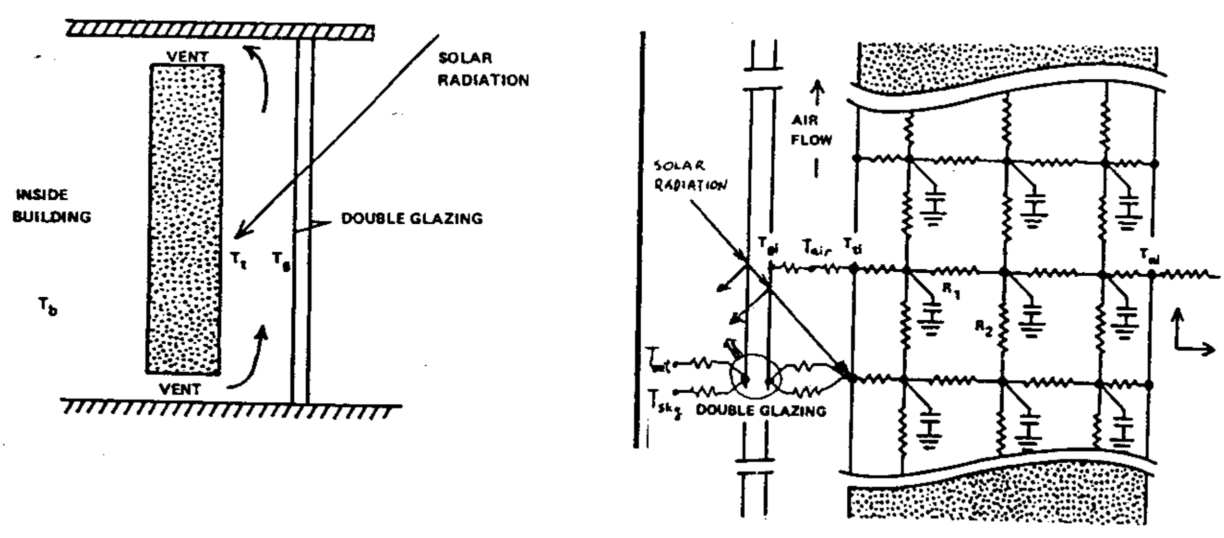


Fig. 5 - Thermal network for Trombe wall analysis

As the climate data varies during the day and during the year, the set of equations describing the building behaviour varies with space and time, giving place to the so-called transient (time-depending) phenomena. Note that besides resitances, there are capacities, representing the thermal inertia, that is, the capacity of massive elements to accumulate thermal energy giving it back at a later time. The thermal inertia is related to the thermal diffusivity,

$$\alpha = \frac{k}{\rho c_p} \tag{28}$$

with the physical meaning that thermal energy diffuses rapidly through materials with high α (*).

The solution will be more exact and detailed if more nodes, resistances and capacities are included in our model. Of course, it will alsobe more complicated to solve the problem. But it is not our goal to discuss this matter. There has been and there are a lot of people working in the field, that produce several softwares that work from personal to the biggest computers , as we will see in this workshop and in the proceedings of the last one (1). As we have remarked in the introduction, architects must know how to use the computational aids, not necessarily know how to programme them. But they need to know the physical principles involved in putting them to work, since the conception of the building design, and also to be sensitive to propose modifications to be validated later by the computer aid. People interested in numerical methods to solve the problem may consult ref. 12, 23 and 24 to start with. It will be also useful to read ref. 25 and 26.

Evaporation

Another important item of discussion is evaporation, that is, the water phase change from liquid to vapor in different conditions of pressure and temperature. The best description of the behaviour of a mixture air-water vapor is given by the psychrometric chart presented in fig. 6.

(*) The thermal inertia has two important characteristics: 1) it introduces a time lag between the time when the maximum external temperature is achieved, and when it is produced in the internal ambient, and 2) it modifies (reduces) the amplitude of the variation of the external temperature.

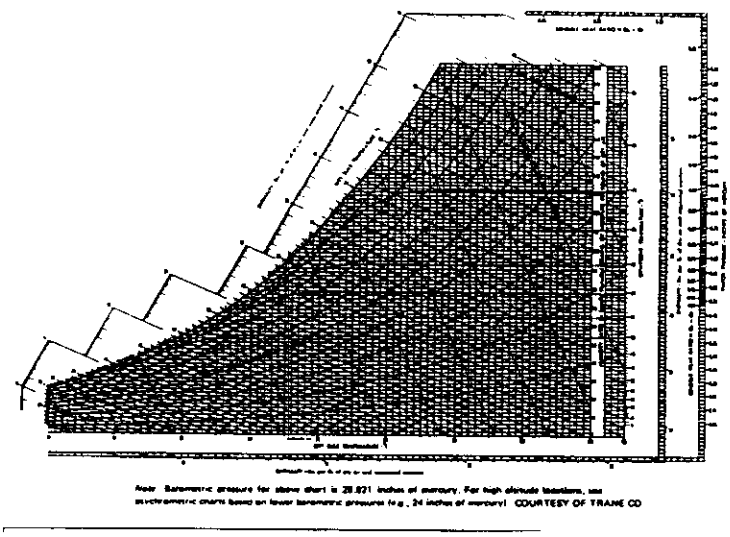


Fig. 6 - The psychrometric chart

The chart is given for a fixed atmospheric pressure, showing the relationship between dry bulb temperature (in abscissa), mixing radio - grams of water vapor per kilogram of dry air (in ordinate), curves of equal relative humidity, lines of equal wet bulb temperature, straight lines of equal specific volume and straight lines of equal enthalpy (heat added or removed from a process at constant pressure). The processes we are interested in are shown in fig. 7.

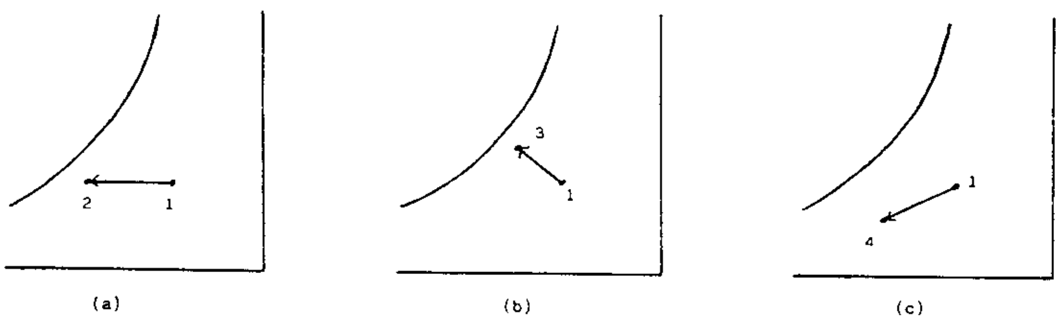


Fig. 7 - Cooling processes in the psychrometric chart

Process 1 to 2 is the cooling of the air mixture with no change of absolute humidity, for example, air cooled by contact with a low temperature surface, giving sensible heat to it. Process 1 to 3 is the adiabatic evaporative cooling, where hot air takes water vapor from a water surface, giving thermal energy to evaporate it, decreasing its temperature. In this process the heat lost by the air goes to the evaporated water with no change of the total energy involved, so it goes through a line of constant enthalpy.

Note that the water evaporation can also take thermal energy from neighbouring bodies, cooling its masses. The cooled mass could then be used to absorb heat from the ambient by convection and/or radiation.

Process 1 to 4, is the result normally produced by an air conditioned device, lowering the air temperature and dehumidifying it. Process 1 to 2, when only sensible heat is exchanged, is governed by equations of convection, like eq. 2, whereas process 1 to 3 (iso-enthalpic) follows the equation:

$$i_1 + W_1\, i_e = i_3 + W_3\, i_e \tag{29}$$

$i_{1,3}$ = enthalpy of state 1 or 3, J (kg of dry air)$^{-1}$
$W_{1,3}$ = mixing radio of state 1 or 3, kg of water (kg of dry air)$^{-1}$
i_e = latent heat, J (kg of water)$^{-1}$

In the process 1 to 4 the refrigeration capacity, RC is given by

$$RC = m\,(i_1 - i_4) \tag{30}$$

where

m = air flow rate, kg s^{-1}
RC = refrigeration capacity, Js^{-1}=W (or kW of electric power)

(for further discussion see a book on air conditioning, for example, ref. 27).

When it is hot, one of the mechanisms to lose heat is through skin transpiration. The layer of water produced on the skin takes heat from the body to evaporate. The produced vapor rapidly saturates the subsequent air layer in contact with the skin, so that it does not accept more water. If this saturated air layer is removed by ventilation the new air is capable of absorbing more water, taking more thermal energy out of the body. This loss of energy diminishes the skin temperature, increasing the sensation of comfort. This is the way of "cooling" by using air (hotter or not than that of the body) that we simply called ventilation. Note that with ventilation we can either lower or raise the temperature of the building. The desired effect is to increase heat losses from the human body, that we will discuss is the following section.

Human heat transfer to the environment

Up to here we have worked with the physical principles of heat transfer involving the building and the internal air. We now want to take a glance at the interaction of the environment with the human body.

The human body produces internal heat and it has to be lost in order to maintain its temperature. It loses heat by conduction, mainly through the feet onto the floor; by conduction, convection and radiation onto its clothes; by convection from the body or clothes into the air; by radiation from body or clothes onto the internal surfaces of the building (or to the external environment through the opening) and by evaporation (by respiration, by skin diffusion and by sweating).

The heat balance equation for the human body is given by

$$(M - \text{Work}) + K + C + R + E = S \qquad (31)$$

all quanties are given per unit of body surface area and all of them having the meaning of rates of energy, in Watt, with

M = produced by metabolism (always positive)
Work = used to do mechanical work (always positive)
K = exchange by conduction (positive or negative)
C = exchange by convection (positive or negative)
R = exchange by radiation (positive or negative)
E = lost by evaporation (almost always negative)
S = rate of heat storage in the body (positive or negative

If S is not zero, the body reacts putting into work mechanisms of regularization by increasing or diminishing the flow of blood, by dilatation or contraction of the capillary vases near the skin, by sweating that covers the skin with water to lose heat by evaporation or by increasing the involuntary mechanical activity of the muscles (shivering and shaking).

All this mechanism of regularization allows the body to maintain its temperature even in adverse climatic conditions. But in a condition where the mechanism has to work hard, people do not feel well and the thermal sensation is of discomfort. So it is not needed S to be zero in equation 31, but it will be nearly zero (or not very high for a long time) in order to feel a sensation of thermal comfort.

As we can see in formula 1, 2 and 27, the rate of heat exchange depends on the area of heat transfer. This area is easy to calculate in the cases of building elements, but difficult to evaluate for the human body. For example, A will be a fraction (usually one half) of the foot base for conduction, the total area of the nude body for convection and a fraction of it for radiation, taking into acocunt that some parts of the skin radiated and absorbed from other parts (the effective radiation area is usually taken as 0.71 of the nude body). Also the area of heat exchange is increased by clothes and the correction factors vary typically for light clothes, from 1.0 for nude to 1.15 for 1.0 clo. (For further discussion see ref. 15 and 28).

The effects of wind velocity in heat exchange by convection together with evaporation can be easily seen in the bioclimatic chart of Olgyay (29) or Givoni (30) for a man at rest. Changes produced during different activities are discussed in ref. 9.10,11 and 23. Also the effect of radiant energy from the building surfaces or from solar energy on thermal comfort as well as the effects of adding or reducing the water vapor in the internal air, increasing or decreasing the losses by evaporation, are quoted in the bioclimatic charts, that will be extensively treated in this Workshop.

All the building techniques suggested by the physical principles discussed do not apply to all realistic situations. The strategy to be adopted will depend on the local climate characteristics and the availability of building materials. For example,whether it is possible to work by a natural way or if an air conditioned system is needed and what should be the better way to reduce its power and its energy consumption.

As a final remark I would like to call your attention to the fact that natural cooling is only a partial view - an important technique to be used from the first steps of the building design - but that needs to be used together with other important items like natural daily illumination and acoustics, in order to produce, besides thermal comfort, and environment-conscious design.

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