Ministry of Higher Education and Scientific Research
University of Ain Temouchent Belhadj Bouchaib
Faculty of Sciences and Technologies
Department of Mechanical Engineering

Title of Course

Heating and Air Coditioning

Course destined to students of:

1st year Master in Mechanical Energetic

Presented by :

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Academic year 2020-2021

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INTRODUCTION

The subject is intended for students in the first year of the master's degree and second semesters in the energy master's training course.

This subject aims to introduce students to the understanding of the operating principles of heating, ventilation, and air conditioning systems, particularly due to their role in the thermal comfort of a building. Various themes are addressed, allowing students to better grasp the necessary compromise between architecture and climate, as well as the alignment between architecture and the energy performance of buildings.

This subject is divided into two parts conducted in parallel:

The first part covers the lectures and is divided into six chapters. The first chapter reviews thermodynamics and heat transfer, introducing general concepts of thermodynamics and modes of transfer. The Algerian thermal regulation and the thermal balance of a building for winter and summer periods are discussed in the second chapter. The third chapter is dedicated to calculating thermal losses and heat production in buildings or spaces. The fourth chapter is focused on studying the general principles of air conditioning, including the calculation of thermal gains, distribution networks, humid air, and the h-x diagram. Chapters five and six describe the operating principles of system regulation and renewable energy.

The second part of this subject takes the form of a collection of directed exercises corresponding to the themes covered in the first part. The corrected exercises presented allow for a deeper understanding of the concepts covered in the lectures and also open up perspectives on complementary notions. Teaching assistants and students will find material for debate and discussion regarding the consideration of HVAC (Heating, Ventilation, and Air Conditioning) for establishing thermal comfort in a habitat.

Heating and Air Conditioning Course

Institute of Technologie

Departement : Departement of mechanical engineering

Target: 1st year master energetics

Title of the course: Heating and Air Conditioning

Duration: 15 weeks

Course timetable: Tuesday: 09h30-11h00

TD timetable: Wednesday: 14h00- 15h30

Classroom : C13

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Availability : Dimanche ; Jeudi

Academic year : 2020-2021

Chapter 1. Review on Thermodynamics and Heat Transfer

I.1 General Concepts of Thermodynamics

Thermodynamics is the study of energy transformations in all its forms, particularly the transformations of heat into work and vice versa.

Thermodynamics applies concretely to many fields; for example,

- ✓ Chemistry
- ✓ Thermodynamic machines (engines, heat pumps, ...)
- ✓ Petroleum refining
- ✓ Astrophysics
- ✓ Biochemistry, as well as many other fields.

The principles upon which thermodynamics is based are:

Principle Zero: It specifies the concept of temperature and defines absolute zero (0 Kelvin).

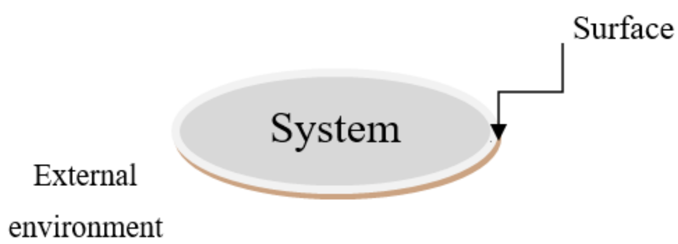
First Principle: It establishes an equivalence between different forms of energy. Energy transforms from one form to another and is conserved**.**

Second Principle: There exists a profound and fundamental asymmetry in nature: although the total quantity of energy is conserved during a transformation (first principle), the distribution of energy changes in an irreversible way (it disperses chaotically). Clausius introduced the concept of entropy, which shows that to convert heat into work, a portion of the energy degrades by creating entropy (increase in the entropy of the Universe).

Third Principle: It establishes the reference for entropy. (Zero entropy at 0 K for pure crystallized substances).

1.1. Definition of a system

A macroscopic system is a portion of the Universe delimited by a real or imaginary envelope (surface).



A system is said to be:

a) Closed if it does not exchange matter with the external environment or with another system.

b) Open if it exchanges matter with the external environment or with another system.

c) Isolated if it exchanges neither energy (work, heat, ...) nor matter with the external environment or with another system.

Note: A closed system can be isolated or not.

1.2. State variables

One can describe the state of a macroscopic system using measurable physical quantities such as temperature (T), pressure (P), or volume (V). If one wishes to describe the system more precisely, additional variables can be associated with it, such as density, heat capacity, coefficient of expansion, and so on.

1.3. Mechanical work performed by a pressure force

Consider a gas confined in a cylinder by a piston. If it is compressed under the action of an external force Fe, the work received by the system during an infinitely small displacement dx is: $\delta W = Fe.dx$.

In the case of compression, for example, the change in volume resulting from the piston's displacement is negative: $dV = - Sdx$ where S is the area of the piston's cross-section.

$$dx = - dV / S \qquad \delta w = -Pe.dV$$

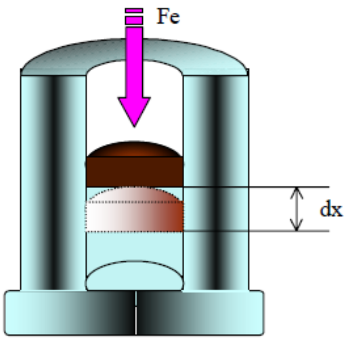


Figure 01 : *Case of compression [1]*

Sign convention:

$\delta W > 0$ if work is received by the system ($dV < 0$, compression)

$\delta W < 0$ if work is lost (or given up) by the system ($dV > 0$, expansion)

1.4. Zeroth Principle. Concept of Thermometric Scales.

1.4.1. Principle Zero

The zeroth principle of thermodynamics is stated as follows: Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other.

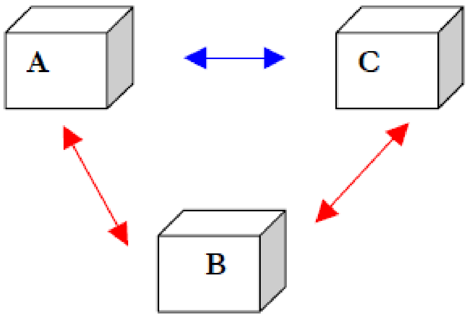


Figure 02 : *Temperature Equilibrium Principle [1]*

If A is in thermal equilibrium with B and if B is in thermal equilibrium with C, then A is also in thermal equilibrium with C. This principle allows the definition of the concept of temperature, with the three mentioned systems being at the same temperature.

1.4.2. First Law of Thermodynamics. Internal Energy

1.4.2.1. Internal Energy

The total energy ($E_{t.}$) of a system in general is equal to the sum:

- Of its kinetic energy ($E_{kin.}$) associated with the motion of its center of gravity.
- Of its potential energy ($E_{pot.}$) which depends on its position in the field of force in which it is located.
- Of a term of energy taking into account its composition, which will be designated by (U) and called internal energy.

$$E_{t.} = E_{kin} + E_{pot} + U \qquad \text{(I.1)}$$

The internal energy of a system takes into account the energy it possesses due to its mass, temperature, chemical composition, interactions between its various constituents, chemical bonds between the atoms of its molecules, intermolecular bonds, etc.

In thermodynamics, efforts are made to ensure that the system under study is stationary, $\Delta E_{kin} = 0$, and that the variation in potential energy during transformations is zero, $\Delta E_{pot} = 0$. Thus, the change in the total energy of a system almost always reduces to the change in its internal energy: $\Delta E_{tA}^{B} = \Delta U_{A}^{B}$ (I.2)

The change in the energy ΔE_{A}^{B} of a closed system during a transformation from state A to state B is equal to the sum of the heat quantities Q_{A}^{B} and the work W_{A}^{B} q that the system has exchanged with the external environment.

Therefore, it can be expressed as follows: $\Delta U_{A}^{B} = Q_{A}^{B} + W_{A}^{B}$ (I.3)

The work W and heat Q, taken separately, are generally not functions of state. Depending on the chosen pair of variables, the differential of U is expressed as follows:

$$U\ (T, P)\ ;\ dU = \left(\frac{\partial U}{\partial T}\right)_P dT + \left(\frac{\partial U}{\partial P}\right)_T dp \qquad (I.4)$$

$$U\ (T, V)\ ;\ dU = \left(\frac{\partial U}{\partial T}\right)_V dT + \left(\frac{\partial U}{\partial V}\right)_T dV \qquad (I.5)$$

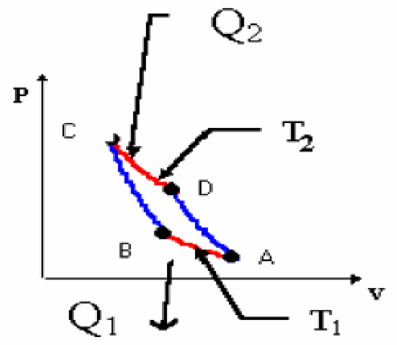
$$U\ (P, V)\ ;\ dU = \left(\frac{\partial U}{\partial P}\right)_V dT + \left(\frac{\partial U}{\partial V}\right)_P dV \qquad (I.6)$$

1.4.3 Second principle - entropie

1.4.3.1. The study of the Carnot cycle for an ideal gas

The system (ideal gas) exchanges heat with two sources: a hot source at temperature (TA = TB) and a cold source at temperature (TC = TD).

The Carnot cycle consists of two reversible isothermal transformations and two reversible adiabatic transformations. This cycle is represented in Clapeyron coordinates (P, V) by the figure below:



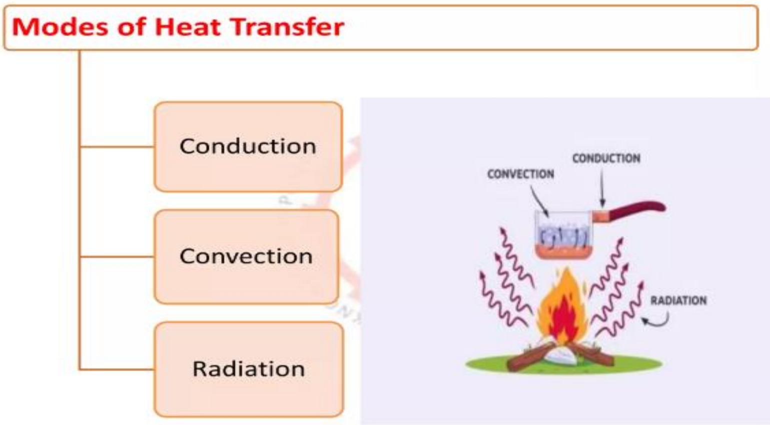
- AB: Isothermal compression,T=T1 = constant
- BC: Adiabatic compression, δQ = 0
- CD: Isothermal expansion, T=T2 = constant
- DA: Adiabatic expansion, δQ = 0

One can calculate the amounts of heat Q_A^B et Q_C^D exchanged by the gas during the two isothermal transformations AB and CD based on the pressures P_A, P_B, P_C, and P_D.

I.2 Modes of heat transfer

Heat transfer is part of the fundamental sciences of engineering and has many industrial applications.

The figure below illustrates the three modes of heat transfer:



2.1 Some Definitions of Heat Transfer

1. **Temperature**

The perception of hot and cold is based on sensations, leading to an irrational assessment of these magnitudes. Therefore, temperature has been defined to provide objectivity in measurements. Temperature characterizes the level at which heat is present in a body, allowing us to say that one body is hotter or cooler than another.

Temperatures in the International System of Units (SI) are expressed in degrees Celsius (°C), but in literature, one may encounter degrees Fahrenheit (°F) and Kelvin (°K).

2. **Heat**

Heat is a form of energy (energy of molecular motion) that flows from a hot point (higher temperature) to a cold point (lower temperature). It is the sensation perceived by our sensory organs when we are in front of, for example, an incandescent body.

The unit of heat is the Joule (J), but the kilocalorie (kcal) is also commonly used.

3. **Heat Flux Through a Surface**

It is the amount of heat that passes through the surface per unit of time.

4. **Heat flux density**

It is the amount of heat that passes through the unit of surface per unit of time, or it is the heat flux per unit of surface.

5. The temperature gradient

The temperature gradient is the vector that characterizes, at a given point, the variation of the temperature function.

2.2 Basic Reminders on Heat Transfer

2.2.1 Heat transfer by conduction

This mode of heat transmission applies more specifically to solids but also concerns fluids at rest. It corresponds to a propagation of heat from one point to another within the material, and the transfer of heat occurs through contact between neighboring particles (atoms or molecules). The material behaves truly as a conductor of heat.

The fundamental law of conduction (Fourier's law) is expressed as follows:

$$\vec{J} = -\lambda \overrightarrow{grad}\, T \qquad \text{(I.7)}$$

$grad$ T : Local Temperature Gradient.

λ: Thermal Conductivity Coefficient of the Transmitting Medium (W/m°K).

The coefficient λ is always positive. In the International System, the heat flux density "J" is expressed in watts per square meter ($W \cdot m^{-2}$), and the temperature "T" in kelvin (K).

Fourier's law is a semi-empirical law analogous to Fick's law for particle diffusion or Ohm's law for electrical conduction. Ohm indeed used an analogy between thermal and electrical phenomena to develop his theory. These three laws can be interpreted in the same way: the inhomogeneity of an intensive parameter (temperature, number of particles per unit volume, electric potential) induces a transport phenomenon that tends to compensate for the imbalance (heat flux, diffusion current, electric current).

2.2.2 Heat transfer by convection

Convection is considered natural or free when the movement of a fluid is influenced by a difference in density. When the movement is imparted by an agitating machine, pump, compressor, or fan. During the convection process, an increase in fluid velocity also enhances the possibilities of transforming laminar flow into turbulent flow, thereby generating turbulent convection that significantly accelerates property exchanges between neighboring layers of the fluid, particularly the heat diffusion within it.

The heat flux transmitted by convection between a wall at temperature Ts and a fluid at temperature T_f can be expressed in the form (Newton's Law):

$$\Phi = hs(T_f - T_s) \qquad (I.8)$$

Φ : Heat flux (W) ;

T_s : Temperature of the Solid Wall;

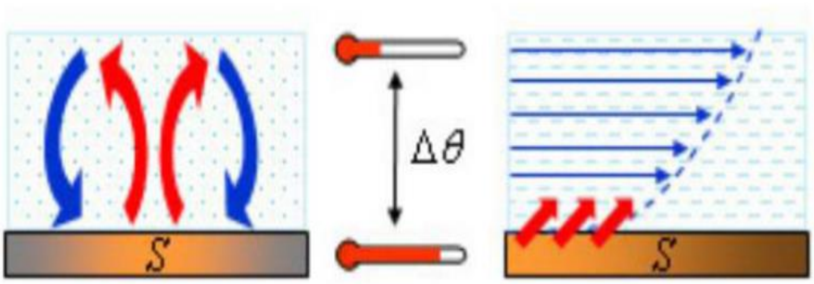
T_f : Temperature of the Fluid Away from the Wall;

S : Exchange Surface(m^2) ;

h : Coefficient of exchange. Its determination involves correlation relationships between dimensionless numbers, determined from the thermophysical properties of the fluid.

Heat transfer by convection is divided into two parts depending on the nature of the flow:

- ✓ **Forced convection** occurs when the flow is induced by artificial circulation (pump, turbine, fan) of a fluid.
- ✓ **Natural convection** takes place when the flow is induced by a difference in density that varies with temperature within the fluid:



(a) (b)

***Figure 03 :** The two modes of heat transfer by convection : (a) natural mode ; (b) forced mode. [2]*

To measure the intensity of heat transfer within the fluid due to its movements and to characterize the heat exchange between the fluid and the wall, **the Nusselt number** is used. The Nusselt number represents the dimensionless thermal gradient at the wall:

$$Nu = \left(\frac{\partial T^+}{\partial y^+}\right)_{wall} = \frac{hx}{\lambda_{fluid}} \qquad (I.9)$$

- ✓ In forced convection, on a : ***Nu=f (Re, Pr)***
- ✓ In natural convection, on a : ***Nu=f (Gr, Pr)***

Reynolds number: $Re = \frac{UL}{\nu}$ (I.10)

Prandtl number: $Pr = \frac{\nu}{\alpha}$ (I.11)

Grashof number: $Gr = \frac{g\beta\Delta T L^2}{\upsilon^2}$ (I.12)

Where :

U : Characteristic velocity [m/s]

L : Characteristic length [m]

ν : Kinematic viscosity [m^2/s]

α : Thermal diffusivity [m^2/s]

g : Acceleration due to gravity [m/s^2]

β : Thermal expansion coefficient [K^{-1}]

A. Coefficient of convective heat transfer

The heat transfer by convection is complex because it results from the superposition of two phenomena:

- ✓ Conduction between fluid particles that come into contact.
- ✓ Mixing of these particles due to the overall movement of the fluid. If this movement is induced only by temperature differences (and thus density), convection is natural. If this movement results from mechanical action (pump, fan...), convection is forced.

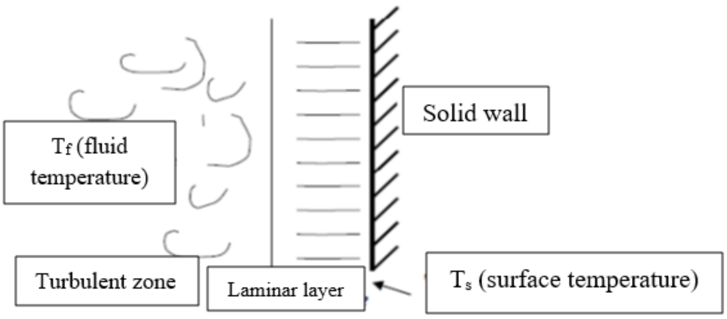


***Figure 04** : Thermal gradient in the laminar layer. [2]*

The heat transfer coefficient "h_c" is determined through experimentation. The results of these experiments are expressed in terms of correlation laws involving dimensionless quantities. There are two types of convection:

a. Natural convection

Natural convection is a phenomenon in fluid mechanics that occurs when a gradient induces movement in the fluid. This gradient can involve various intensive quantities such as temperature, solute concentration, or surface tension. In some applications, heat transfer by natural convection is sometimes small compared to other heat transfer modes (conduction -

radiation), and therefore, it can be neglected. Otherwise, it is the dominant mechanism in heat transfer. There are situations where it is necessary to suppress natural convection, such as in the case of heat loss from steam pipelines, windows, or solar collectors. On the other hand, efforts are made to increase heat transfer by natural convection to cool microelectronic components releasing heat due to the Joule effect.

This results in natural convection or turbulence depending on the value of the Grashof number (Gr) or the Rayleigh number (Ra).

with :

$$Gr = \frac{g\beta\rho^2\Delta T L^3}{\mu^2} \qquad \text{(I.13)}$$

where :

L : Linear dimension used to calculate the exchange surface (height of a plate, diameter of a cylinder).

ΔT : Différence de température entre la paroi et le fluide.

g : Acceleration due to gravity.

ρ,μ : The density and dynamic viscosity of the fluid.

β : Coefficient de dilatation isobare de fluide.

with :

$$\beta = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p \qquad \text{(I.14)}$$

For ideal gases, $\beta = \frac{1}{T}$

b. Forced convection

Forced convection is induced by mechanical actions (fans, turbines, pumps, etc.) on a fluid. The transfer is faster than in the case of natural convection. Here are some examples of forced convection in appliances: central heating with a blower, electric heaters with a fan, solar water heaters, and convection ovens. The human body has its own system of forced convection, the circulatory system.

The flow can be laminar or turbulent depending on the value of the Reynolds number (Re): $R_e = \frac{Vd}{\nu}$ (I.15)

V : The flow velocity

d : Characteristic scale of the flow, it is the diameter in the case of flow in pipes.

ν: The kinematic viscosity.

2.2.3 Heat Transfer by Radiation

Heat transfer by radiation corresponds to the transport of thermal energy in the form of electromagnetic waves similar to light. In fact, any object, even placed in a vacuum, emits thermal energy in the form of radiation that is conveyed without material support. This emission is all the more significant when the temperature of the emitting body is high. However, it becomes notable only from around 700 to 800°C. In the case of the sun, whose surface temperature is around 6000°C, thermal emission is particularly significant.

Simultaneously, all other bodies placed in the path of this radiation absorb a portion of it and, as a result, become recipients of heat.

In the end, three phenomena are distinguished in this mode of transfer :

a. Emission

b. Propagation   c. Absorption

Chapitre 2
Thermique du bâtiment

II.1 Algerian Thermal Regulation (DTR Documents)

1.1. Introduction.

DTR is the regulatory technical document of code C.3.2 for the thermal regulation of residential buildings, published by the Ministry of Housing in cooperation with CNERIB (National Center for Integrated Study and Research in Building), with the aim of providing an initial response to issues related to building thermal performance.

This regulatory requirement aims to limit heat losses with the goal of saving 20 to 30% of the consumed heating energy. The results of energy audits managed by the National Agency for the Promotion and Rationalization of Energy (APRUE, Algeria) related to existing buildings have shown that the increase in greenhouse gas emissions is largely due to the deterioration of the thermal quality of new and old buildings in Algeria, which is due to:
to the orientation of households towards modern architectures not adapted to our socio-cultural and climatic context,

- to real estate developers who are not future managers of the buildings and tend to minimize investments without concern for the energy bill once these buildings are constructed,
- to the budgets of civil buildings which are often insufficient for the construction of energy-efficient buildings,
- to very short completion deadlines for buildings that encourage the duplication of the same building architecture without taking into account the specificity of the climate in each region during construction.

All these factors have contributed to the increasingly widespread use of conventional heating and cooling systems to address the inadequacy due to the thermal quality of our buildings. The establishment of thermal and energy regulations for new buildings becomes, therefore, a necessity given the future energy prospects of the country and the significant contribution of this sector to greenhouse gas emissions.

1.2 Key Principles of Thermal Regulation

The principles that form the basis of thermal regulations can be presented in the following manner:

1.2.1. First principle: limit the overall energy consumption of buildings

Energy conservation serves both to combat the greenhouse effect, in compliance with the competitive balance between energy sectors (environmental issue), to preserve energy resources, and to reduce the bill paid by occupants (social issue). The overall consumption target set by regulations corresponds to significant gains: (example in French regulations) around 20% in residential and around 40% in tertiary sectors.

1.2.2. Second principle: Require results rather than impose solutions

The thermal regulation imposes overall performance, a maximum energy consumption, and a maximum indoor temperature in summer while leaving significant freedom to clients, architects, and engineering firms on how to achieve these performances.

Designers can freely choose and combine construction materials, construction methods, heating, ventilation, and hot water production equipment, in order to achieve the desired result, allowing clients to select solutions adapted to the specificity of their market or the particular context of an operation. This encourages innovative initiatives among project leaders to optimize the overall cost of their projects.

Regarding energy consumption, designers can thus act on three main levers:

- The thermal treatment of the building envelope (choice of materials and construction processes, insulation, treatment of thermal bridges, solar factor, and protection of glazed openings).
- The ventilation system,
- Heating and domestic hot water production equipment.

To avoid any exaggeration in arbitrations, which would harm the overall coherence of the building and ultimately be detrimental to users, the regulations provide "safeguards" to limit the possibility of manipulating various parameters of energy consumption:

- Insulation of opaque walls,
- Thermal bridges,
- Types of windows,
- Ventilation system,
- Heating system,
- Hot water production system,
- Lighting devices

1.2.3. Third principle: Continuous improvement of performance

The regulations provide for expanding and strengthening thermal regulations every 5 years to achieve national objectives for reducing greenhouse gas emissions. Five years is the time needed for innovative construction practices to demonstrate their value and become widespread (CSTB, 2005). High Energy Performance labels prepare for these strengthening steps by promoting the progression of products, equipment, and solutions.

1.2.4. Fourth principle: Sophisticated calculation tools to facilitate optimizations

The regulation imposes the application of precise methods to assess the energy consumption and indoor summer temperature of a building. These methods result from a complete and detailed modeling of thermal phenomena within a building. They essentially aim to:

- Define the ceiling values (energy consumption, indoor summer and winter temperatures) of the building,
- Calculate the project's position in relation to these ceiling values.

The relatively complex modeling on which these methods are based requires the use of computer resources. The designer of a building can thus adjust the building's characteristics through successive iterations to meet the program set by the client and simultaneously satisfy the requirements of thermal regulations under the best cost conditions. SimulArch19, which we propose, is a simulation and verification calculation code for the selected parameters in the overall project concept.

1.3 The Algerian thermal regulations

In Algeria, the 1997 thermal regulation for residential buildings was designed to reduce heating consumption by approximately 25%. Currently, there is an ongoing effort to increase this level of energy savings to more than 40%. To achieve this, numerical simulations have been conducted on typical housing units. The study indicates that by focusing solely on limiting thermal transmission losses, it is possible to meet this new goal while significantly reducing the summer air conditioning load. A new thermal regulation could be based on the following two principles :

Reserving the 1997 regulations for individual housing, establishing new, more stringent regulatory coefficients for collective housing. (SIDI MOHAMED and all, 2002). Under the title "Thermal Regulations for Residential Buildings: DTR C 3–2," the rules for calculating heat losses, as defined in DTR C 3–2, set minimum thermal performance standards and also include calculation conventions for the sizing of heating installations. The Algerian regulations draw heavily from the French regulations; however, the calculation methods used are simpler. They allow, at least within certain limits, computerized calculation of heating needs. This is a positive aspect as it enables the utilization of a building's thermal inertia, a crucial factor given the distinctive climate and construction types in Algeria.

Regulations that consider thermal comfort are especially relevant during hot periods. Such regulations are of paramount importance due to the challenges of comfort during the summer and the energy consumption associated with air conditioning widely used in many regions of Algeria.

II.2 Thermal needs

2.1 Introduction

Thermal needs represent heating losses. They are obtained by calculating surface losses plus linear losses and air renewal losses (thermal losses to heat incoming outdoor air). Once the thermal needs are calculated and expressed in watts, the engineer or study technician determines the heating elements of the emitters, whether they are radiators, underfloor heating, radiant panels, fan convectors, or air handling units (AHUs). With buildings becoming increasingly thermally insulated, thermal needs are decreasing. However, air renewal losses have minimum flow rates to heat and cannot be reduced. The only possibility is to recover heat from the air extraction to warm up the incoming fresh air. This is the case with double-flux air handling units equipped with an energy recovery unit.

2.2 Definition of heat transfer

Heat transfer is the propagation of heat from a hot body to another body that is cooler or completely cold. This exchange continues until the temperatures of the two bodies equalize. There are three fundamental modes of heat transfer:

1. **Conduction:** Heat spreads within a body from particle to particle.
2. **Convection:** In this case, heat transfer occurs from a liquid or gaseous fluid to a solid body, for example, between air and a surface.
3. **Radiation:** Heat is transmitted from one body to another in the form of radiant energy.

2.3 Useful thermal characteristics of construction walls - "K coefficient"

For heat loss calculations alongside interior and exterior temperatures, a key role is played by the overall heat transmission coefficient "K." It characterizes, from a thermal perspective, the building elements, especially the walls. Walls exist in various forms, both in terms of the number of layers and their positions. For instance, there are walls made of a single layer, two layers with different materials and thicknesses, or multiple layers arranged side by side to create a homogeneous wall. Some walls consist of several layers positioned differently. In this case, the wall behaves differently in terms of thermal transfer, meaning it exhibits different "K" transmission coefficients.

2.3.1 The "K" coefficient depends primarily on:

- The thickness of each component of the considered wall.
- The shape of the wall.

- On the thermal conductivity coefficient (λ) (Kcal / h m°C) of the materials composing the wall. This coefficient expresses the materials' capacity to transmit heat.

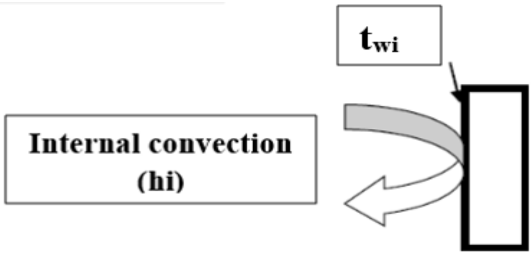
2.3.2 Calculation of the heat transmission coefficient "K":

2.3.2.1 In the case of a single wall:

In a steady-state condition, the expression for the heat flux through a wall of thickness "e" and thermal conductivity "λ" from the inside to the outside is given by the following relationships:

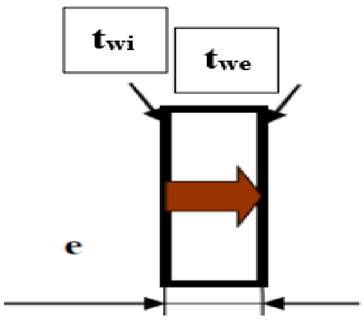
- **By internal convection**

$$Q = h_i . S . (t_i - t_{wi}) \qquad \text{(II.1)}$$



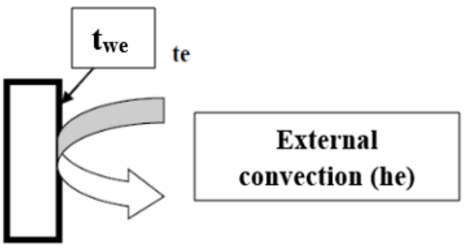
- **By conduction through the material**

$$Q = \frac{\lambda}{e} S(t_{wi} - t_{we}) \qquad \text{(II.2)}$$



- **By external convection :**

$$Q = h_e . S(t_{pe} - t_e) \qquad \text{(II.3)}$$



where :

t_{wi} = Internal surface temperature of the wall in °C

t_{we} = External surface temperature of the wall in °C

h_i = internal convective heat transfer coefficient in W/m^2.°C

h_e= external convective heat transfer coefficient in W/m^2°C

S = surface of the wall in m^2

By highlighting the temperature differences in the equations, 1,2 and 3

$$(t_i - t_{wi}) = \frac{Q}{hi.S} \qquad (II.4)$$

$$(t_{wi} - t_{we}) = \frac{Q}{\lambda.\frac{S}{e}} \qquad (II.5)$$

$$(t_{we} - t_e) = \frac{Q}{he.S} \qquad (II.6)$$

By summing up term by term the expressions on the left and on the right, we will obtain:

$$(t_i - t_e) = \frac{Q}{S}\left[\frac{1}{h_i} + \frac{e}{\lambda} + \frac{1}{h_e}\right] \qquad (II.7)$$

$$Q = \frac{1}{\frac{1}{h_i}+\frac{e}{\lambda}+\frac{1}{h_e}} S(t_i - t_e) \qquad (II.8)$$

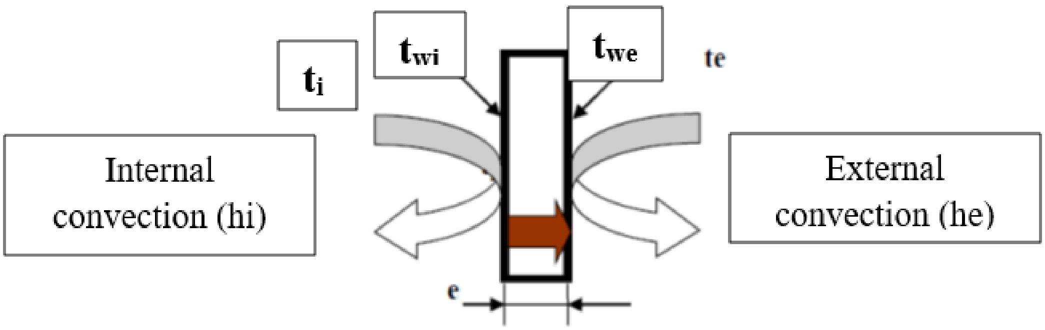
Or, alternatively, by setting:

$$\frac{1}{k} = \frac{1}{h_i} + \frac{e}{\lambda} + \frac{1}{h_e} \qquad (II.9)$$

Or again:

$$K = \frac{1}{\frac{1}{h_i}+\frac{e}{\lambda}+\frac{1}{h_e}} \qquad (II.10)$$

The term k in equation 10 is called the heat transmission coefficient of the flat wall composed of a layer of material with thickness e and conductivity λ.



Also, values are generally adopted from tables that directly express the values based on the position of the wall, the direction, and the sense of the heat flow. $\frac{1}{h_e}$ ou $\frac{1}{h_i}$ are the expressions of internal and external convective resistances expressed in (m^2.°C/W)

Position of the wall	**Direction of the flow**	$\frac{1}{h_i}$	$\frac{1}{h_e}$	$\frac{1}{h_i}+\frac{1}{h_e}$
Vertical	Horizontal	0.11	0.06	0.17
Horizontal	Upward	0.09	0.05	0.14
Horizontal	downward	0.17	0.05	0.22

Table 01: *Internal and external convective resistances in (m^2°C/W) [15]*

A flat wall is characterized by its transmission coefficient K (sometimes noted as U), which is equal to the inverse of the resistance R:

$$k = \frac{1}{R} \qquad \left(\frac{w}{m^2 °C}\right) \qquad (II.11)$$

For a single-layer wall, the thermal resistance is given by the following formula:

$$R = \frac{1}{k} = \frac{1}{h_i} + \frac{e}{\lambda} + \frac{1}{h_e} \qquad \frac{m^2 °C}{w} \qquad (II.12)$$

The ratio e/λ is called the thermal resistance of the considered layer in (m^2.°C/W). It represents the material's ability to resist the passage of heat.

2.3.2.2 Case of a composite wall"

Generally, exterior walls are composed of multiple heterogeneous (different) layers with different thermo-physical properties (thermal conductivity **λ**, specific heat **c**, density **ρ**), in addition to varying thickness e from one layer to another. For a composite wall, the thermal resistance **R** is given by the following relationship:

$$R = \frac{1}{k} = \frac{1}{h_i} + \sum\left(\frac{e_i}{\lambda_i}\right) + \frac{1}{h_e} \qquad (II.13)$$

$\sum\left(\frac{e_i}{\lambda_i}\right)$: it is the sum of the thermal resistances of the layers composing the wall.

Note 1 : *For prefabricated products such as brick, concrete blocks, and hollow blocks, the useful thermal resistance* ***Ru*** *is used. The values of Ru are provided in the following table:*

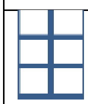
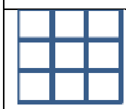
Values of Ru in (m^2°C/w) Clay bricks and hollow clay blocks					
thickness	5cm	7.5cm	10cm	12.5cm	15cm
	0.09				
		0.15	0.20		
				0.25	0.27

Table 02: *Thermal resistances Ru of clay bricks (m^2°C/W) [15]*

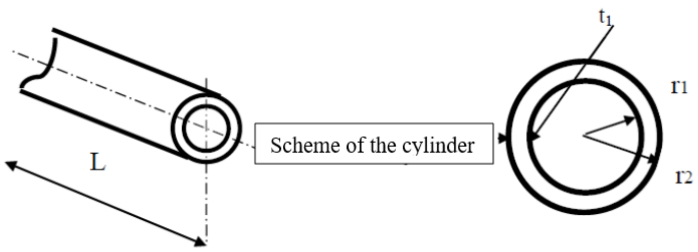
Note 2 : *If one of the layers composing the wall is an air gap, the thermal resistance* ***Ra*** *can be expressed as the thickness e divided by the thermal conductivity λ of the air. In air gaps, heat transfer occurs not only by conduction but also by convection and radiation. The thermal resistances* ***Ra*** *for air gaps encountered in construction can be assigned as per the following table:*

Thermal resistances Ra of non-ventilated air gaps (m^2 °C/W)								
Position of the air	Direction of the flow	Thickness of the air gap en [mm]						
		5 to 7	7.1 to 9	9.1 to 11	11.1 to 13	14 to 24	25 to 50	55 to 300
Vertical	Horizontal	0.11	0.13	0.14	0.15	0.16	0.16	0.16
Horizontal	upward	0.11	0.12	0.13	0.14	0.14	0.14	0.14
Horizontal	downward	0.12	0.13	0.14	0.15	0.16	0.18	0.20

Table 03: *Thermal resistances Ra of non-ventilated air gaps (m^2°C/W) [15]*

2.2.2.3 Case of a tubular wall

Consider a cylindrical section (tube) with inner radius r1 and outer radius r2, length L, and material characterized by conductivity λ.



The Fourier equation is written in the following form:

$$Q = -\lambda S.\,\text{grad}T = -\lambda.\,S\frac{dT}{dr} \qquad \text{(II.14)}$$

$$S = 2.\,\pi R.\,L \qquad \text{(II.15)}$$

By substituting into the expression for the flux Q, we will have:

$$Q = 2\,\pi\,r\,L\,\lambda\frac{dT}{dr} \qquad \text{(II.16)}$$

$$Q\frac{dr}{r} = -2\,\pi\,L\,\lambda\,dT \qquad \text{(II.17)}$$

$$Q\int_{r1}^{r2}\frac{dr}{r} = -2\,\pi\,L\,\lambda\int_{t1}^{t2}dT \qquad \text{(II.18)}$$

$$Q\,\ln\frac{r_2}{r_1} = 2\,\pi\,L\,\lambda\,(t_1 - t_2) \qquad \text{(II.19)}$$

$$Q = \frac{2\,\pi\,L\,(t_1 - t_2)}{\frac{1}{\lambda}\ln\frac{r_1}{r_2}} \qquad \text{(II.20)}$$

By introducing, as we had already done for the flat wall, convection at the internal and external surfaces of the cylinder, we will have:

By convection at the internal surface :

$$Q = h_i s_i (t_i - t_{wi}) = h_i 2\,\pi\, r_1\, L\,(t_i - t_1) \qquad \text{(II.21)}$$

By conduction through the material:

$$Q = \frac{2\,\pi\, L\,(t_1 - t_2)}{\frac{1}{\lambda}\lambda \ln\frac{r_2}{r_1}} \qquad \text{(II.22)}$$

By convection at the external surface

$$Q = h_e s_e (t_{we} - t_e) = h_e . 2\,\pi\, r_2\, L\,(t_2 - t_e) \qquad \text{(II.23)}$$

The quantity Q will ultimately be equal to:

$$Q = \frac{2\,\pi\, L\,(t_i - t_e)}{\frac{1}{h_i r_1} + \frac{1}{\lambda}\ln\frac{r_2}{r_1} + \frac{1}{h_e r_2}} \qquad \text{(II.24)}$$

2.3 Calculation of the minimum thermal resistance 'R $_{min}$':

To verify the external structure of a building (external wall, terraces), one must compare its overall thermal resistance to the required minimum thermal resistance R_{min}, which is given by the following formula:

$$R_{min} = \frac{t_i - t_e}{\Delta t_{max} h_i}\,.n \qquad \text{(II.25)}$$

For a good choice of wall thicknesses, it is necessary to verify this inequality: R > Rmin, where:

- ti: temperature of indoor air depending on the purpose of the premises in °C.
- te: temperature of outdoor air depending on the climatic region in °C.
- n: Coefficient that takes into account the type of position of the exterior walls (from a table).
- Δt_{max}: the maximum temperature difference between indoor air and the interior surface of the exterior walls.

Type of exterior wall	**n**
Open passage, floor covering	1
Attic floor, exterior walls, and roof with ventilated air layer	0.9
Walls, floors defining cold spaces, located below or above ground level with a maximum of 1 m, with openings (windows, ventilation holes).	0.6

Table 04a: *Coefficient n for exterior wall [17]*

Type of construction	**φ%**	**Ti °C**	**Δt_{max} °C**	
			wall (ext)	**terrace**
Social-use premises (hospitals, daycare centers)	50	22	3	2.5
Dwellings	60	18	3.5	3
Social-use premises with normal humidity and temperature conditions (theaters, cinemas, schools, clubs).	60	18	4	3.5
Industrial premises with normal humidity conditions and negligible heat dissipation (mechanical halls).	60	16	6	5
Same as the previous one, with low humidity conditions (welding and assembly halls).	50	16	7	6
Industrial premises with very low humidity conditions and significant heat dissipation (thermal machining halls).	45	20	9	7

Table 04b: *Maximum temperature difference between indoor air and the interior surface of the walls. [17]*

II.3 Thermal insulation

3.1 Generalities

The implementation of thermal insulation aims to reduce heat losses, consequently improving comfort and decreasing the occupants' expenses (financial savings). But that's not all; insulation is also beneficial for the environment because, by reducing energy consumption, it helps preserve energy resources and limit greenhouse gas emissions.

3.2 Thermal conductivity

The thermal conductivity coefficient (λ) of a material is a fundamental parameter in insulation calculations. It indicates the amount of heat that passes through a layer with a thickness of 1 meter and a surface area of 1 square meter in one hour. For example, the thermal conductivity of air (λ) is 0.023 [W/m .K], and that of the most common insulators ranges between 0.02 and 1.0 [W/m. K].

3.3 The insulators

3.3.1 The characteristics of insulators

- Low thermal conductivity (λ).
- Chemical neutrality (non-toxic, non-corrosive, odorless).
- Non-flammable.
- Excellent fire resistance.
- Impermeable to water vapor.

3.3.2 The different types of insulators

- Expanded polystyrene.
- Rigid polyurethane foam.
- Rigid foam based on polyvinyl chloride (PVC).
- Mineral fibers.
- Cellular glass (foam glass).
- Cork panels, etc.

For more details, refer to the appendix.

3.3.3 Insulation on the inside or on the outside?

Thermal insulation placed on the inside leads to quicker cooling at night (low thermal inertia), but its implementation is easy, even in rehabilitation projects. There is no need to provide protection against weather conditions, and it is the most comfortable solution in summer.

Insulation placed on the outside increases the wall's capacity for heat accumulation (high thermal inertia), resulting in a longer cooling time for a space. While it is a better solution in winter, it requires protection against weather conditions, and its cost is higher.

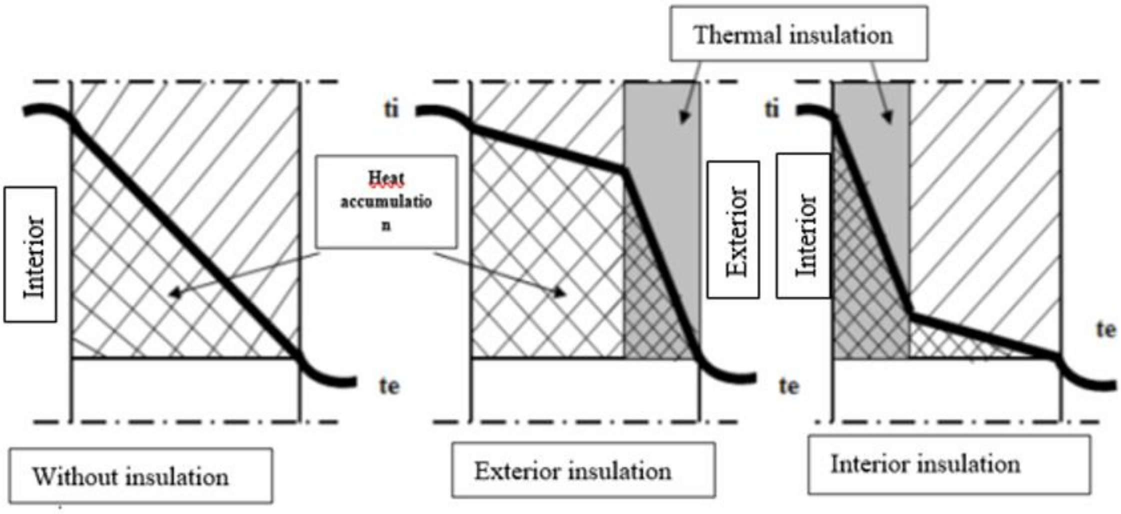


Figure 01: *Temperature profile of a wall based on the insulation placement [15]*

3.4 Determination of the economical thickness of the insulation

The thermal losses of an insulated building decrease as the thickness of the insulation increases. As seen in Figure 1, where curve 'a' illustrates the relationship between the thickness of the insulation and thermal losses, very thin layers of insulation already cause a noticeable decrease in losses. However, as the thickness of the insulating layer increases, the reduction in losses diminishes. On the other hand, curve 'b' in the same figure shows that insulation costs increase with the thickness of the insulation. Therefore, there is a value beyond which additional insulation is no longer beneficial. This limit—the economical thickness of the insulation—is determined from curve 'c,' where its minimum indicates the most economical insulation thickness.

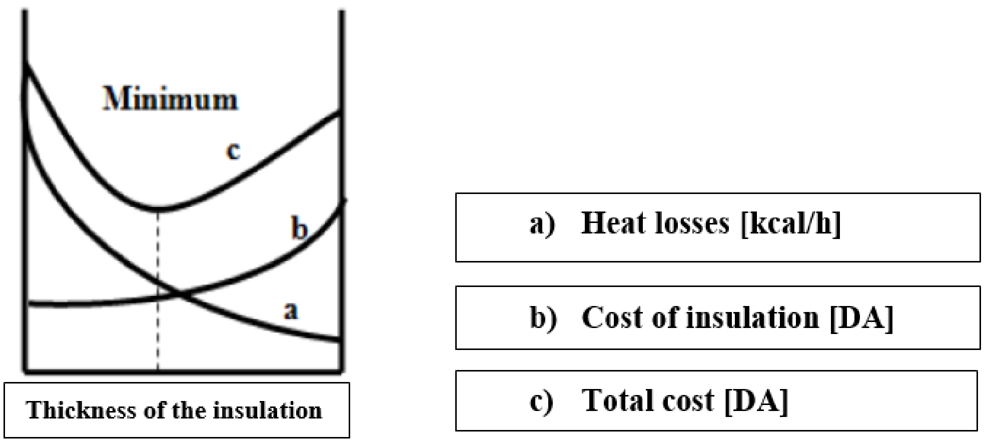


Figure 02: *Heat losses and insulation cost as a function of insulation thickness.*

3.5 Importance and treatment of thermal bridges

The area of lesser thermal resistance is then called a "thermal bridge." Thermal bridges can occur anywhere in the building envelope where thermal resistance is weakened, such as corners, connections of partition walls or slabs, balconies, etc. These thermal bridges should be avoided for two main reasons:

- The heat flux at these locations is higher, resulting in additional energy requirements for heating or air conditioning.
- The interior surface temperature at these thermal bridges is lower than on a regular surface. If the temperature difference is too significant, dust may accumulate in these areas, leading to unsightly stains. Moreover, if the surface temperature is too low relative to the indoor climate (temperature and humidity), superficial condensation may occur, resulting in mold and stains.

3.5.1 Types of thermal bridges

We distinguish geometric thermal bridges such as angles and corners, and material thermal bridges where a heat-conducting material crosses the insulation layer. Thermal bridges are also classified into linear bridges, which have a certain length, and punctual bridges, where the interruption of the insulation layer remains local. Any curvature in the insulation layer or in the wall constitutes a geometric thermal bridge. The isotherms (lines of constant temperature) must follow the curvature of the wall, and the heat flux lines, perpendicular to them, tighten inward toward the curvature.

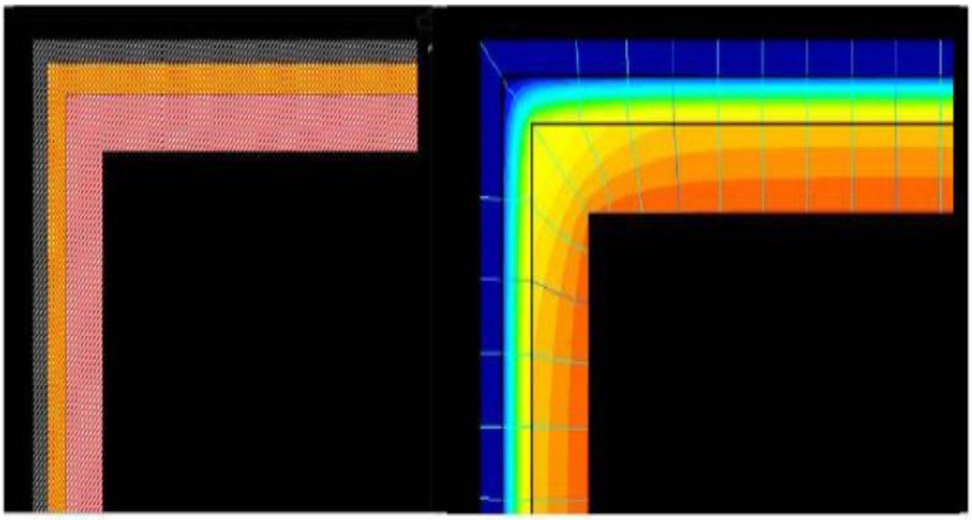


Figure 03 : *Geometric thermal bridge: building corner. On the left, in plan, on the right, isotherms (colored zones) and flux lines. [15]*

The Figure 3 shows a typical geometric thermal bridge, formed by an angle between two walls, where the wall is made of bricks with mineral wool and an exterior lining with cement blocks. The red corresponds to 20°C, and the blue to 0°C. The hue changes with each degree. The thin lines represent heat flow lines, drawn every W/m. It can be observed that the interior and exterior temperatures at the corner are slightly lower than those in the full wall. It is also noticeable that the heat flow lines are somewhat denser towards the interior of the corner compared to the full wall. Geometric thermal bridges generally do not have significant effects, especially on heat losses, because the insulating layer is not interrupted; it is only deformed. However, under critical conditions, the temperature decrease on the interior surface may be sufficient to promote the growth of mold.

Material thermal bridges occur wherever the insulating layer is interrupted or crossed by a more conductive material. Figure 4 illustrates a material thermal bridge consisting of a slab resting on a wall with interior insulation. The red corresponds to 20°C, and the blue to 0°C. The hue changes with each degree. The thin lines represent heat flow lines, drawn every W/m. It is evident that the heat flow lines concentrate strongly through the bridge, like a river in a gorge, and the isotherms diverge, similar to the water level dropping near a dam breach. A clear cooling and concentration of heat flow lines can be observed near the material thermal bridge. Material thermal bridges often have more severe consequences than geometric bridges.

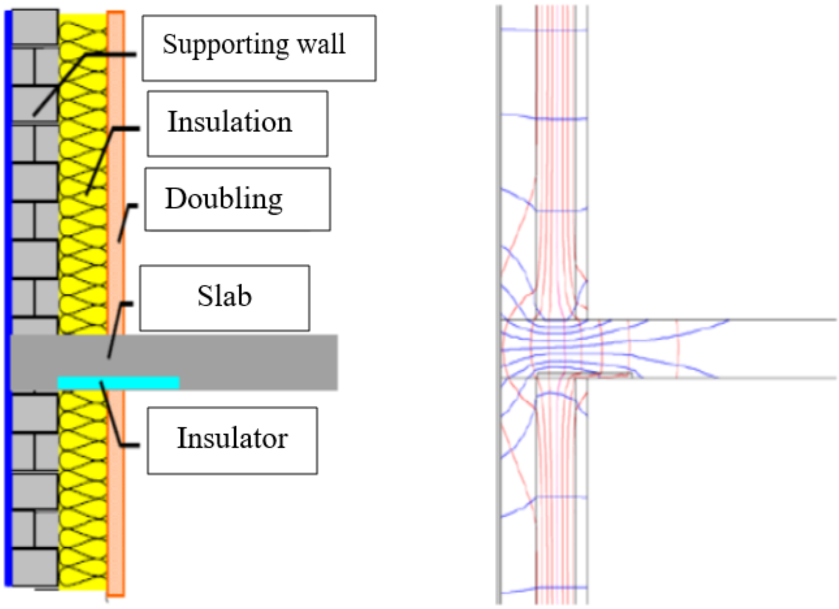


Figure 04 : *Material thermal bridge: slab resting on a load-bearing wall with interior insulation. On the left, cross-section, on the right, isotherms (every 2 K) and heat flow lines (tous les W/m). [15]*

From the perspective of thermal losses, the example above can be modeled (or represented) as an additional heat leak along a horizontal line inserted into a wall. This is a linear thermal bridge, to which a linear heat loss coefficient (in W/(m·K)) and a length can be assigned. A metal fixing bar traversing a wall can be modeled as an additional localized point heat loss, constituting a punctual thermal bridge, to which a heat loss coefficient (in W/K) is attributed.

***Figure 05 :** linear thermal bridge [15]*

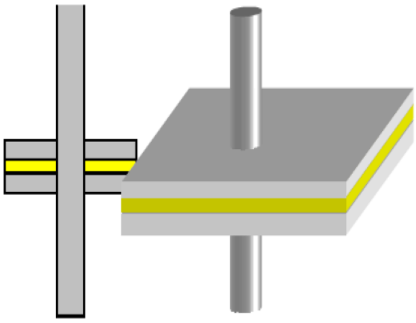


***Figure 06** : point thermal bridge [15]*

How to recognize a thermal bridge?

On the plan and section of construction details, a material thermal bridge appears as an interruption in the insulation layer. It is therefore easy to detect and should be corrected or addressed appropriately before construction! Note: plans and section details represent only a portion of the envelope element, and it is possible that a thermal bridge, especially a point thermal bridge, exists outside of this section. The more complex the construction, the higher the likelihood of finding thermal bridges. In an existing building, a thermal bridge is primarily detected by its effects: the emergence of mold, condensation, or cold and hot spots. It can also be detected using thermography. Thermography provides an image of the external surface temperature. Since this temperature is higher where the external surface is better heated, especially by thermal bridges, it is also, to some extent, an image of thermal bridges.

***Figure 07:**On the left, thermography of the residential part of a farm. On the right, a photograph.[17]*

In Figure 7, the thermal bridges of the slab, window sills, and windows are clearly visible. The radiator is activated against the sill of the second window from the left on the ground floor and beneath the two windows on the right on the upper floor. However, the roof near the chimney is not a thermal bridge; it is heated by the chimney! Notice the cooling at the corner of the building (geometric thermal bridge). Significant heat losses through the basement are also evident, often observed in older buildings where the basement and the ground floor slab were not insulated because they are not heated and do not face the exterior. While it is essential to avoid thermal bridges, it is not always possible. In such cases, their impact should be considered in the building's thermal balance.

The following four rules help reduce the risk of thermal bridging:

1. **Prevention Rule:** Whenever possible, avoid interrupting the thermal envelope.
2. **Penetration Rule:** Where interruption is unavoidable, the thermal resistance in the insulation layer should be as high as possible.
3. **Articulation Rule:** At joints between building elements, insulation layers should meet without interruption or displacement.
4. **Geometry Rule:** Prefer obtuse angles whenever possible; acute angles, in fact, promote heat dispersion.

To minimize the impact of thermal bridges, several principles can be applied:

- **Divide a significant thermal bridge into smaller ones.** This is possible if the bridge serves a mechanical function, for example.

Figure 08 : *Rule of thermal bridge division. [17]*

- **Heating the thermal bridge.** This measure does not improve the thermal quality of the bridge but reduces the risk of soiling or condensation. The heating is achieved by connecting the bridge to a wider metal plate on the warm side. This method is widely used in metal construction.

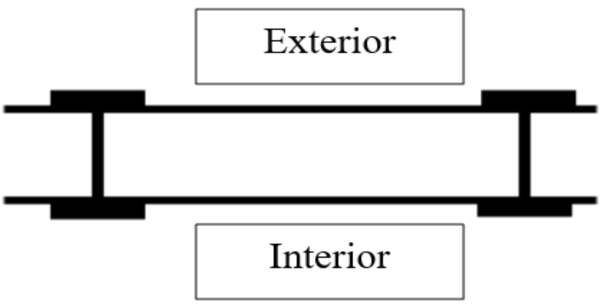


Figure 09 : *Heating rule of a thermal bridge. [17]*

- **Strengthen** the insulation near the thermal bridge wherever possible. The purpose of these reinforcements is to elongate the heat flow lines. This method is often employed for slab edges, partition walls, or slabs extending into balconies.

4. Thermal comfort

Thermal comfort is defined as a state of satisfaction with the thermal environment. It is determined by the dynamic balance established through thermal exchange between the body and its surroundings.

4.1 The parameters of thermal comfort

Thermal comfort depends on 6 parameters:

1. **Metabolism:** Metabolism is the internal heat production in the human body, allowing it to maintain a temperature around 36.7 °C. Work metabolism corresponding to a specific activity adds to the baseline metabolism of the body at rest.
2. **Clothing:** Clothing represents thermal resistance to heat exchange between the skin surface and the environment.
3. Ambient air temperature (Ta).
4. Surface temperature of walls (Tp).
5. Relative humidity of the air (φ).
6. **Air velocity:** Air velocity influences heat exchange through convection. In living spaces, air velocities generally do not exceed 0.2 m/s. Indeed, individuals begin to perceive air movement at this speed.

4.2 Evaluation of Thermal Comfort

It is the operative temperature (average of air temperature and surface temperature) that is taken as a reference. It mainly depends on the occupants' activity in relation to the relative humidity level (40-70%). Generally, the operative temperature is around 19 °C for normal office activities.

4.3 Specific Sources of Discomfort

Surface temperature of a wall significantly lower than the ambient temperature

A wall is considered cold when its surface temperature is more than 3°C lower than the air temperature in the room. Generally, single and **double-pane** ordinary windows are considered cold surfaces, meaning that inevitable discomfort due to cold radiation occurs in their vicinity. This phenomenon is particularly significant when the surface area is large.

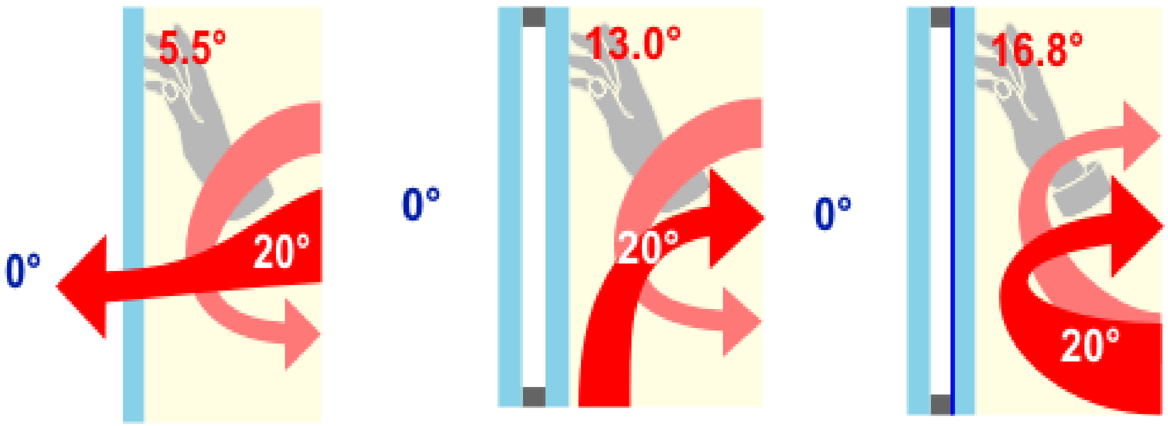


Figure 10 : *The effect of glass temperature on thermal comfort.*

The effect of this cold surface will, however, be less noticeable in the following cases:

- if it is offset by a heat source that reduces the impact of its radiation: for example, by having a heater under the window, or by an air supply vent creating a curtain of warm air,

5. Measurement of comfort

5.1 PPD Method Based on Air Temperature

Under normal conditions, the human body maintains its core temperature around 36.7 °C. This temperature is consistently higher than the ambient temperature, so a balance must be struck to ensure the well-being of the individual.

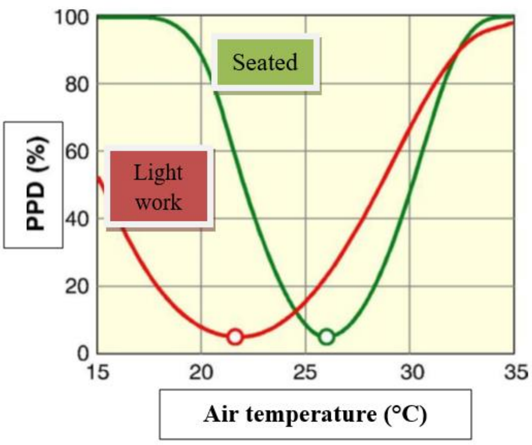


Figure 11 : *Measurement of thermal comfort.*

The figure opposite considers the perception of thermal comfort as expressed by the subjects themselves. It shows the **predictable percentages of dissatisfaction (PPD)**, expressed on the vertical axis, for individuals at rest in a seated position or engaging in light work. It is impossible to define a temperature that suits everyone: at best, there are still 4% dissatisfied. The curve representing light work shifts towards lower temperatures: individuals with more heat to lose prefer lower temperatures. On the other hand, the curve for individuals at rest is narrower: these individuals are more sensitive to slight temperature variations. The mechanisms of the human body's self-regulation reveal a zone where the variation in thermal comfort is low: this is the thermal comfort range.

5.2 Survey Results

The various parameters discussed in paragraph 2 that are important for thermal comfort interact with each other. Understanding their interrelationships, their effects on occupant satisfaction, and their measurement is necessary for constructing satisfactory dwellings. Professor **Fanger** (1970) used an original approach to solve this problem. Fanger and his colleagues, followed by several researchers in numerous countries, subjected a large number of subjects to various well-defined microclimates. The subjects had to express their sensations through a vote on a scale ranging from -3 to +3:

5.3 PPD/ PMV method

The Predicted Mean Vote (PMV) is the average predicted rating given by a large group of individuals expressing their thermal comfort sensation on Fanger's scale:

1. A PMV value of zero indicates an optimal sensation of thermal comfort.
2. A negative PMV value means that the temperature is lower than the ideal temperature.
3. Conversely, a positive value signals that it is higher.

Chapter 3
General Principles of Heating

III.1 Calculation of thermal losses

1.1 Introduction

The term "thermal losses" refers to the amounts of thermal energy given up by a space, on one hand, to the outdoor air through transmission across its walls, and on the other hand, to the outdoor air entering the space through various openings. To achieve thermal equilibrium in the space, it is necessary to supply it with an amount of heat equal to the losses.

1.2 Calculation Principle

The total basic losses (D) of a space include:

- Losses through heat transmission across the walls (D_t)
- Losses due to air renewal (D_r)

It is thus:

$$D = D_t + D_r \quad (W) \qquad \text{(III.1)}$$

Heat transmission losses D_t

$$D_t = [\sum(K.A) + \sum(K.L)](t_i - t_e) \qquad (W) \qquad \text{(III.2)}$$

with

K: heat transmission coefficient of the wall in W/m² .K

A: interior surface area of the wall in m².

k: linear transmission coefficient of each connection in W/m.K.

L: interior length of the connection in meters.

ti: indoor temperature of the space in °C.

te: outdoor temperature in °C.

Losses due to air renewal D_r

$$D_r = 0.34\ n\ V(t_i - t_e) \qquad (W) \qquad \text{(III.4)}$$

with

V: Volume of the space in m³.

n: air exchange rate.

0.34: corresponds to the specific heat capacity of air [Wh/m³.K].

1.3 Calculation of the volumetric heat loss coefficient of a building

To compare the thermal quality of two buildings, the volumetric heat loss coefficient, called "G coefficient," is used. It is given by the following relationship:

$$G = \frac{\sum d}{Vh} \quad in \ \left(\frac{w}{m^3 °C}\right) \qquad \text{(III.5)}$$

Σd : Sum of the building's thermal losses for a 1°C temperature difference between the interior and exterior.

Vh: The livable volume after subtracting the walls, floors, partitions, and ducts.

1.4 Principle of degree-days

Energy consumption is linked to the temperature difference between the indoor environment and the building's exterior. However, temperatures vary from one location to another. The concept of "Degree-Days" was introduced to determine the amount of heat consumed over a given period and to facilitate comparisons between buildings in different climatic zones. The principle involves adding up, day by day, the temperature differences between the indoor and outdoor environments. For example, if the average temperature inside is 20°C and outside is 5°C, we would have 15 degree-days. Similarly, 3 days at 0°C outside would be counted as 60 Degree-Days. By summing up all the temperature differences between inside and outside over all the days of the heating period, you get a number proportional to the building's heat requirement: The Degree-Days for that location.

In general, the number of Degree-Days for a heating period is equal to the product of the number of days heated multiplied by the difference between the average indoor temperature of the considered space and the average outdoor temperature.

DJ = Number of heated days x (Average indoor temperature - Average outdoor temperature).

What is a "daily average temperature"? A building has a certain inertia. Therefore, its heating requirement has been considered proportional to the daily average temperature (rather than the coldest temperature of the night). It has been agreed to use the arithmetic average between the nighttime minimum temperature and the daytime maximum temperature as a reference. For example, if the minimum temperature is -5°C at 3:00 AM and the maximum temperature is +7°C at 3:00 PM, it would be recorded as a day with a daily average temperature of 1°C.

1.5 Calculation of heat losses according to the DIN 4701 method

To establish consistent foundations for the design of local heating surfaces and the total heating power to be installed, the method for calculating heat requirements has been standardized under "DIN 4701". The standard simultaneously compiles essential calculation values, such as indoor and outdoor temperatures, coefficients "K" for various types of wall, floor, and window constructions, and values for air infiltrations through doors and windows.

1.5.1 The heat requirements for transmission losses " Q_T"

The standard 4701 makes a distinction, for a specific space, between heat losses through transmission "$\mathbf{Q_O}$" and corresponding heat requirements "$\mathbf{Q_T}$" for these same losses. "$\mathbf{Q_T}$" can be expressed as follows:

$$Q_T = Q_O\,(1+Z_u+Z_A+Z_H) \qquad \text{Kcal/h} \qquad \text{(III.6)}$$

with :

Z_u: Enhancement factor for heating system shutdown.

Z_A: Enhancement factor for compensation for cold exterior surfaces.

Z_H: Enhancement factor for orientation.

Q_O: Heat losses through transmission.

$$Q_0 = \sum q_0 \qquad \frac{\text{Kcal}}{\text{h}} \qquad \text{(III.7)}$$

$$q_0 = K.S.(t_i - t_e) \qquad \text{(III.8)}$$

q_o: Represents heat losses through transmission for each envelope surface of a space releasing heat, measured in [Kcal/h].

K: The overall heat transmission coefficient in [Kcal/m².h.°C].

S: The surface area of the construction element in [m²].

ti: The indoor temperature in [°C].

te: The temperature outside or in the adjacent space in [°C].

The enhancement factor "Zu" for heating system shutdown:

This coefficient takes into account the additional heat quantity needed to raise the indoor temperature of a building after a certain period of heating system shutdown. It is important to distinguish between the following three modes of operation:

Mode of Operation I: Continuous operation 24/24, such as residential buildings, hospitals, nursing homes, etc.

Mode of Operation II: Daily interruption of heat supply for a duration of 8 to 12 hours, such as offices, stores.

Mode of Operation III: Daily interruption of heat supply for a duration of 12 to 16 hours; this mode is recommended for social-cultural buildings and factories.

The enhancement factor "Z_A" for compensating cold exterior surfaces:

Since human comfort in a space depends not only on the air temperature but also on the average temperature of the space's envelope, rooms with exterior walls containing large windows behave less favorably in terms of thermal comfort than other walls that are thick or have small windows.

Combining the enhancements "Z_A" and "Z_u"

Both enhancements depend on the coefficient "D," which expresses the average permeability of all elements in the envelope of a space. The coefficient "D" of a space is calculated using the formula:

$$D = \frac{Q_0}{S_{tot}(t_i - t_e)} \qquad \text{(III.9)}$$

S_{tot}: is the total surface area of all envelopes in the spaces, including exterior walls with windows, interior walls with doors, floors, and roof. By calculating the coefficient "D" and considering the mode of operation, we find the unique enhancement "Z_D," which is equal to:

$$Z_D = Z_u - Z_A \qquad \text{(III.10)}$$

Coefficient "D"				
Mode of operation	0.1 à0 .29	0.30 à0.69	0.70 à 1.49	1.5
Reduced operation	7	7	7	7
Shutdown for 8 to 12 hours	20	15	15	15
Shutdown for 12 to 16 hours	30	25	20	20

Table 01 *The enhancement coefficient* Z_D in % *[13]*

The enhancement factor 'Z_H' for orientation

The coefficient "Z_H" takes into account the differences in sunlight exposure on the facades of the space. The values of "ZH" are provided in the following table:

Orientation	S	SO	O	NO	N	NE	E	SE
Enhancement Z_H	-5	-5	0	+5	+5	+5	0	-5

Table 02 *The enhancement coefficient* Z_H in %

1.5.2 The heat requirements for ventilation losses

The quantity of air that enters a space due to wind through the gaps in closed doors and windows depends on the dimensions of the non-sealed areas of the building parts exposed to the wind and the pressure differences between the outside and the inside. The heat requirements to compensate for ventilation losses Q_L can be calculated using the equation:

$$Q_L = \sum(a.l).R.H.(t_i - t_e)Z_E \qquad \text{(III.11)}$$

a : The permeability of windows and doors exposed to the wind, the values of "a" in [m³/h] are provided in the following table:

Types of openings		**a**
Windows: Wood & Synthetic Materials	Single windows	3
	Compound windows	2.5
	Double windows and single windows with guaranteed tightness	2
Windows: Steel & Metal Materials	Single windows	1.5
	Compound windows	1.5
	Double windows and single windows with guaranteed tightness	1.2
Interior doors	Non-sealed (without threshold)	40
	Sealed (with seuil)	15

Table 03 *The permeability of windows and doors exposed to the wind. [13]*

l : The length of the joints of windows and doors exposed to the wind, "l" in [m].

The characteristic of the space R

	Windows Wood & Synthetic Materials		**Windows Steel and Metal Materials**	
	Interior doors		**Interior doors**	
Characteristic of the space R	**Sealed**	**Non-sealed**	**Sealed**	**Non-sealed**
	< 1.5	< 3	< 2.5	**< 6**
	1.5….3	3….9	2.5….6	**6….20**

Table 04 *SE/SP surface ratio for different types of openings [13]*

- **SE:** Wind-exposed surfaces of windows and exterior doors.

- **SP:** Surfaces of doors facing the wind..

- For sliding doors, we can always set R=1

The building characteristic H is given in the table for various types of constructions and wind influences.

Regions	Sites	Row house	Detached house
Regions with moderate winds	Protected site	0.24	0.34
	Exceptionally site	0.41	0.58
	Exceptionally exposed site	0.60	0.84
Regions with strong winds"	*Protected Site*	0.41	0.58
	Exceptionally Site	0.60	0.84
	Exceptionally exposed site	0.82	1.13

Table 05 *The building characteristic H*

Concerning the location of a space in relation to the action of the wind, three cases are distinguished:

Protected site: this is the case of densely constructed city centers.

Exposed site: this is the case of tall houses that significantly exceed their surroundings. *Exceptionally exposed site*: this is the case of isolated houses built on elevated areas on coastal strips without trees.

Ze: enhancement for corner windows **Ze = 1.2**, for single windows **Ze = 1**.

And finally, we find the heating requirements of a building:

$$\varphi_{tot} = \varphi_T - \varphi_L \qquad \frac{Kcal}{h} \qquad \text{(III.12)}$$

1.6 The summer thermal balance of a building

For summer, it is necessary to know not only the temperature but also the humidity of the outdoor air as well as the intensity of solar radiation based on various parameters (climatic zone, month, and time of day). To conduct the thermal balance of a space for the summer period, all internal and external heat gains must be taken into account.

1.6.1 External contributions: these contributions are due to three factors

a. air infiltration (hot outdoor air)
b. sunlight
c. thermal inertia of the building.

1.6.1.1 Contributions through the transmission across the walls Qt:

The quantities of heat that penetrate inside through the walls and roofs are given by the fundamental equation of heat transmission:

$$Q_t = K.S.(t_{e-} - t_i) \qquad \frac{Kcal}{h} \qquad \text{(III.13)}$$

This equation allows determining the amount of heat transmitted through internal walls and the floor. Regarding external walls, determining the transmitted flux is much more difficult. The difficulty in the calculation arises from the fact that the external temperature "**te**" varies periodically, as does solar radiation, which is also subject to periodic fluctuations.

This variation influences the surface temperature of the external wall, which fluctuates approximately with a certain amplitude Φ. This periodic variation propagates inside the wall but with a certain time lag, meaning that the maximum temperature always occurs later by a certain time (concept of thermal inertia). Materials that cause a significant delay, such as concrete, solid brick, and stone, have high values of density and thermal capacity (ability to store heat before transmitting it).

For this purpose, the **'concept of equivalent external temperature'** has been introduced for the calculation of the quantity of heat through external walls:

$$Q_w = K.S.\Delta t_{eq}.cor \qquad \frac{Kcal}{h} \qquad (III.14)$$

Q_w: is the heat contribution at time Z**.**

K: is the heat transmission coefficient.

S: are the surfaces of the walls and roof.

Δt_{eq}.cor: corrected equivalent, calculated as follows:

$$\Delta t_{eq}cor = \Delta t_{eq} + (t_{em} - 24.5) + (26 - t_i) + a_T \qquad \frac{Kcal}{h} \qquad (III.15)$$

where :

Δt_{eq}: the temperature difference that takes into account the intensity of solar radiation at different times of the day, exposure, and the mass of the wall.

t_{em}: is the actual average temperature of the outdoor air.

ti: temperature of the air in the room

a_T: correction due to the disturbance factor.

a_T = -1.5°C for an industrial atmosphere.

1.6.1.2 Contributions through glazed surfaces Qvi:

1.6.1.2.1 Solar radiation contributions Qs:

When solar radiation with intensity I strikes a glass pane, part of the radiation **It** passes through: **It = εt . I** where **εt**: transmittance coefficient of the glass alone, another part Ir is reflected: Ir = r.I where r: reflection factor; finally, the remaining part **Ia** is absorbed by the glass and then transmitted to the air by convection: **I a = a . Ia** being the absorption coefficient of the. In total, therefore:

$$I = \varepsilon t.\ I + r\ .\ I + a.\ I \qquad (III.16)$$

The amount of heat Qvi radiated at a given moment through a glazing is calculated according to the equation:

$$Qvi = SS.\ I + (S - SS)\ Idiff \qquad Kcal/h \qquad (III.17)$$

SS: is the sunlit glazed area in m2

S: is the total glazed area in m2

I: is the total solar radiation through an unprotected single window at time Z in [Kcal/h.m2].

Idiff: is the diffuse radiation at time Z for the North direction in [Kcal/h.m2].

In reality, windows in air-conditioned spaces are generally equipped with sun protection devices. This allows for a corresponding reduction in external gains from solar radiation. Therefore, the heat quantity Q'vi radiated through a protected glazed surface will be:

$$Q'vi = [S_S.\ I + (S-S_S)I_{diff}].b \qquad Kcal/h \qquad (III.18)$$

b: Permeability factor for the main sun protection devices for windows.

1.6.1.2.2 Contributions by QTV transmission:

It is a heat gain that enters the room through the windows as a result of temperature difference between inside and outside and is calculated according to the general equation:

$$QTV = K.\ S.\ (te - ti) \qquad Kcal/h \qquad (III.19)$$

K: is the heat transmission coefficient of the glass.

S: is the total surface of the glass.

te: is the outside temperature.

ti: is the indoor temperature.

So the contributions through the windows will be:

$$Q_V = Q_S + Q_{TV} \qquad Kcal/h \qquad (III.20)$$

1.6.3 Solar protection

► Solar protection by glazing:

There are special glazings that reduce the amount of heat transmitted to the interior by absorbing or reflecting the incident solar radiation. Care should be taken to ensure that the transparency of the glazing is not too reduced, otherwise the brightness behind such glazing would be lower than that behind normal glazing. The most interesting glasses are those for which the transparency index is as high as possible, and the solar transmittance coefficient is as low as possible.

► Solar protection by special devices:

Protection can be achieved using various lightweight materials such as wood or metal (louvered shutters), and sunshades made of concrete or masonry are all means of shading the South, East, and West facades, possibly the North for low latitudes in the Sahara. There are three types of architectural forms for sun protection.

*** Breeze – horizontal sun:** it is an effective protection for South, South – East and South - West orientation.

Figure 01 : *Breeze devices – horizontal sun [13]*

*** Breeze – vertical sun:** this type is well recommended for East – West oriented windows

Figure 02 : *Breeze Devices – Vertical Sun [13]*

*** Honeycomb:** It is a combination of vertical and horizontal sunshades

Figure 03 : *Breeze devices – vertical and horizontal sun [13]*

III.2 Heat production

2.1 The heat pump (HP)

A heat pump is a device that transfers thermal energy (heat) from a low-temperature medium (cold source) to a high-temperature medium (hot source). This device reverses the natural direction of spontaneous thermal energy transfer.

Depending on the direction of the pumping device, a heat pump can be considered either as :

- a heating system if one wishes to increase the temperature of the hot source;
- or as a refrigeration system if one wishes to lower the temperature of the cold source.

2.2 The operating principle of a heat pump

The calories present in the air, soil, and groundwater are a constantly available, free, and renewable energy source thanks to solar radiation, winds, and precipitation.

The heat pump can extract this omnipresent heat and raise it to a higher temperature level in homes for heating purposes.
A heat pump consists of 4 main elements:

- A compressor,
- An exchanger to capture energy outside (evaporator),
- A second exchanger to return it inside (condenser),
- A regulator.

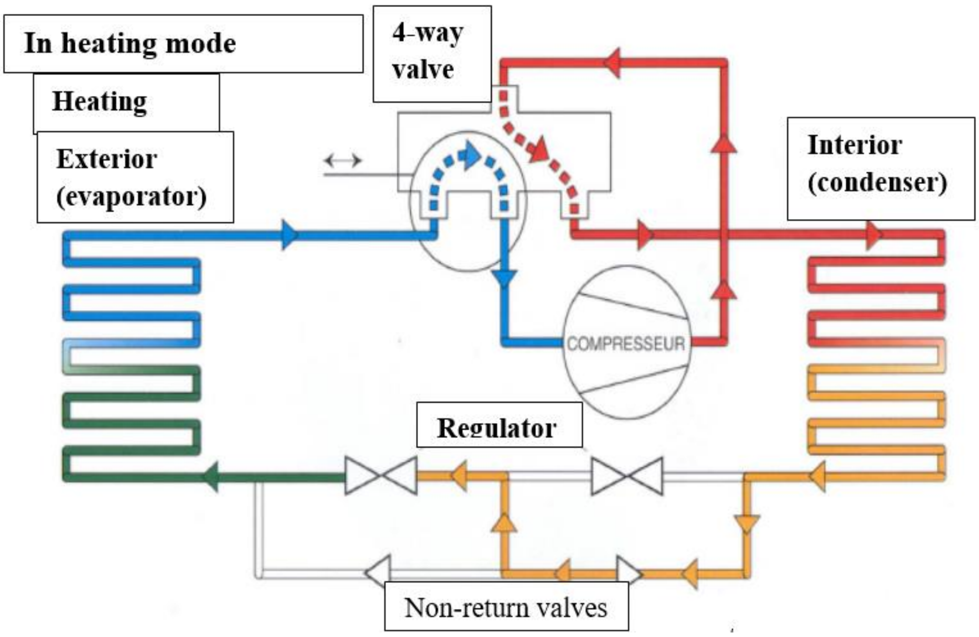


Figure 01 : *heat pump cycle diagram [7]*

The heat pump allows for:

- Extracting energy from the external environment (ground/water/air) through the evaporator.
- Increasing the temperature level of this thermal energy via the compressor.
- Transferring this energy to the desired temperature level inside the space that needs heating.

2.3 The efficiency of a heat pump

- In air conditioning, the minimum energy performance of cooling installations is expressed in terms of Energy Efficiency in cooling mode.

$$\mathrm{EER} = \frac{\text{The total cooling power}}{\textit{Absorbed electrical power}} \qquad (01)$$

- In heating, the term used is the Coefficient of Performance (COP) in heating mode.

$$\mathrm{EER} = \frac{\text{The total heating power}}{\textit{Absorbed electrical power}} \qquad (02)$$

2.4 The theoretical maximum efficiency of a heat pump is the Carnot COP.

This is the maximum efficiency of the thermodynamic cycle.

With η depending on the performance of the heat pump (surface and type of heat exchanger, type of heat transfer fluid...). But the COP of the Carnot cycle is not constant.

$$\mathrm{COP_{carnot}} = \frac{\mathrm{T_{exterior}}}{\mathrm{T_{exterior}} - \mathrm{T_{interior}}} \qquad (03)$$

So :

- The performance of a heat pump depends on external conditions.
- It is advisable not to demand too high or too low temperatures from the heat pump.

2.5 EER of an air conditioning

The Energy Efficiency Ratio (EER) represents the energy performance of an air conditioner, but it varies depending on external temperatures and setpoint temperatures. A more relevant coefficient is the European Seasonal Energy Efficiency Ratio (ESEER), which is an annual seasonal coefficient. It is calculated using a formula that takes into account EER values at different power regulation percentages for a unit, based on a duration of time for each of them.Plus les EER et ESEER sont élevés, plus la consommation énergétique sera faible.

2.6 Global Warming Potential (GWP) of refrigerants.

The GWP is an indication of the harmfulness of a gas in relation to the greenhouse effect

Molecule	CO_2	Méthane	Propane	R22	R143a	R410a	R407c	Ammoniac	water
GWP	1	23	3	1700	1300	1980	1650	0	0

2.7 The different types of heat pumps

HP WATER/WATER : The heat source and the heat transfer fluid are water.

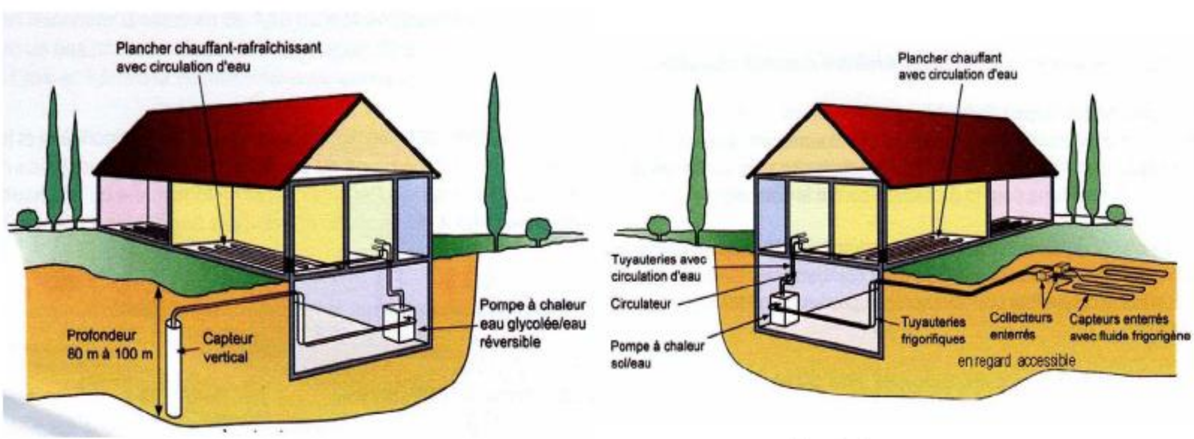


Figure 2 : *HP water/water [20]*

a) **HP AIR/WATER** : "The heat source is the outdoor air, while the heat transfer fluid is water.

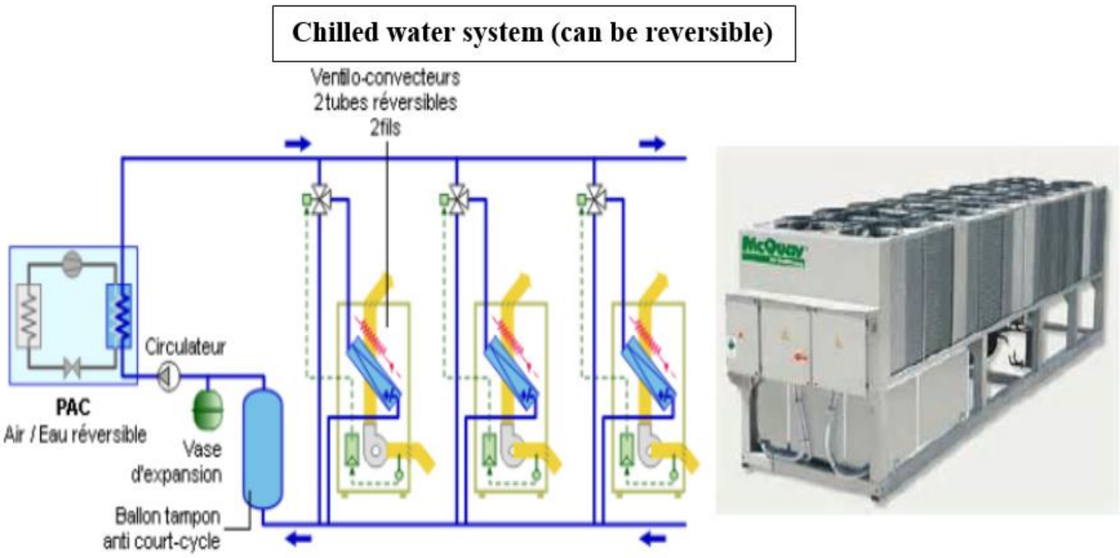


Figure 3 : *HP air/water [20]*

b) **HP AIR/AIR** : The heat source and the heat transfer fluid are air. *[20]*

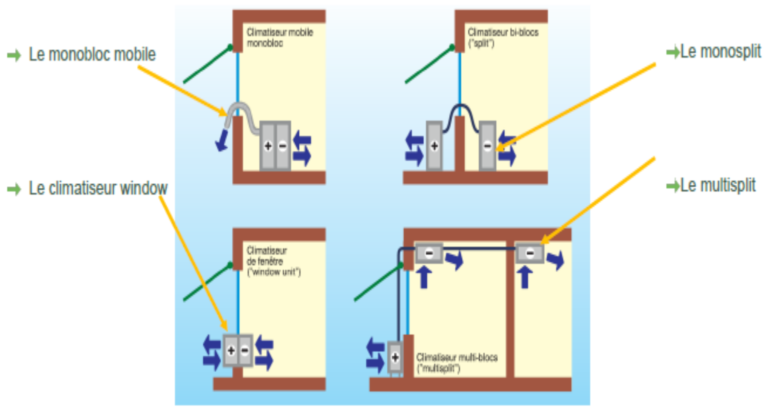


Figure 4 : *HP air/air [20]*

c) The geothermal heat pump

A geothermal heat pump allows extracting heat from the ground to heat the water in the heating and sanitary circuit. This installation is a bit more complex to implement. It requires deploying a vast network of heat exchangers underground, either horizontally or vertically. More challenging to install and more expensive, this system, however, has the advantage of providing better efficiency throughout the year. Beyond a certain depth, the temperature in the ground varies very little, regardless of the season.

d) The hydrothermal heat pump

Less common, the water-water heat pump operates on the same principle as a geothermal heat pump. The difference lies in the fact that it extracts heat from groundwater, at the level of water tables. It is also a very efficient solution.

2.8 The regulatory minimum performances

category	Mode of operating	Split and Multi-Spring air conditioning	Single-block air conditioning
Air condensing air conditioners	cooling	EER > 2.8	EER > 2.6
	heating	COP > 3.2	COP > 3.0
Air conditioning with water condensation	cooling	EER > 3.1	EER > 3.8
	heating	COP > 3.2	COP > 3.0

Chapter 4:
General Principles in Air Conditioning

IV.1 Calculation of Thermal Loads

1.1. Introduction

The calculation of the air conditioning or air conditioning thermal balance makes it possible to determine the power of the installation that will meet the requested criteria. This calculation will be made on the basis of the actual gains, that is to say at the time when the calorific inputs reach their maximum in the local. One can distinguish:

- Internal loads: these are sensitive and/or latent heat releases having their sources inside the room (occupants, lighting and other equipment),

- External loads: these are the inputs of sensitive heat due to sunlight and conduction through external walls and roofs.

1.2. Calculation of an Air Conditioning Thermal Balance

Before starting the calculation of the thermal balance, it is necessary to be aware of all the factors that could affect its assessment. Accurate, detailed, and comprehensive measurements form the foundation of the balance. It is through the understanding of these elements and careful analysis of the balance that one can determine the most economical and efficient installation, considering the desired results. Taking these various parameters into account helps avoid the use of safety factors in the assessment of balances, which can lead to the oversizing of air conditioning equipment.

Below are the main elements to consider:

- ❖ Orientation of the space: position of the spaces to be conditioned in relation to:
    - Cardinal points, geographical location (latitude, longitude), climate,
    - Nearby buildings casting shadows,
    - Reflective surfaces: water, sand, parking, etc.
- ❖ Architectural plans, details showing the internal structure of the building, hand sketches.
- ❖ Dimensions of the space: length, width, ceiling height.
- ❖ Construction materials: nature of materials, thickness of walls, roofs, ceilings, floors.
- ❖ Colors of materials: colors of walls and roof.
- ❖ External conditions of the space: adjacent conditioned or non-conditioned spaces, temperature of non-conditioned spaces, floor on ground or on crawl space, maximum sunlight exposure of the space.
- ❖ Conditions to be maintained inside the space (temperature and relative humidity).

- ❖ Purpose of the space: office, hospital, shop, store, workshop, etc.
- ❖ Windows: dimensions and locations, wood or metal framing, type of glazing, type of blinds, dimensions of awnings and projections.
- ❖ Doors: location, type, dimension, frequency of openings.
- ❖ Occupants: activities and numbers, duration of occupancy of the space.
- ❖ Household appliances, motors: location, rated power; duration of operation.
- ❖ Location of equipment and distribution network (layout of water pipes and air ducts).

1.3. Calculation of calorific inputs

Below, we present a simplified calculation method to determine the calorific inputs in a room.

1.3.1 The simplified calculation of the thermal balance

a) External loads

Heat gain through transmission across exterior surfaces (walls, roof, ceiling, and floor) and windows.

$$Q_{Str} = U.\ S.\Delta\ \theta \qquad \text{IV.1}$$

• U = Thermal transmission coefficient of the considered wall or window in W/m²°C

• S = Surface area of the considered wall or window (total area of the opening corresponding to the recess in the wall) (m²)

• Δθ = Temperature difference between the two faces of the considered wall [°C] (exterior-interior).

✓ **Heat gain from solar radiation through the walls**

The amount of heat crossing the wall [Q_w] :

$$Q_{SRw} = \alpha.\ F.\ S.\ R_w \qquad \text{IV.2}$$

α: Coefficient of absorption of the wall receiving the radiation.

S: Surface area of the walls in m²

F: Solar radiation factor

R_w : Solar radiation absorbed on the surface of the wall in W/m²

The absorption coefficient **'α'** depends on the color and nature of the wall.

The radiation factor **'F'** indicates the portion of heat absorbed by the surface and transmitted through the wall of the space.

The value of solar radiation **'R_w'** on a wall depends on:

- The latitude under which the space is located,
- The orientation of the wall,
- The time for which the calculation will be performed.

✓ **Heat gain from solar radiation on the glazings (windows)**

The amount of heat passing through the glass (Q_g) :

$$Q_{SRg} = \alpha .\ g.\ S.\ R_g \quad [W] \qquad IV.3$$

α: Absorption coefficient of the glazing.

g: The reduction factor is a function of the method of window protection against solar radiation.

S: Glazed surface. (m^2)

R_g: Intensity of solar radiation on the windows W/m^2.

- ✓ **Heat gain through air renewal and infiltration.**

The air renewal in an air-conditioned space is necessary for hygiene reasons. It is generally achieved through ventilation (natural or mechanical) of the spaces as well as through infiltration, introducing outdoor air into the air-conditioned space. It is a source of sensible and latent heat gain in the conditioned space.

Sensible heat gains through air renewal:

$$Q_{Sr}= q_v.\ (\theta e-\theta i)\ .\ 0{,}34\ (W) \qquad IV.4$$

Latent heat gains through air renewal:

$$Q_{Lr}= q_v\ .\ (\omega e-\omega i)\ .\ 0{,}84\ (W) \qquad IV.5$$

***qv*:** outside air renewal flow rate [m^3/h]

- if ventilation is natural, air renewal can be considered as equal to one room volume per hour (1 vol/h),
- if ventilation is mechanical, air renewal can be considered as (1.5 vol/h),

***θe*:** base outdoor temperature

***θi*:** base indoor temperature

***ωe*:** outdoor air moisture content in g/kg dry air

***ωi*:** indoor air moisture content in g/kg dry air

b) Internal loads

Heat gain from occupants is given based on the indoor temperature and the level of activity. There are two types of gains generated by occupants:

Sensible heat gains from occupants : $Q_{Soc}= n.\ C_{Soc}$ [W] IV.6

Latent heat gains from occupants.: $Q_{Loc}= n.\ C_{loc}$ [W] IV.7

n = Number of occupants.

C_{Soc}= Sensible heat from occupants. (W)

C_{Loc}= Latent heat from occupants. (W)

- ✓ **Heat gain from lighting**

It constitutes a source of sensible heat and depends on the type of lamp :

Fluorescent lamp $Q_{Secl.} = 1{,}25\ P$ [W] IV.8

Incandescent lamp $Q_{Secl.} = P$ [W] IV.9

• P = Lamp power [W]

In the case of fluorescent lamps, the additional 25% represents the heat generated by the electromagnetic ballast.

Heat gain from machines and equipment: Most devices contribute both sensible and latent heat. The heat gains from machines and equipment ($Q_{\_equip.}$). The values in these tables have been determined based on information from various manufacturers.

These gains should be reduced (by a weighting factor) based on their operating durations. For example, it is assumed that a device running only half an hour per hour releases half of its nominal electrical power as heat gain.

1.4. The total thermal loads

The total thermal balance (Q_T) is the sum of all external and internal loads. It is more practical to sum the sensible loads (Q_S) and latent loads (Q_L). Therefore:

$$Q_T = Q_S + Q_L \qquad \text{IV.10}$$

1.5. Total Sensible Loads

These are the sensible heat gains in the space, resulting from the temperature difference between the interior and the exterior; we have:

$$Q_S = Q_{Str} + Q_{SRw} + Q_{SRg} + Q_{Sr} + Q_{Soc} + Q_{Sécl.} + Q_{Séquip.} \qquad \text{IV.11}$$

Total Latent Loads: These are the contributions of latent heat due to the difference in the quantity of water vapor contained in the outdoor and indoor air.

$$Q_L = Q_{Lr} + Q_{Loc} + Q_{Léquip} \qquad \text{IV.12}$$

IV.2 Air Conditioning Systems and Distribution Networks

2.1. Introduction

In summer, an air conditioning system should maintain the room temperature 5 to 6 °C below the outdoor temperature and the humidity level at an acceptable level (65%), depending on external conditions.

For aesthetic and noise reasons, it is crucial to carefully choose the location of the outdoor unit to avoid inconveniencing neighbors who may complain and force you to relocate the heat pump. It should not be placed in a heavily sunny area, as the condenser may struggle to dissipate heat.

There are several ways to classify air conditioning systems; typically, four product families are distinguished:

- Direct expansion systems;
- Air-to-air systems;
- All-water systems;
- Water loop heat pump systems.

2.2. Direct Expansion Systems

The direct expansion air conditioner produces cold air by extracting heat from indoor air; it cools it and can discharge it outside. The refrigerant fluid of the machine circulates in the heat exchangers in contact with indoor air (evaporator) and outdoor air (air condenser).

On the evaporator, the air-cooling leads to the formation of condensates. Their evacuation is necessary; it can be done by gravity when the evaporator is positioned above a drainage point. Alternatively, some air conditioners are equipped with a mini lifting pump allowing the evacuation of condensates.

This category includes several devices.

2.2.1 The components of air conditioning systems

Cooling a building can be done in several ways. If the needs are occasional or localized, the owner may use low-power devices to independently cool each room.

This type of air conditioning is called decentralized and involves individual air conditioners. If the needs are overall and regular, the owner will prefer one or more higher-power devices cooling all or part of the building with varying degrees of independence between different zones.

This type of air conditioning is called centralized. The following diagram illustrates a centralized system.

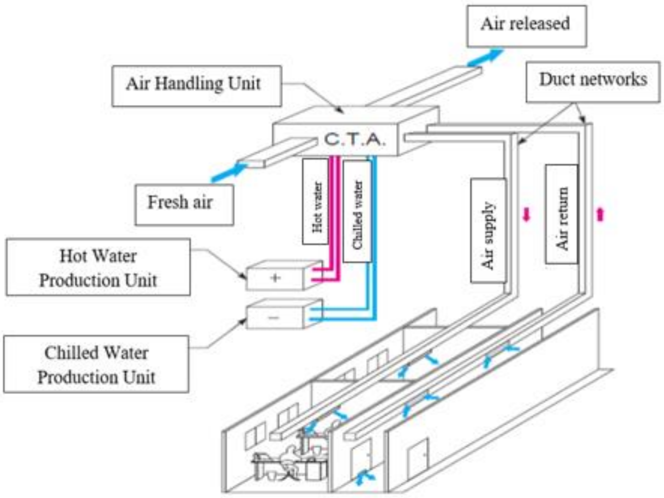


Figure 01. *Centralized System [7]*

2.2.1.1 Air Filtration

The increased reliability and reduced costs of variable speed offer significant potential for savings in ventilation and water circulation. However, this trend is counteracted by the growing importance of indoor air quality, which can result in increased minimum airflows, enhanced filtration, and consequently, rising energy expenses.

The efficiency of air filters is evaluated using different methods based on their effectiveness and the reference standard used. The most commonly used methods that directly identify the required filter type based on recommendations include:

- According to standard EN 779
- According to Eurovent 4/5
- According to standard Pr EN 1822

	Standard EN 779	**Eurovent 4/5**	**Average Efficiency (yield) %**
Filter bank	Class	Class	
Gravimetric Coarse Δp max : 250 Pa	G1 G2 G3 G4	EU1 EU2 EU3 EU4	Am*<65 65≤Am<80 80≤Am<90 90≤Am
Fine **Opacimetry** Δp max : 450 Pa	G5 G6 G7 G8 G9	EU5 EU6 EU7 EU8 EU9	40≤Em*<60 60≤Em*<80 80≤Em*<90 90≤Em*<+95 95≤Em
	Standard pr EN 1822		**Overall efficiency MPPS***

HEPA	H10-H11-H12-H13-H14		
ULPA	H15-H16-H17		99,9995 99,99995 99,999995
Am Em MPPS HEPA ULPA	Filter efficiency (weight retention proportion) Opacimetry filtration efficiency Penetrating particle efficiency High Efficiency Particulate Air (HEPA) Ultra Low Penetration Air (ULPA)		

<u>The filtration must ensure:</u>

- Protection of the air handling unit (AHU) against fouling and microorganism development: Required AHU inlet: F6 (65% ASHRAE); Preferred: F7 (85% ASHRAE).
- Protection of the air distribution ductwork and its terminals: AHU outlet: High-efficiency filters: F9 (95% ASHRAE).
- Air treatment to guarantee the cleanliness class:
    - Zone 2: F9 (95% ASHRAE) sufficient at the AHU outlet or in the duct.
    - Zones 3 and 4: Very high-efficiency filters (absolute filters) H13 (99.95% DOP), preferably located at the entrance of the treated room.
- Protection of the return ductwork: F6 (65% ASHRAE)
- Monitoring of filter clogging is ensured by measuring the pressure drop (pressure sensor – Pitot tube) to guarantee timely replacement and: Maintain airflow; Maintain local pressure levels.

Protect very high-efficiency filters (lifespan: 3 to 5 years)

Figure 02 : *Filter clogging measurement [7]*

The choice of the filter class can be based on the following indications:

Class	Applications
G1 ou G2	For example, for garage unit heaters, where filtration doesn't need to be very advanced, or if finer filters cause issues with pressure drop.

G3 ou G4	For fan coil units,
M5 ou M6	for easily cleanable spaces without dust-sensitive objects: exhibition halls, sports halls, swimming pools.
F7	offices, conference rooms, libraries, museums, classrooms, laboratories, kitchens and restaurants.
F8 ou F9	computer rooms, hospitals (areas housing patients, excluding operating rooms and other 'clean' or sterile areas).
H10 à H14	for controlled contamination rooms: laboratories requiring very pure air, operating or sterilization rooms, cleanrooms, nuclear facilities.
U15 à U17	Sterile rooms, cleanrooms, nuclear facilities,...

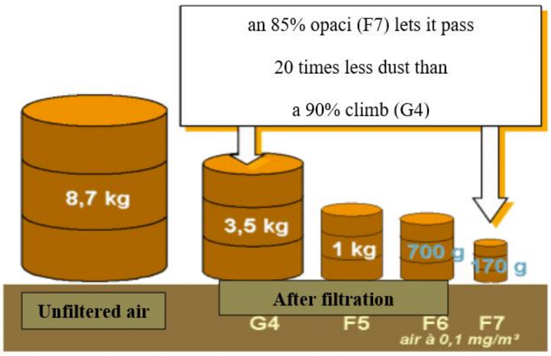


Figure 03 : *Filter model [7]*

2.2.1.2 Cooling and heating Batteries

The hot battery provides preheating or heating of the air (using hot water, shielded resistances, or bare wires). The cold battery provides cooling, with or without dehumidification (using cold water or a refrigerant).

The battery is composed of multiple tubes onto which fins are crimped or welded. The tubes form several parallel circuits, connected by a distributor and a collector, to limit pressure drop and enhance the efficiency of the battery.

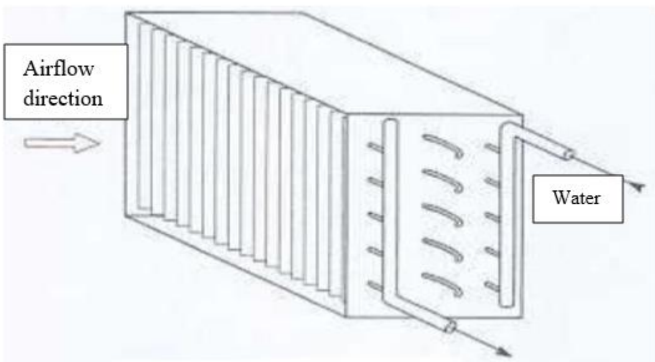


Figure 04 *Battery with 5 circuits and 3 rows [7]*

The water inlet is connected to the collector located at the air outlet of the coil to achieve a counter-current system between air and water. Water inlets and outlets are often marked with nameplates to avoid any mistakes.

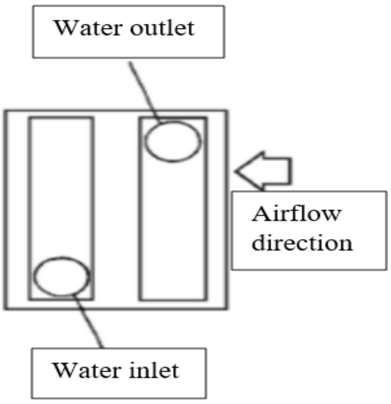


Figure 05 : *Battery unit [7]*

What is the benefit of working in countercurrent? The maximum power exchanged by the Battery is given by the formula:

$$p = k * S * \Delta\theta \quad \text{en kW}$$

K = The heat exchange coefficient (in W/m²·K) provided by the battery manufacturer

S = Battery exchange surface (m²)

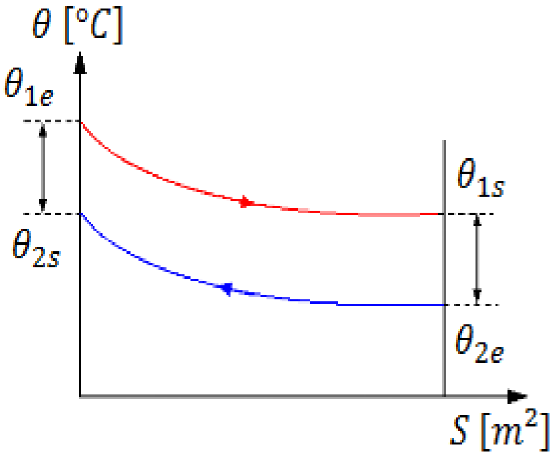


Figure 06 : *The temperature evolution in a parallel flow heat exchanger*

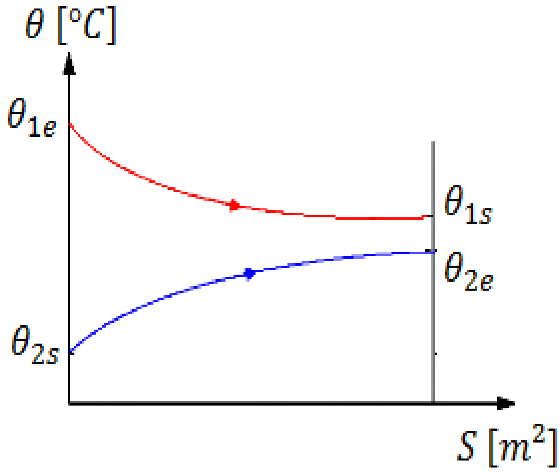


Figure 07 : *The temperature evolution in a counter-current heat exchanger [7]*

2.1.1.3 Humidifiers

An humidifier is used to increase the water content of the treated air, that is, to increase the absolute humidity. For humidification to occur, there must be close and intensive contact between the air and the moisture source. This moisture source can be either sprayed water or steam. There are two main families of humidifiers: water scrubber (recycled water) and steam humidifiers. Various types of humidifiers include:

- ✓ Water humidifiers.

✓ Scrubber humidifiers.
✓ Evaporation humidifiers.
✓ Humidifiers with fixed nozzles and water spraying atomized by compressed air.
✓ Humidifiers with water spraying atomized by rotating nozzle.
✓ Humidifiers with water spraying atomized by centrifugation.

2.1.1.4 fans (ventilators)

A fan is a turbomachine capable of creating a pressure difference (less than 30000 Pa), allowing the flow of air between the upstream and downstream. The fan provides a significant portion of the mechanical energy it receives to the air. The total pressure loss related to the resistance of the distribution network to the flow of a given air volume is called the **"head loss"** of the network.

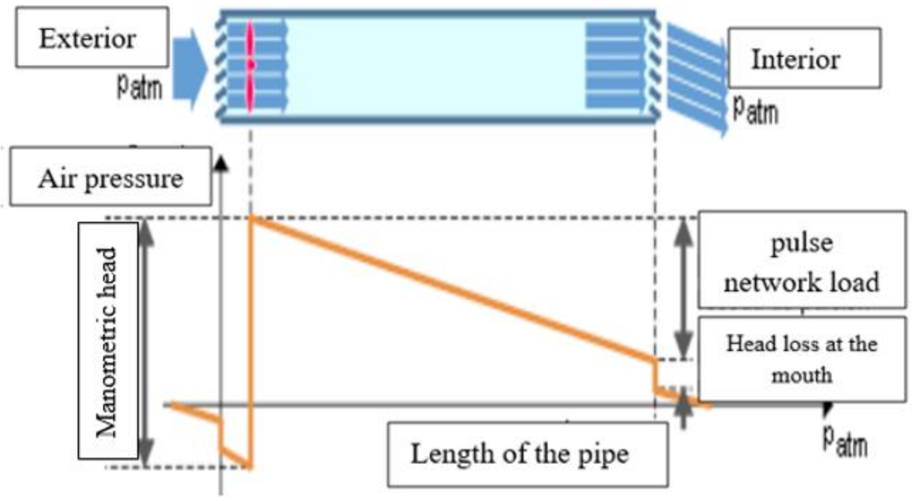
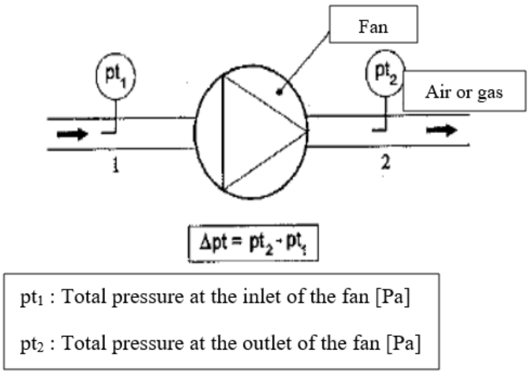


Figure 08 : *turbomachine fan [7]*

The total pressure difference Δpt is called the **"manometric head"** of the fan or **"fan head".**



If a fan is connected to a ventilation system, it will stabilize its flow rate at a value where the pressure it provides equals the resistance of the system. This point is the only possible operating point and corresponds to the intersection of the characteristic curves of the fan and the system. It defines the manometric head and flow rate provided by the fan when, operating at a given speed, it is connected to the considered network.

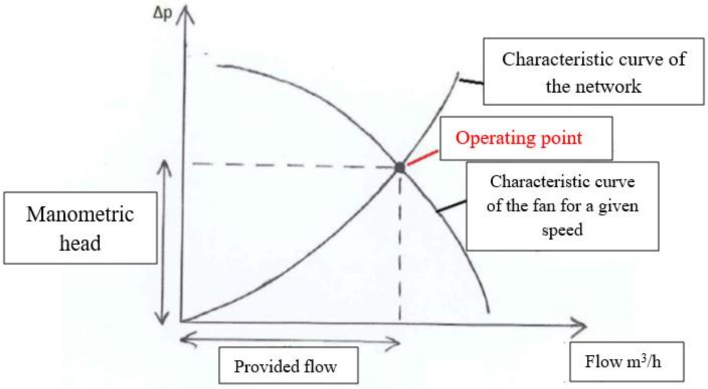


Figure 09 : *Fan characteristic [7]*

2.1.1.5 Types of Fans

Several classifications are possible. The most common classification is based on the trajectory of the air in the wheel. We distinguish between centrifugal fans, helical fans, and tangential fans.

helical

tangential

centrifugal

2.3 New and reject air grilles

They protect against rain and the entry of rodents or birds thanks to a metal grille.

The European standard EN 13779 defines certain provisions to be followed for outdoor air intakes:

- ✓ The preferential placement of the air intake is facing the prevailing winds.
- ✓ The sizing of the unprotected air intake is based on a maximum air velocity of 2 m/s.
- ✓ The main distances to be respected for the air intake (relative to the ground, pollutant sources, air discharge, etc.)

For air discharge grilles, the provisions to be respected are as follows:

- ✓ Air discharges must be more than 8 m from a neighboring building.
- ✓ Air discharges must be more than 2 m from a fresh air intake located on the same wall, preferably above it.
- ✓ The air flow per vent must not exceed 0.5 m^3/s, and the air velocity at the vent must exceed 5 m/s.

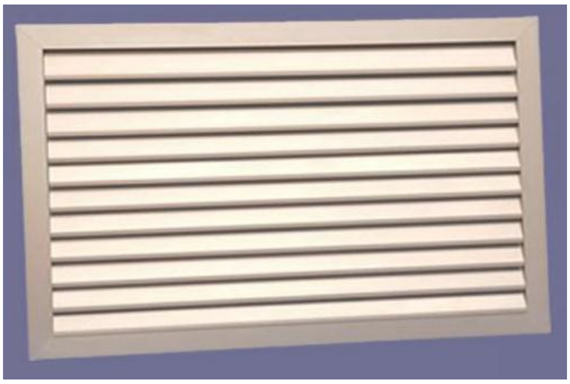


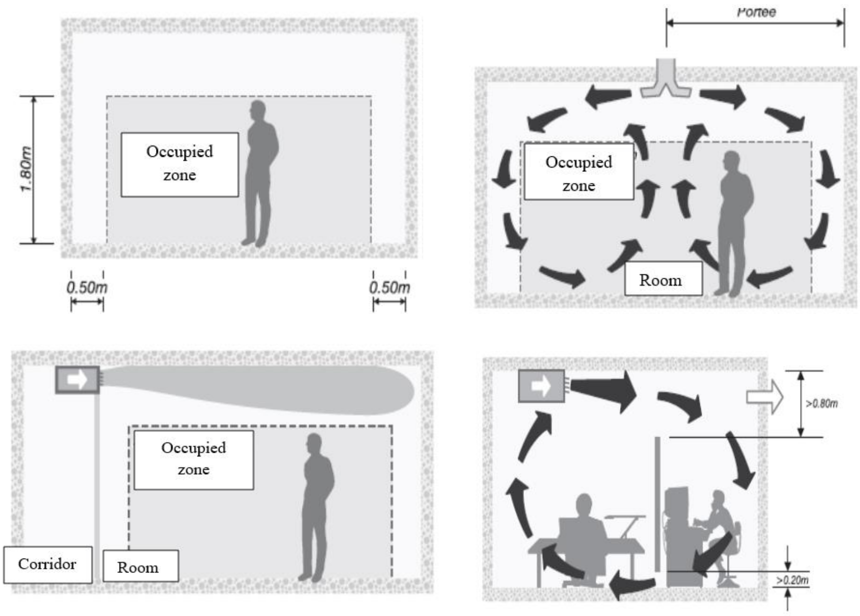
Figure 10 : *air grilles [7]*

For fresh air intakes, the recommendations are as follows:

- ✓ Do not place them above strongly sunlit dark horizontal surfaces, such as flat roofs covered with a black waterproof membrane, without protection.
- ✓ Maintain a horizontal distance of at least 8 meters from waste collection points, parking areas for three or more frequently used cars, loading areas, traffic zones, sewer openings, smokestacks, and other similar sources of pollution.

2.4 Position of the outlets

The movement of air in indoor spaces depends on the arrangement of supply and return air vents in relation to the occupants' locations. In practice, it is necessary for the air velocity to drop below a certain limit in the occupied zone (according to EUROVENT: European Association of Air Handling and Refrigerating Equipment Manufacturers). Under no circumstances should the air jet come into contact with occupants before it has mixed with the ambient air.



As for the supply and exhaust vents, the concept of throw comes into play.

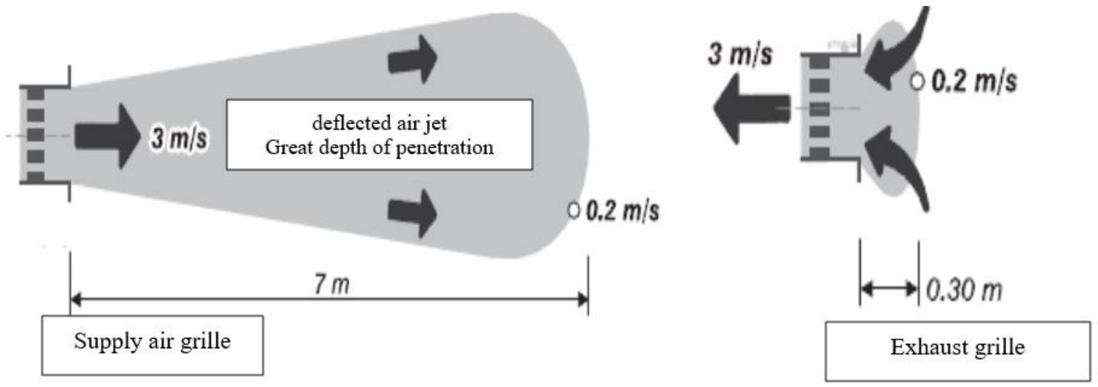


***Figure 11 :** supply and exhaust grille [7]*

For the exhaust vent, the air velocity is not critical for thermal comfort, but it can be important for acoustic comfort.

The position of the exhaust vent and recommended exhaust velocities.		
Above the occupied zone	4,5	m/s
In the occupied zone, away from the seats	3,5-4,5	m/s
In the occupied zone, near the seats	2,5-3,5	m/s
Door grilles	1,5-2	m/s
Under the doors	1-1,5	m/s

2.5 Air diffusion principles

Two principles of air distribution in a room are applied: **air distribution by mixing** and by **displacement**.

2.4.1 Air distribution by mixing: the air in the room is drawn in by the blown air jet.

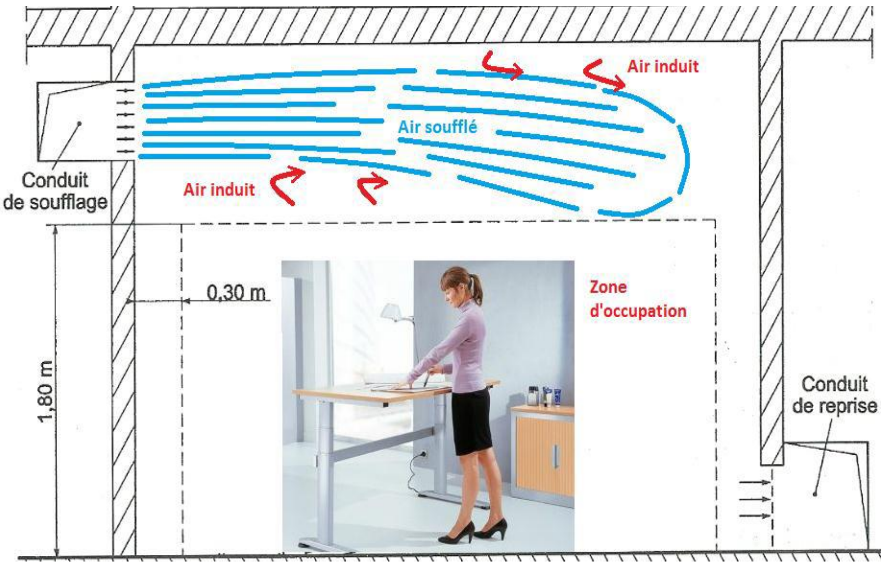


***Figure 12 :** Air distribution in a room. [7]*

2.4.2 Air distribution by displacement: air distribution by substitution for spaces that need constant cooling. The air is not distributed by dilution or induction, as in conventional systems where the air blown at the top mixes with the ambient air, causing a stirring of pollutants and heat released. Instead, it is distributed by **displacement**:

- ✓ Air is injected at the lower part of the spaces, at **a very low velocity** (0.12 to 0.30 m/s) and with **a very small blowing gap** (+/- 2 to 5°C).
- ✓ Due to **thermal buoyancy,** the air warmed by contact with occupants and other heat sources rises above the occupied zone (1 to 1.50m above the floor).
- ✓ It is filtered (minimum 50% opacimetric) and **drawn in at the ceiling** to be mixed with fresh air and processed in the central unit.

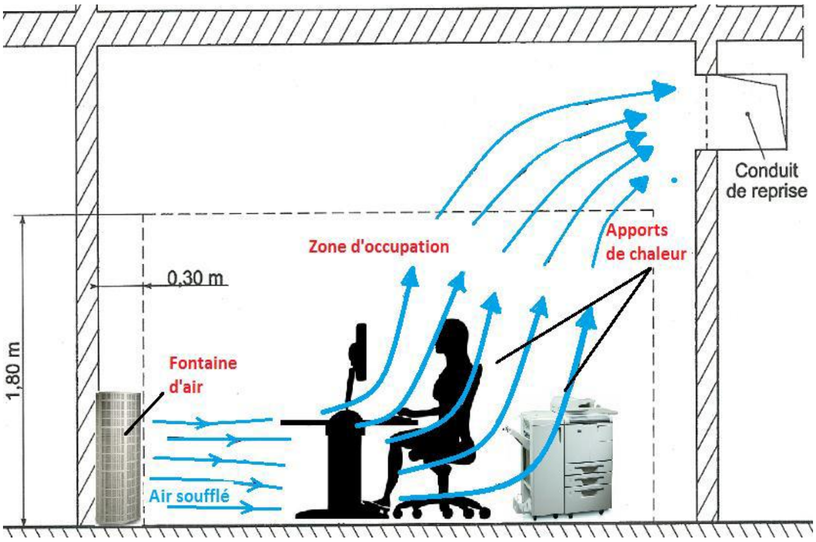


Figure 13 : *Air circulation. [7]*

The air quality is significantly improved, as harmful particles only traverse the space once (instead of **60 times** in dilution systems). Acoustic comfort is perfect due to very low blowing velocities (**NR 25**). The uniqueness of this technology lies in **the diffusion baffles**. Air displacement diffusers have a very large diffusion surface and a respectable height. Air is blown through a micro-perforated grille after passing through a sound attenuator and an expansion chamber. Air displacement systems are well-suited for **high-occupancy spaces, those with high heat dissipation, and large volumes, including:**

- Entertainment spaces: theaters, cinemas, auditoriums
- Public spaces: hotel lobbies and patios, cafes, and restaurants
- Industrial spaces: laboratories, kitchens, clean rooms
- Healthcare facilities: operating rooms, intensive care units
- Educational spaces: lecture halls, classrooms

IV.3 Moist air and h-x diagram

3.1 Presentation of the diagram

Plot for a given atmospheric pressure P, the moist air diagram «DAH » or psychrometric chart, allows for reading all the characteristics used for an air treatment study. Here is a methodology for interpreting the « DAH »:

The temperature axis (abscissa) indicates the air temperature, ranging from -15°C to 55°C. The absolute humidity axis (ordinate) or moisture content indicates the moisture content of the air. This is the amount of vapor present in 1 kilogram of dry air. It is expressed in grams of water vapor per kilogram of dry air and denoted as r [g water/kg dry air] (abbreviated as g/kg). Graduated from 0g/kg to 30g/kg.

The air's saturation with water vapor limits the curve of the graph to the left, representing the maximum amount of water vapor the air can hold without condensation. When the air contains this amount of vapor, it is said to be saturated with humidity or has a humidity level of 100%.

There is a relationship between temperature and saturation humidity. The saturation vapor content increases significantly with the air temperature. Warm air can hold a large amount of water vapor.

3.2 Relative humidity

Relative humidity (or hygrometry) represents, at a given temperature, the ratio between the absolute humidity of the air under consideration and the maximum humidity it could reach if saturated with vapor (saturation absolute humidity). Relative humidity is denoted by φ and is expressed as a percentage. A humidity level of 100% corresponds to saturation. Humidity values below 100% correspond to the iso-degree curves plotted inside the diagram below.

3.3 Dew (rosé) temperature & Humid temperature & Dry temperature

1. Dew (rosé) temperature (tr) in °C

It is the temperature at which the water vapor contained in the air begins to condense when the air cools. In other words, it is the temperature at which, for a given humidity content (w), the vapor reaches the saturation vapor pressure.

2. Humid temperature (th) in °C

The wet-bulb temperature (th) is the temperature read on a thermometer (called a psychrometric thermometer) with a bulb covered with cotton saturated with water and placed in an air stream. The air in contact with the bulb undergoes evaporation, leading to a lowering of the bulb temperature that stabilizes when the air becomes saturated.

3. Dry temperature (ts) in °C

The dry-bulb temperature (ts) of the air is the temperature identified and read on a thermometer placed in an air stream, shielded from any radiation.

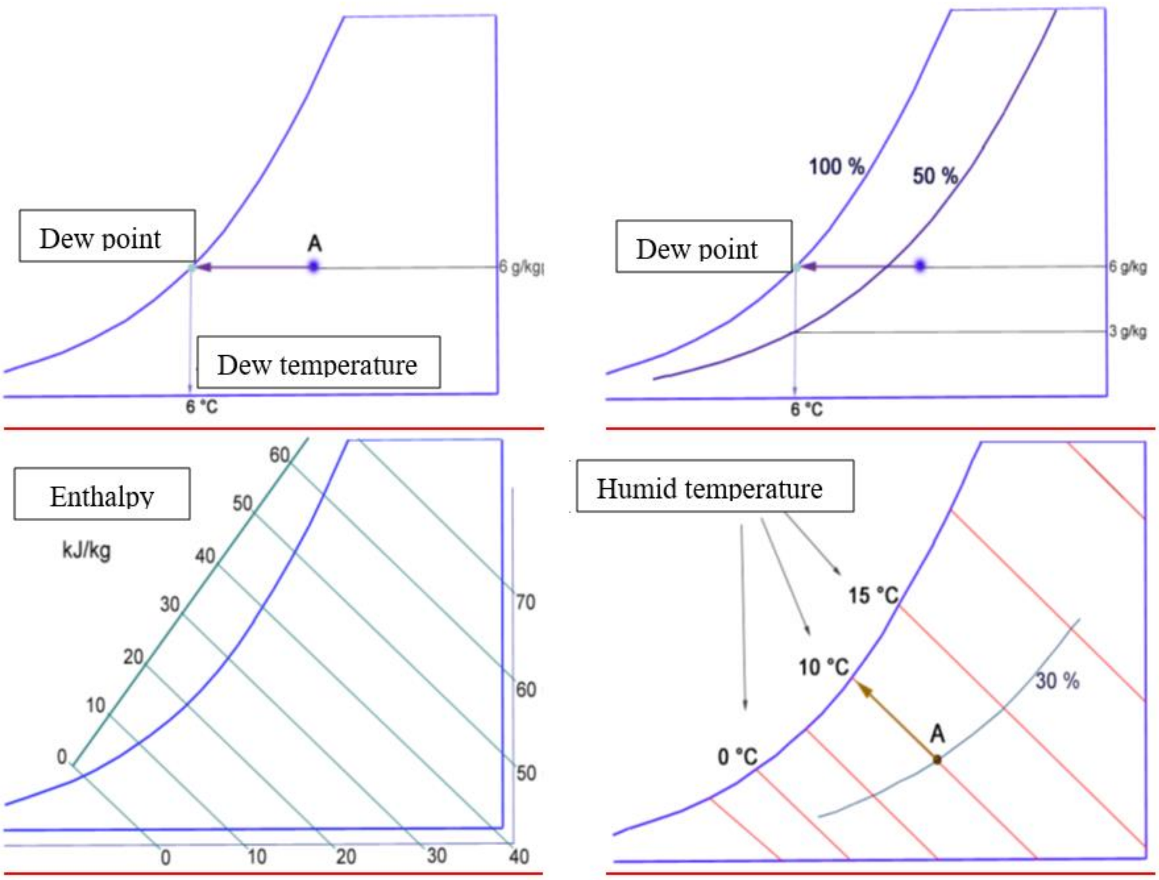
Note: We always have tr < th < ts. In the particular case of saturation, we have:

3.4 Specific volume of air

It is the volume occupied by one kilogram of dry air accompanied by a few grams of vapor mixed with it. It is denoted as Vs in m³/kg_air.

The specific volume of air increases with temperature (as air expands when heated). It also increases with humidity content (as water vapor is less dense than dry air).

The reading of the specific volume Vs is done using iso-volume lines drawn from 0.74 to 0.95 at intervals of 0.01 m³/kg_air. These lines may not appear on all diagrams as this characteristic is not always used.



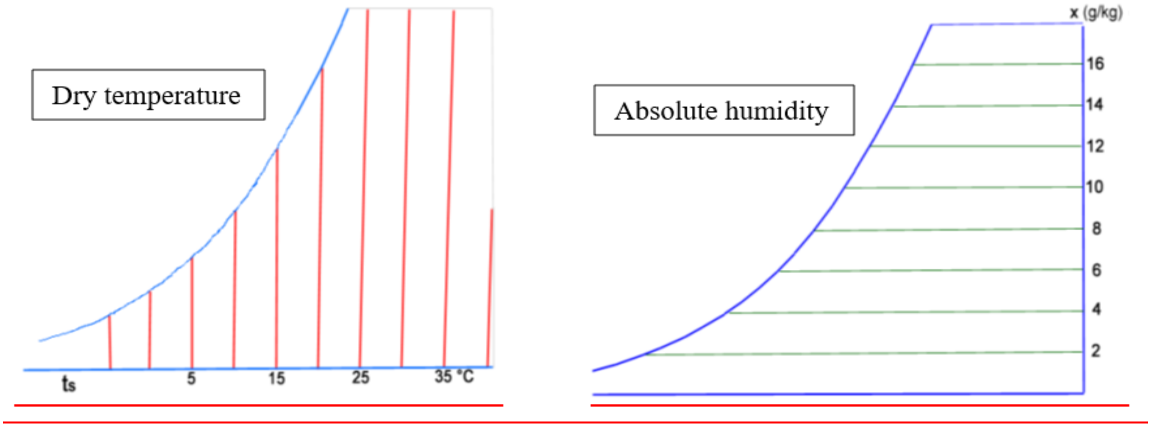


Figure 01 : *Physical characteristics of a psychometric diagram*

IV.4 Cold production

4.1. Cold history

The production of cold is a relatively recent process in historical terms. During antiquity, Greeks and Romans preserved winter cold in the form of snow or ice stored in underground shelters insulated with straw or hay, allowing them to cool drinks and food even during the summer. It was during this same period of history that it was discovered that lower temperatures could be achieved by mixing crushed ice and sea salt. More recently, in the 19th century, the production of cold developed rapidly with the advancement of knowledge in electricity.

4.2. Modes of cold production and applications*

The production of cold, which involves absorbing heat from a medium, can be achieved through various methods. Similarly, the applications of cold are very diverse.

4.3. The processes of cold production

There are three (3) cold production processes

1) refrigerant mixtures.
2) the expansion of a compressed gas.
3) the evaporation of a pure liquid.

4.4. Refrigeration machine

A refrigeration machine is a thermodynamic machine designed to maintain a space or environment at a temperature lower than that of the surrounding environment.

It is a system that transfers heat from a low-temperature medium to a medium where the temperature is higher.

4.5. Refrigeration cycle

The refrigeration cycle is a thermodynamic cycle. It enables lowering the temperature of a relatively cold medium (the cold source) and simultaneously increasing the temperature of another relatively warm medium (the hot source) through the expenditure of mechanical energy.

It is notably used in refrigerators and heat pumps.

4.6. Main components of a refrigeration circuit

To create a refrigeration circuit, at least five components are required:

- **Refrigerant:** A refrigerant fluid whose state changes are induced to primarily absorb or release latent heat in the desired location.
- **Compressor:** Its role is to provide mechanical energy to the refrigerant fluid, enabling it to undergo the required changes.
- **Condenser:** The refrigerant fluid condenses in this component, transferring energy to the medium to be heated.
- **Pressure Reducer (often inaccurately called an Expansion Valve):** It lowers the boiling point of the refrigerant fluid.
- **Evaporator:** In this component, the refrigerant fluid evaporates, absorbing the necessary energy from the medium to be cooled.

After passing through the evaporator, the refrigerant fluid returns to the compressor, and the refrigeration cycle begins again.

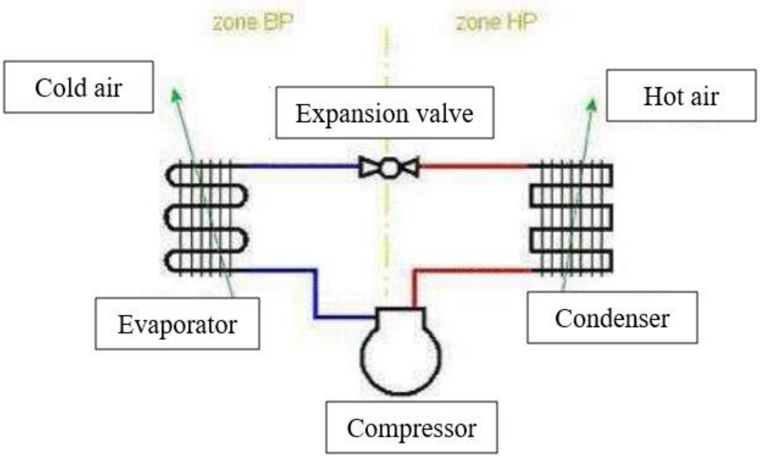


Figure 01 : *Basic diagram of a refrigeration machine [7]*

4.7. Fundamental characteristics of a refrigerant fluid

The refrigerant is a substance that circulates within the system. Thanks to the endothermic and exothermic phenomena resulting from the transformations it undergoes, it absorbs heat at the cold source and releases it at the hot source. For a substance to serve as a refrigerant, the following criteria must be met:

- Its boiling point should be as low as possible at atmospheric pressure.
- The condensation pressure should not be too high.
- It should not corrode the oil or metals in the refrigeration system.
- It should be as non-toxic, non-flammable, and non-explosive as possible.

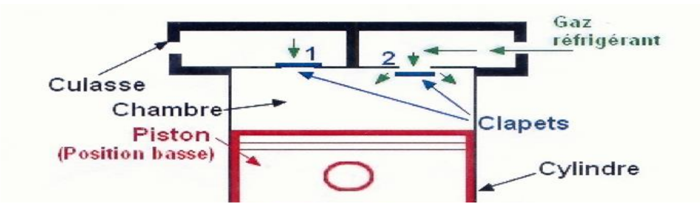
4.7.1. Compressor

The compressor is essential. Without it, the operation of the cold room is impossible. The compressor draws in the low-pressure and low-temperature gas. The mechanical energy of the compressor allows an increase in pressure and temperature.

Gas suction

The suction system is created by the piston, which generates a vacuum.

Scheme: **Step 1 : Suction**



Compressor Discharge

The gas is then compressed by pistons in the chamber where the outlet orifice is small, allowing an increase in gas pressure directed towards the compressor's outlet, always in a vapor state with a temperature of 70°C.

Step 2 : le refoulement

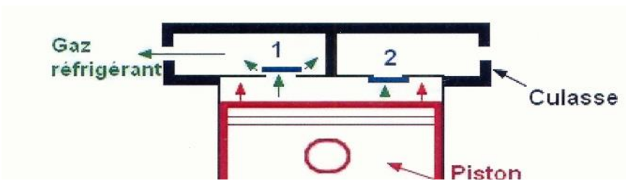


Figure 02 *: Compressor Schematic (Suction and Discharge) [7]*

4.7.2. Condenser

The condenser is an heat exchanger that allows the evacuation of heat contained in the gaseous refrigerant from the compressor by liquefying it. This condensation (liquefaction) is achieved by cooling the gaseous refrigerant at constant pressure through a medium that can be water or air.

This heat removal occurs in three stages:

- Superheating of the refrigerant vapors (evacuation by sensible heat - segment AB)
- Condensation of vapors (evacuation by latent heat - main stage - segment BC)
- Subcooling of the liquid refrigerant (evacuation by sensible heat - segment CD)

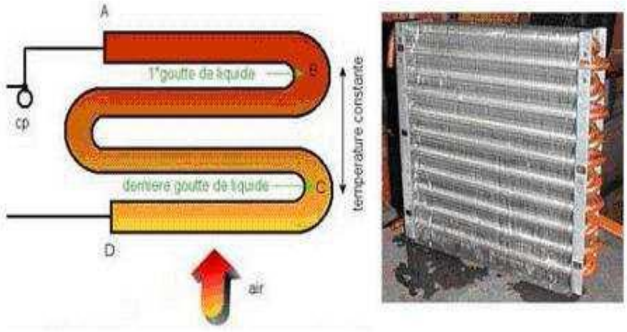


Figure 03 : *air condenser [7]*

4.7.3. Expander

The expansion valve reduces the pressure of the liquid refrigerant (creating pressure losses) coming from the condenser before introducing it into the evaporator to allow its vaporization at a low temperature in the evaporator.

It also regulates the amount of liquid refrigerant entering the evaporator based on the cooling needs (only for thermostatic expansion valves). For capillary-type expansion valves (capillary tubes), the flow of refrigerant entering the evaporator depends on the inner diameter (from 0.6 to 1.5 mm) and length (from 1.80 to 3.50 m) of the tube, as well as the pressure difference between the condenser and the evaporator.

It is a device for expanding high pressure to low pressure, usually through throttling, through which the refrigerant flows to the evaporator.

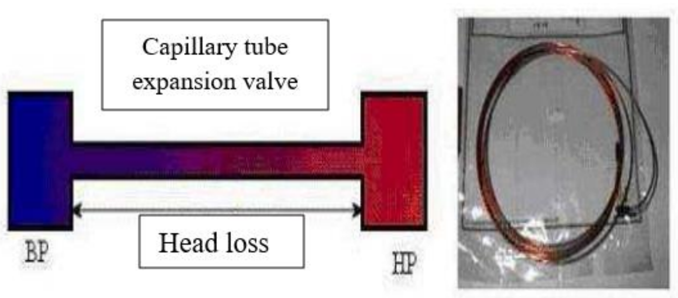


Figure 04 : *Capillary-type expansion valve [7]*

4.7.4. Evaporator

The evaporator is a heat exchanger in which the low-temperature and low-pressure liquid refrigerant absorbs heat from the cooling medium (air or water) at constant pressure, thereby becoming a gas.

This heat absorption occurs in two stages:

- Evaporation of the liquid refrigerant (absorption of latent heat - main stage - segment AB)
- Superheating of vapors resulting from the evaporation of the liquid refrigerant (absorption of sensible heat - segment BC)

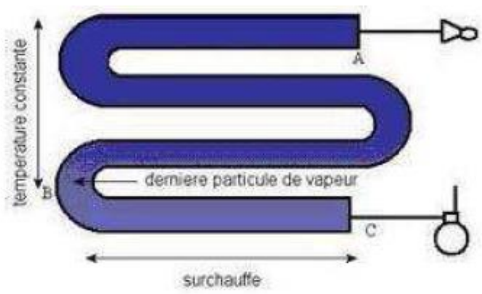


Figure 05 *: Evaporator [7]*

4.8. Thermal cycle balance

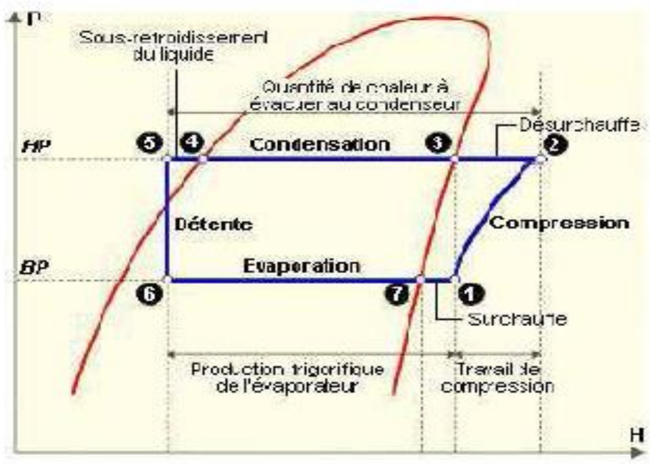


Figure 06 : *Enthalpy diagram of the refrigeration cycle. [7]*

From the first law of thermodynamics, there is a conservation of energy: meaning that the amount of heat rejected to the cold fluid in the condenser $\mathbf{Q_c}$ by the refrigerant must be equal to the sum of the heat absorbed at the evaporator $\mathbf{Q_0}$ to produce the cold, plus the work $\mathbf{W_{th}}$ consumed or the energy received to operate the compressor. Hence the equation:

$$Q_c + Q_0 = W_{th} \qquad \text{(IV.13)}$$

The choice of the enthalpy scale (h in [kJ/kg]) on the abscissa is very practical for the quantitative exploitation of the Mollier diagram because it allows direct reading of enthalpies hi at various points i (1, 2, 3, 4, 5, 6, 7) of the machine's cycle. This way, the first principle is verified on the abscissa scale as we observe that: The work expended by the compressor:

$$W_{th} = h_2 - h_1 \qquad \text{(IV.14)}$$

The amount of heat released by the condenser:

$$Q_c = h_5 - h_2 \qquad \text{(IV.15)}$$

The amount of cold produced by the evaporator:

$$Q_0 = h_1 - h_6 \qquad \text{(IV.16)}$$

Chapter 5:
Systems Regulation

V.1 Introduction :

The indoor climate of buildings is subject to both internal and external disturbances. These mainly include occupants, internal gains from sunlight, outdoor temperature, and wind. The random nature of these disturbances, especially sunlight and user actions (management of blinds and window openings), makes it challenging to achieve optimal management of heat and cold inputs. The thermal comfort of occupants may be affected (overheating, excessively low morning temperatures), and the consumption of heat and cold may become excessive. Paradoxically, this type of issue is more commonly encountered in well-insulated buildings with significant passive solar gains, as illustrated in Figure 1.

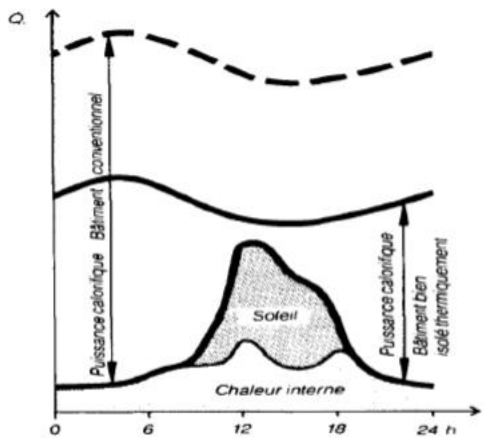


Figure 01 : *Thermal loss of a building (solar gains) [12]*

A building is constantly subjected to external influences (temperature, sunlight, wind) that disturb its thermal state. The control system, with the objective of making the variations in external climate imperceptible to occupants, will partially or completely take into account meteorological phenomena and the thermal characteristics of the premises.

Furthermore, the dynamic behavior of spaces and air treatment systems, comfort requirements, as well as a better control of costs involving rigorous management of installations make the regulation of heating and air conditioning systems a discipline that requires knowledge in diverse specialties such as control engineering, computer science, thermal engineering, and metrology.

The primary era of the thermostat is over. Proportional, integral, and derivative control actions dedicated to HVAC applications are evolving. Regulation systems are integrated into centralized technical management architectures encompassing functions such as remote control, remote monitoring, control and self-control, or remote tracking and energy accounting.

Before delving into all these concepts, the notions regarding the general principles of regulation will be reviewed, and the various sensors and actuators encountered in heating and air conditioning will be mentioned. Beyond a simple catalog of standard solutions, the general methodology for designing a control system, and the hardware and software solutions will be addressed, ranging from simple temperature regulation in a room to a complex system controlled by a building management technical installation.

V.2 Reminders on the control of a process

The reader will find useful references in the general articles 'Principles of control loops [R 7 090]' and 'Types of control loops [R 7 100]' in the Automation section of the Industrial Computing treatise.

V.2.1 Open-loop control

The regulation of a system involves finding a way to keep the controlled variable y(t) as close as possible to the setpoint yc.

One initial solution is to **set the controls once and for all**. Adjusting the water temperature in a shower is an example of an open-loop system (Figure 2). External variations (disturbances) such as pressure or temperature on any of the water supplies can change the value of the controlled variable (temperature of the mixture in this example), which is noticeably felt by the user.

Another example of open-loop control is depicted in Figure 3. The regulator R adjusts the water circuit temperature to a value that is a function of the outdoor temperature by acting on the burner power. Temperature variations indoors will be observed if disturbances alter the system's balance: sunlight, internal heat gains, air infiltration, etc.

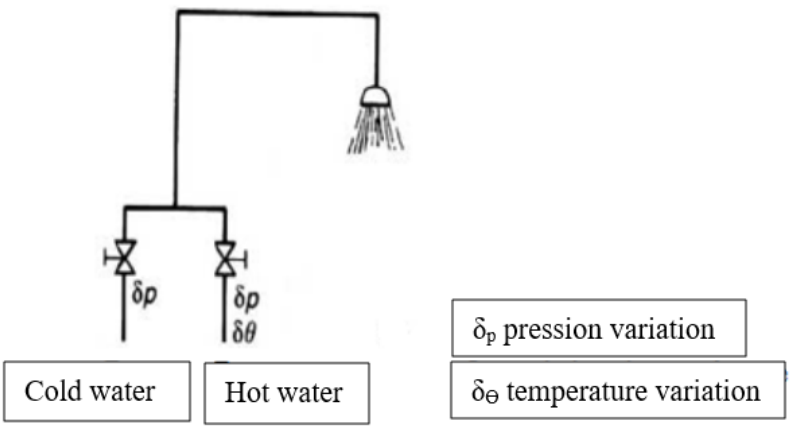


Figure 02 : *– Example of adjusting control devices (valves): Open-loop system [12]*

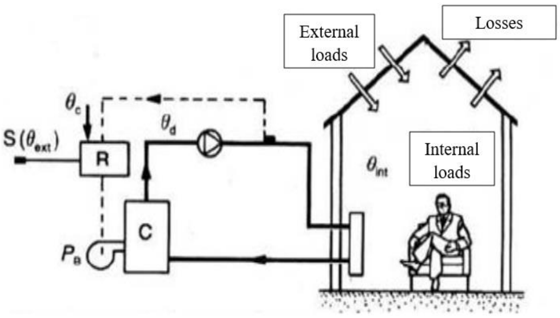


Figure 02 : *Regulation principle [12]*

Disturbing variable: outside temperature θ_{out}

Output variable: inside temperature θ_{in}

Setpoint (consigne) variable: temperature θ_c

Controlled variable: departure temperature θ_d

Control variable: burner power P_b

$$\theta_d = \theta_c = f(\theta_{out}) \qquad (V.01)$$

C: boiler

R: regulator

S: external temperature probes

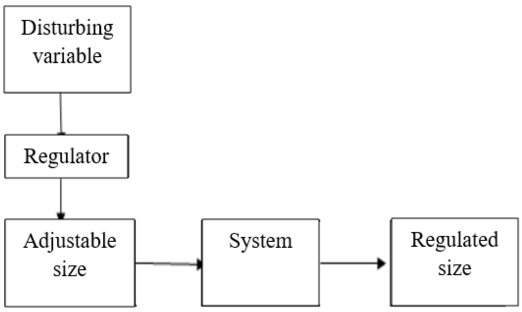


Figure 03 : *Example of open-loop control [12]*

In open-loop control, the output signal does not react to the input signal. It is a fast yet imprecise regulation method in systems experiencing significant disturbances but remains stable.

This control mode requires, on the one hand, the ability to measure the disturbing variable and, on the other hand, the prior definition of a relationship between the disturbance and the control variable.

$$p = G_V.(T_{cons} - T_{out}) \qquad (V.\ 2)$$

where :

P : provided power (W)

G_V : thermal loss coefficient of the building (W/°C)

T_{cons} : setpoint (consigne) temperature (°C)

T_{out} : outside temperature (°C)

V.2.2 Closed-loop control

The only way to ensure that the controlled variable reaches or is equal to the setpoint value is to measure it continuously and use it for adjustment. That's why, in closed-loop control, the guiding measurement is the controlled variable (Figure 4).

Taking into account disturbing factors (internal and external inputs or losses) can be achieved using feedback that constantly acts on the control signal u(t) based on the error e(t) that exists between the setpoint and the measured value.

Therefore, closed-loop control applies to the system a control signal in the form:

$$\mu(t) = f[e(t).t] \qquad \text{(V. 3)}$$

Where : $e(t) = y_c - y(t)$.

In the example of Figure IV.4 $y_c = \theta_c$ et $y(t) = \theta_{int}(t)$.

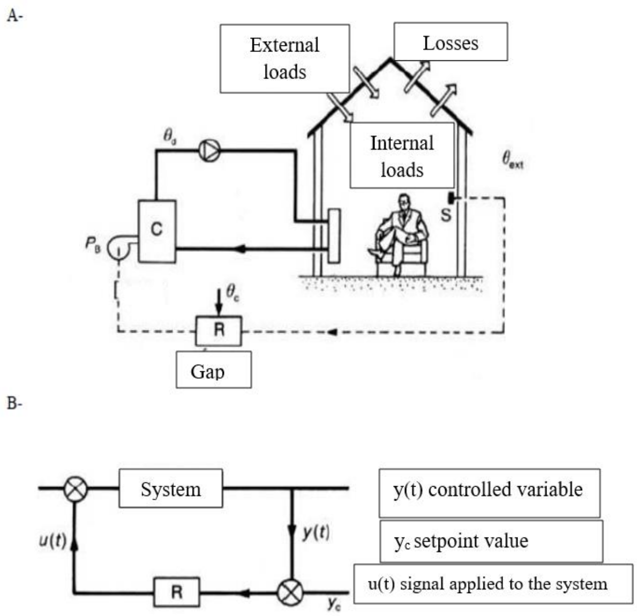


Figure 04 (A-B) : *Closed-loop control [12]*

This concept, the most important in control systems, will be used throughout the following paragraphs.

A symbolic representation can be created for any control system; that of the closed-loop is provided in Figure V.4.

V.3 Different modes of regulation

To understand the challenges with the current regulatory structure of higher education, as well as the challenges of reforming that structure, it helps to understand the potential and limitations of the different approaches to regulation more generally.

As my colleague Cary Coglianese has written, the government has many different regulatory tools in its belt, and it regulates different industries in different ways. Three main approaches to regulation are "command and control," performance-based, and management-based. Each approach has strengths and weaknesses. Selecting the type of regulation to apply to a sector of the economy will have major impacts on the targeted institutions and on the potential for success in achieving regulatory goals.

Traditionally, the majority of regulations have taken the form of what is frequently referred to as command and control regulation (also sometimes called "means-based" or "technology-based"). Under this approach, the regulatory agency sets forth methods, materials, and the processes by which the regulated entity must operate. The now dissolved U.S. Atomic Energy Commission, for example, directed which technology must be used in approved nuclear power plants and regulated the processes by which companies produce nuclear power.

Command and control regulation, in theory, creates certainty—for the government, the regulated entity, and the public—that a body of experts have carefully developed the safest and most efficient mode of operation for the sector. This type of regulation is relatively easy for the regulator to observe and evaluate, and therefore to determine compliance. However, many have critiqued command and control as a highly expensive form of regulation, as one that increases the costs of products to the public, and as stifling of innovation. Critics also question whether regulators have the ability to develop the most efficient technological or procedural safeguards.

As critiques of government bureaucracy have increased in recent decades, support for an alternative to command and control has grown. With one such alternative, performance-based regulation, the regulator does not dictate the materials or processes the regulated entity must use to achieve societal goals, but rather sets ultimate production standards that the entity must meet. This approach allows the regulated entity the flexibility to determine the most efficient way to meet that standard. Take, for example, carbon monoxide emission regulations implemented under the Clean Air Act, which do not require the use of specific technologies or processes, but rather leave those choices to the regulated industries and instead mandate that emissions cannot exceed a set limit. In every administration since at least the Clinton Administration, performance-based regulation has been advocated quite explicitly within White House directives to regulators working in a variety of areas. It is an approach with bipartisan support.

Good management-based regulation, analysts have argued, must be shaped by the regulator to ensure that the proper goals are being planned for and the plans developed can actually be implemented. Although it has limitations, the small amount of study on this relatively new approach to regulation has found that sectors imposing management-based regulation have seen increases in safety and productivity.

In recent decades, policymakers have debated frequently what type of regulation is most appropriate in a given sector of the economy. In many complex areas, such as higher education, the regulatory scheme involves a mixture of approaches. Command and control regulation still predominates, but efforts to adopt performance-based regulation continue to grow. At the same time, there is evidence that more regulatory agencies in the U.S. and abroad are considering management-based regulation to deal with the complexities of modern economic and social systems.

In order to assess how to improve regulation of higher education, it is essential to consider the strengths and weaknesses of the major policy options. Educational reformers need to take into account what we already know about the available regulatory tools.

V.3.1 Regulation by all or nothing

L’organe de commande ne peut occuper que deux positions : position ouverte ou position fermée. Le passage de l’une à l’autre est réalisé lors du franchissement du point de consigne. Pour éviter des phénomènes d’oscillations (appelés pompages), on introduit une plage neutre appelée aussi différentiel : le changement de position n’intervient qu’après un dépassement (en plus ou en moins) du point de consigne supérieur au demi-différentiel (Figure.5)

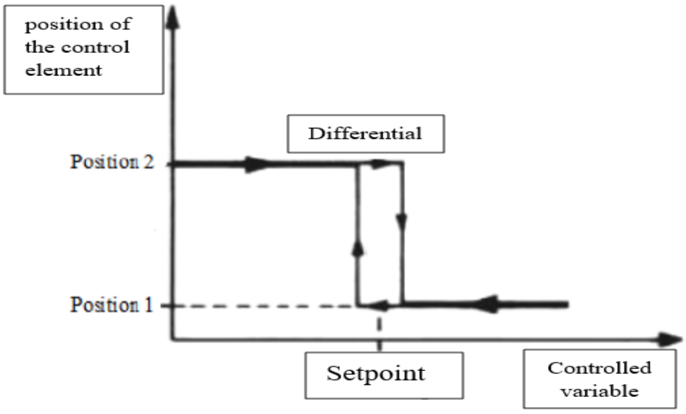


Figure 05 : *Regulation by all or nothing [12]*

V.3.2 control of a process

A building does not respond instantaneously to a solicitation, which could be a variation in external climatic conditions or a shutdown of the heating system. The systems that the HVAC engineer must regulate, therefore, exhibit delays (response times, time lags).

Three examples of delays that may exist in installations, individually or combined, are provided below.

- **Delay introduced by the inertia of the building:**

Consider, for example, a building module (Figure 6.a) consisting of a wall that absorbs and stores heat. The simplified equation for the thermal balance is given by the following relationship:

$$E(t) = GV[\theta_{int}(t) - \theta_{int}(t)]dt + M_{cp}d_{\theta} \qquad \text{(V. 4)}$$

where:

E Energy dissipated in the system,

GV Characteristic parameter of losses,

*Mc*p Parameter characterizing the heat accumulation in the wall.

If we apply a power step inside the room, the expression for the indoor temperature is given (with the other parameters remaining constant):

$$\theta_{in}(t) = \theta_{ino} + \frac{E}{GV}\left[1 - exp\left(-\frac{GV}{M_{cp}}\ t\right)\right] \qquad \text{(V.5)}$$

With: θ_{in0} as the indoor temperature before the application of the power step.

In the case of a change in outdoor temperature (from θ_{out0} to θ_{out1}) in the form of a step, the indoor temperature is given by the relationship:

$$\theta_{in}(t) = \theta_{out1} + (\theta_{out0} - \theta_{out1})exp\left(-\frac{GV}{M_{cp}}\ t\right) \qquad \text{(V.6)}$$

In both cases, the time constant GV / Mcp is a characteristic of the building.

More comprehensive models allow understanding thermal fluxes based on various excitations (temperature, solar flux) and, as a result, provide access to all usual calculations in building thermodynamics.

The Figure 6.b depicts the evolution of the indoor temperature in a intermittently occupied space for an assumption of constant external demands.

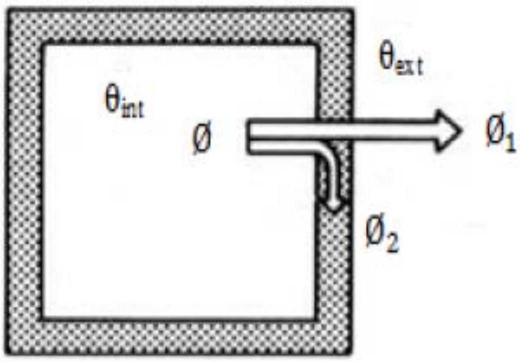
The temperature inside the room is maintained constant between 8 am and 6 pm. From 6 pm, the shutdown of the heat emitters leads to a decrease in indoor temperature, which can be distinguished in two phases:

- The first phase corresponds to the thermal discharge of light masses (air, furniture, etc.), resulting in a sudden variation in indoor temperature;
- In the second phase, heavy masses discharge, resulting in a slower decline in indoor temperature. The opposite phenomenon occurs from 11 pm, which is the time of the system's reactivation (scenario 1); a second power boost occurs starting from 7 am to achieve the desired temperature by the arrival of occupants at 8 am.

A second scenario can be envisioned by minimizing the indoor temperature and initiating a single significant power boost starting at 5:30 am [14].

The choice between the two scenarios depends on the cost of energy, which can vary throughout the day.

A - Wall exchanging heat



Ø : Thermal flux

$$\emptyset_1 = GV(\theta_{int} - \theta_{ext}) \qquad \emptyset_2 = M_{cp}.\frac{\Delta\theta}{t} \qquad (V.7)$$

A- The evolution of indoor temperature according to heating scenarios.

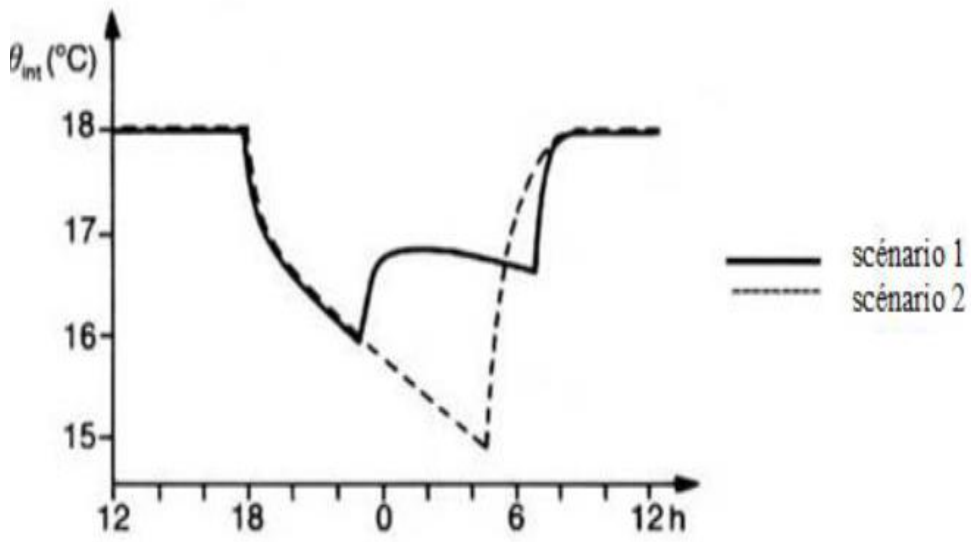


Figure 06 (A.B) : *Delay caused by the inertia of the building. [12]*

- **Delay due to probe-actuator distance:**

The flow velocity of a liquid inside a pipeline varies between 0.5 and 2 m/s. Therefore, the effect of the actuator is not instantly detected by the sensor, but after a time that can be estimated at approximately 1 second per linear meter of the pipeline (Figure 7a).

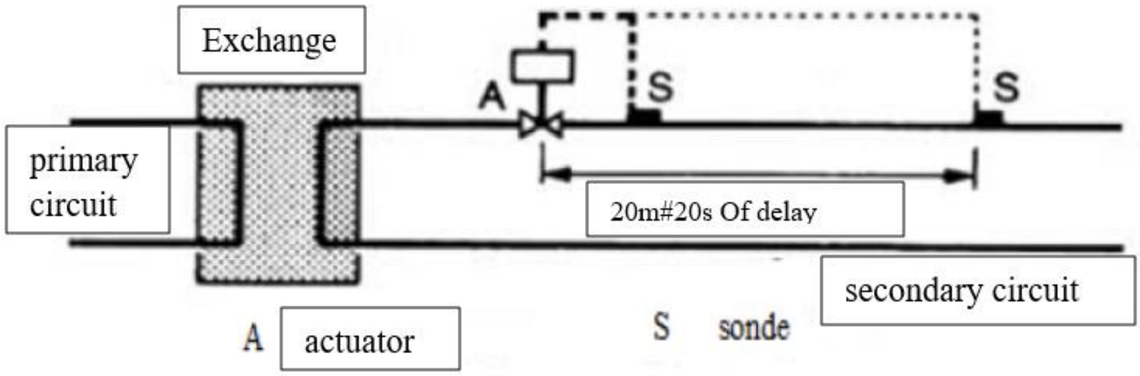
This delay, which introduces a floating regulation because the controller does not instantly measure its effect, can be used to dampen the control of power step systems. Heat pumps are sometimes controlled based on the return temperature of the network.

- **Delay introduced by the inertia of the temperature sensor:**

A temperature sensor behaves like a first-order system with resistance and capacitance. When the sensor is subjected to a sudden temperature change (Figure 7b), the response of the detector evolves according to an exponential law.

A sensor placed in a liquid reacts faster than the same sensor placed in a gas; indeed, the convection coefficient of a gas is approximately 1,000 times lower than that of a liquid [15].

A- Distance of the temperature probe from the actuator



B- Inertia of the temperature probe

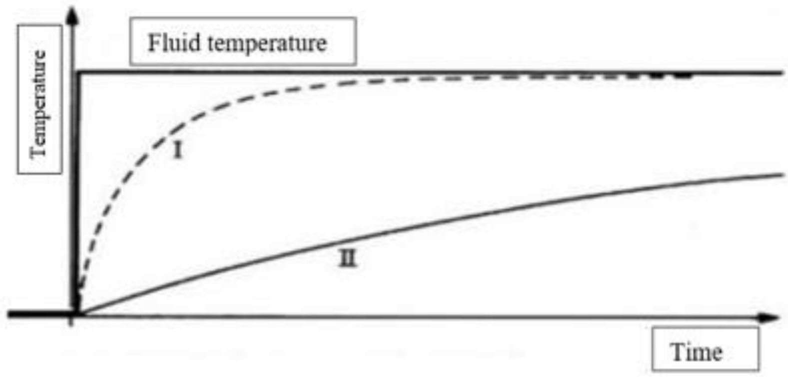


Figure 07. (A.B) : *Delay due to temperature probe [12]*

I: Temperature measured by the detector of a probe placed in a liquid flow II: Temperature measured by the detector of a probe placed in a gas flow

V.4 Application to the regulation of a building:

The building is divided into zones. Each zone has its circuit, with a water temperature prepared according to its specific needs (external sensor, time programming, etc.). However, each room may have different requirements from those of its zone!

Furthermore, regulating based solely on the external temperature does not account for a series of disturbing elements:

- Variable air renewal in the building depending on the wind,
- Variable internal contributions (occupants, office equipment, etc.) depending on the rooms,
- Variable external contributions (sun, shadow from a neighboring building, etc.),
- The impact of an increase in ventilation losses on indoor temperature is immediate, while a decrease in external temperature is slow due to the building's inertia,

- Thermal imbalance between heating bodies.

It is therefore necessary to use local ambient regulation per room, in addition to central regulation based on external conditions:

- To ensure comfort in all rooms,
- Without overheating (and therefore overconsumption) in favored rooms.

We propose to conduct a simplified study of an automatic regulation system for building thermal simulation installations. The system in question, from a technological point of view, consists of a solar air conditioning/heating system for the six-floor climatic chamber (floor = chamber).

To control the temperature of the chambers, the use of temperature controllers and detectors is recommended.

The system's objective is to control the chamber's temperature despite disturbances suffered by the system and from the outside. The block diagram of this air conditioning/heating system is generally explained in the following Figure 8 [12]:

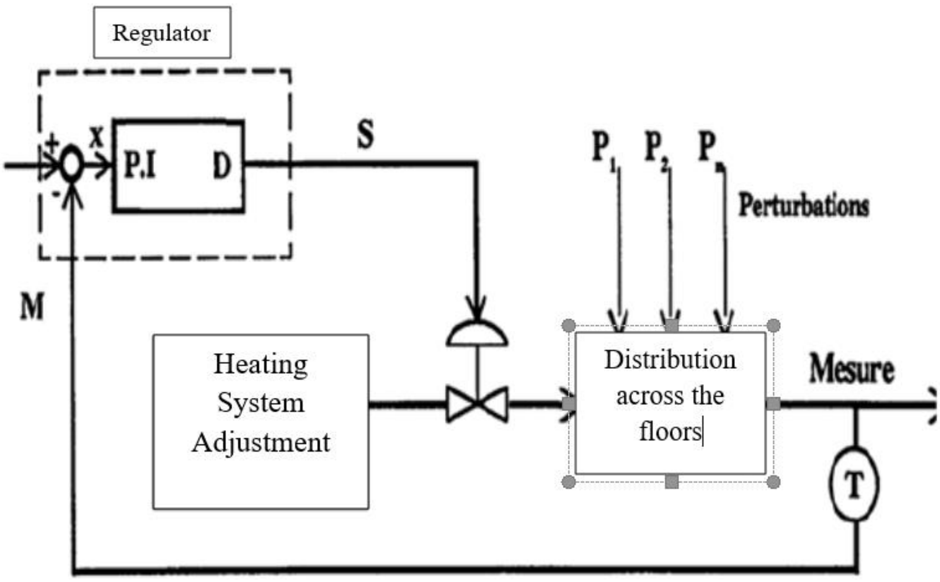


Figure 08 : *Building Regulation Principle [12]*

Chapter 6
Renewable Energy

VI.1. Introduction

Renewable energies are inexhaustible sources derived from natural elements such as the sun, wind, waterfalls, tides, Earth's heat, and the growth of plants. They are referred to as "flow" energies in contrast to "stock" energies, which consist of limited deposits of fossil fuels (oil, coal, gas, uranium). Unlike fossil energy sources, the exploitation of renewable energies generates little to no waste and polluting emissions. They are considered the energies of the future. However, they are still underutilized compared to their potential, as renewable energies currently only cover about 20% of global electricity consumption.

Utilizing renewable energies has numerous advantages. It helps combat the greenhouse effect, particularly by reducing carbon dioxide emissions into the atmosphere. Additionally, it contributes to intelligent management of local resources and job creation.

VI.2 Current context

VI.2.1 Energy around the world

During the industrial revolution, the level of CO_2 in the atmosphere began to increase with the widespread use of oil as the main source of energy. Over the past decades, the pace has accelerated with the industrialization of many countries. In fact, humanity currently consumes thirty times more energy than a century ago [10].

At the end of the 19th century, the first ecological disasters appeared with the development of the industrial revolution, which caused a significant rise in the consumption of natural resources.

The 20th century witnessed the first visible ecological disasters, such as oil spills and industrial pollution. Scientists began to understand pollution phenomena and warned the international community about the effects of this pollution. Following an awareness of these issues, several international conferences took place, and protocols were signed [10].

Algerian legislation on environmental protection includes several laws that continue to evolve over time based on new data. The first laws date back to 1978 and 1983 and focus on site protection and the creation of national parks. More recent laws, the latest of which date back to 2015, concern the establishment of the National Observatory for the Environment and Sustainable Development as well as the National Environmental Fund, not to mention other laws and decrees related to coastal protection and the development of clean energy [10].

Furthermore, the use of fossil fuels poses two major problems: the release of CO_2 into the atmosphere, a greenhouse gas, and the extraction of non-renewable resources, susceptible to depletion. These two issues represent significant challenges today for the governments of industrialized countries and for major international organizations.

VI.3 Fossil Fuels and Their Influence on the Environment

The 19th century experienced the most significant climate warming. The causes are to be found not so much in nature as in the concentration of CO2 and other gases in the atmosphere due to human activity. Although some divergences exist, the scientific community agrees that the worsening of the greenhouse effect due to human activity plays a leading role in current climate changes. Furthermore, it is expected that greenhouse gases and temperature will continue to increase in the years to come.

a- Greenhouse effect

The greenhouse effect is a natural process resulting from the influence of the atmosphere on various thermal fluxes contributing to surface temperatures on a planet. Understanding this mechanism is necessary to explain the observed temperatures on Earth and Venus. In the solar system, the majority of the thermal energy received by a planet comes from solar radiation, and in the absence of an atmosphere, a planet radiates ideally like a black body. However, the atmosphere of a planet absorbs and reflects a portion of this radiation, thus altering the thermal balance. Therefore, the atmosphere acts as insulation, isolating Earth from the vacuum of space, much like a greenhouse isolates plants from the external air [18].

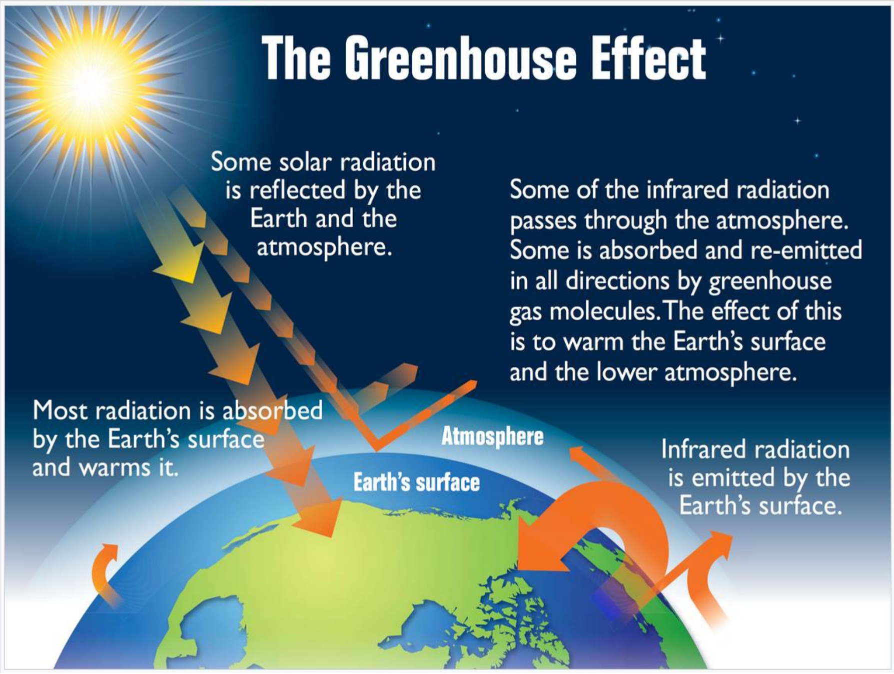


***Figure 01** : Explanatory diagram of the greenhouse effect [18]*

VI.4. Different Renewable Energy Modes

4.1 Solar Energy

Transformation of solar energy into electricity or heat using solar panels or collectors. The sun is the main source of various forms of renewable energy available on Earth. There are three types:

a. Photovoltaic Solar Energy

Photovoltaic solar energy directly converts light (solar or other) into electricity. It uses photovoltaic modules composed of solar cells or photovoltaic cells to achieve this energy transformation.

Figure 02 *: Photovoltaic Module [20]*

b. Solar Thermal Energy

It is radically different from photovoltaic solar energy; instead, it produces heat from infrared solar radiation to heat water or air. In this case, thermal collectors are used, which involve a completely different technology. In everyday language, these are referred to as 'solar water heaters' or 'hot air collectors.

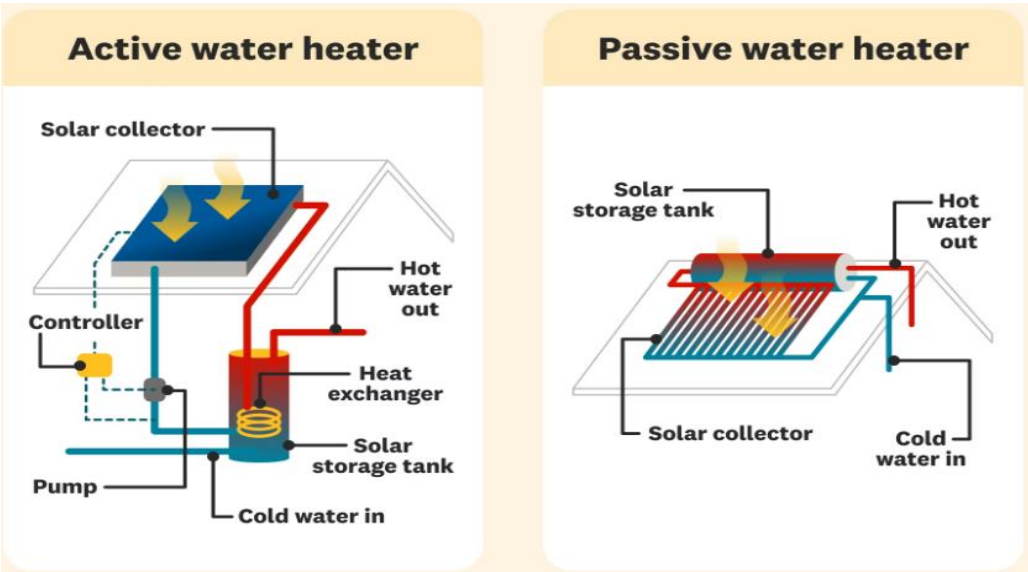


Figure 03 : *Solar water heater [21]*

c. Thermodynamic solar energy

There is also what is called Thermodynamic solar energy, which operates on the principle of concentrating solar rays using curved mirrors onto a focal point located on a tower. This focal point stores the heat and later releases it in the form of mechanical energy, often using a steam turbine, for example.

Figure 04 : *Solar tower [19]*

4.2 Wind Energy:

Wind energy allows for the conversion of the kinetic energy of the wind into power used to generate electricity, for example. This type of energy is very ancient and is among the first energies utilized by humans. While this technique is highly environmentally friendly, its cost can sometimes be high.

The efficiency of a wind turbine strongly depends on the location where it is placed. The sites most exposed to the wind are those situated at the tops of mountains, along the coast, or in the middle of oceans.

Wind turbines generate a considerable amount of noise. Ongoing research in this field aims to reduce the noise pollution caused by these machines. Wind turbines are equipped with auxiliary systems to store the energy.

Figure 05 : *Wind Energy [19]*

4.3 Hydraulic Energy

Hydraulic energy is currently by far the primary source of electricity production in the world. Most often, electricity is generated from water in dams.

The water falls from a significant height, and the kinetic energy it generates is used to operate turbines and generators that convert this energy into electrical energy. The turbine rotates the generator's rotor, which produces a magnetic field inside the stator, essentially a giant coil that generates electricity. Mechanical energy is thus transformed into electrical energy. This system of electricity production from water is the most widespread in the world. Table 3.9 shows the size and capacity of hydraulic power plants.

There is another technique that is less common but is used in countries adjacent to the oceans. This involves electricity production from wave energy. Similar to hydraulic power plants, the potential energy of the water is converted into electrical energy. Waves are sinusoidal with peaks and troughs. The amplitude of the waves depends on the weather: it is more significant during windy or stormy conditions. The motion of the waves is converted into mechanical energy, which rotates an electrical generator. Wave energy is captured using floats or blades that transmit it to the rotors of electrical generators. Tidal energy can also be harnessed.

Hydraulic energy is cost-effective. Only the energy conversion devices require investment. Moreover, it is a clean energy source that does not produce polluting emissions.

Figure 06 : *Dam [19]*

4.4 Geothermal Energy

Utilizing the heat from the subsurface, geothermal energy can be used to heat buildings (with average or low temperatures) or to generate electricity through steam production (with high temperatures).

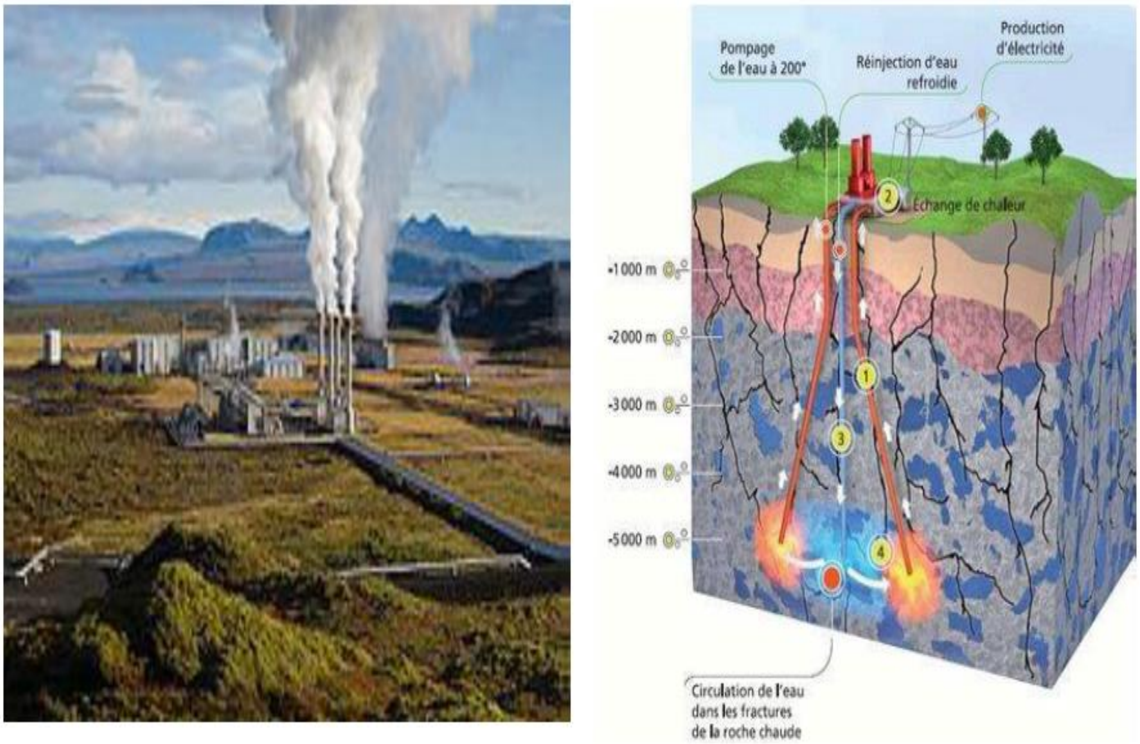


Figure 07 : *Centrale géothermique de Nesjavellir en Islande. [20]*

4.5 Biogas

Biogas is the gas produced by the fermentation of organic matter in the absence of oxygen. It is a combustible gas consisting mainly of methane and carbon dioxide. It can be burned on-site to obtain heat and electricity or purified to obtain biomethane usable as natural gas for vehicles or injectable into the natural gas distribution network.

Methanization occurs spontaneously in marshes (marsh gas), rice fields, large tropical reservoirs, or hydroelectric dams, as well as in landfills containing organic waste or matter (animal, plant, fungal, or bacterial). It can also be artificially induced in digesters, especially to treat sewage sludge and organic waste from industrial or agricultural sources.

4.6 Composition

The composition of biogas varies depending upon the substrate composition, as well as the conditions within the anaerobic reactor (temperature, pH, and substrate concentration). Landfill gas typically has methane concentrations around 50%. Advanced waste treatment technologies can produce biogas with 55–75% methane, which for reactors with free liquids can be increased to 80–90% methane using in-situ gas purification techniques. As produced, biogas contains water vapor. The fractional volume of water vapor is a function of biogas temperature; correction of measured gas volume for water vapour content and thermal expansion is easily done via simple mathematics which yields the standardized volume of dry biogas.

For 1000 kg (wet weight) of input to a typical biodigester, total solids may be 30% of the wet weight while volatile suspended solids may be 90% of the total solids. Protein would be 20% of the volatile solids, carbohydrates would be 70% of the volatile solids, and finally fats would be 10% of the volatile solids.

4.7 Contaminants

a) Sulfur compounds

Toxic and foul smelling Hydrogen sulfide (H_2S) is the most common contaminant in biogas, but other sulfur-containing compounds, such as thiols may be present. Left in the biogas stream, hydrogen sulfide is corrosive and when combusted yields sulfur dioxide (SO^2) and sulfuric acid (H^2SO^4), also corrosive and environmentally hazardous compounds.

b) Ammonia

Ammonia (NH^3) is produced from organic compounds containing nitrogen, such as the amino acids in proteins. If not separated from the biogas, combustion results in NO_x emissions.

Siloxanes

In some cases, biogas contains siloxanes. They are formed from the anaerobic decomposition of materials commonly found in soaps and detergents. During combustion of biogas containing siloxanes, silicon is released and can combine with free oxygen or other elements in the combustion gas. Deposits are formed containing mostly silica (SiO^2) or silicates and can contain calcium, sulfur, zinc, phosphorus. Such white mineral deposits accumulate to a surface thickness of several millimeters and must be removed by chemical or mechanical means.

Practical and cost-effective technologies to remove siloxanes and other biogas contaminants are available.

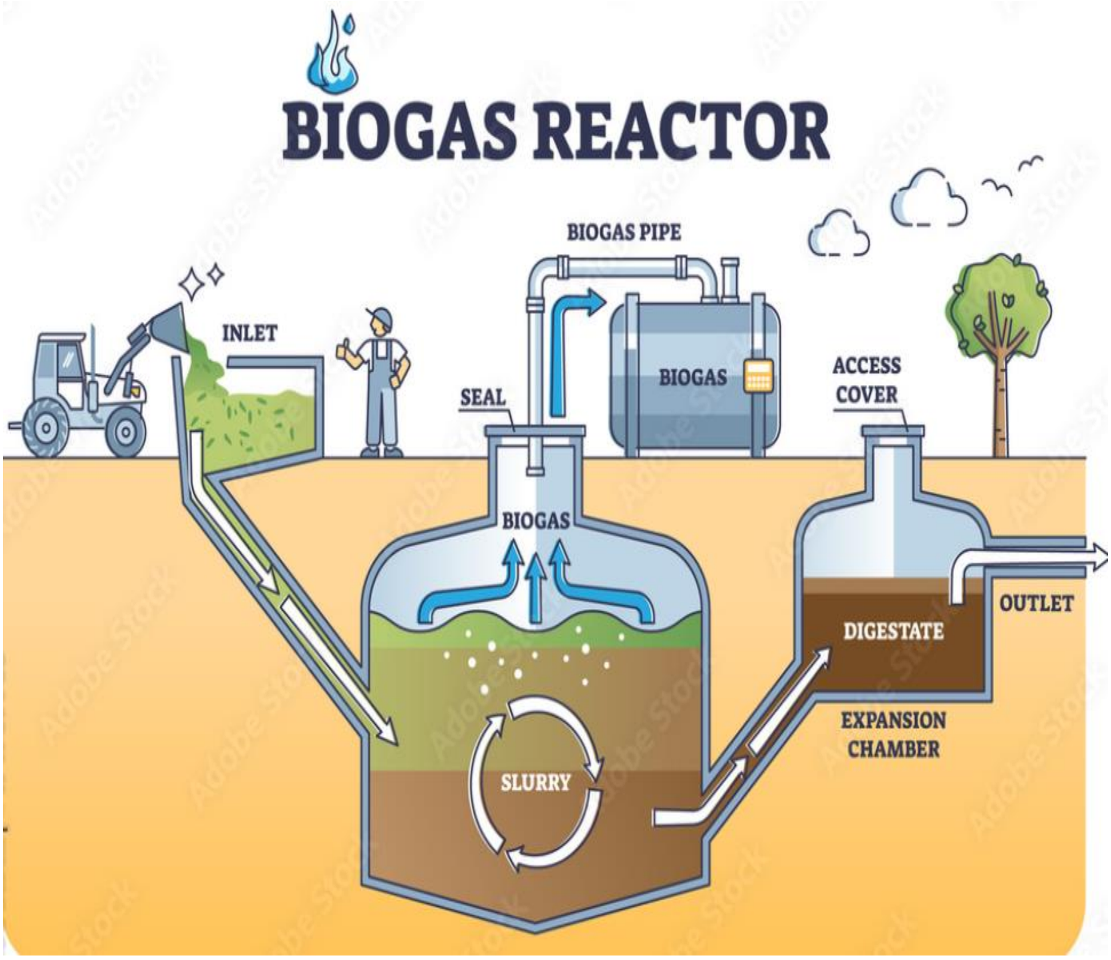


Figure 08 : *The principle of biogas reactor [20]*

4.8 Biomass

Biomass (plant mass) includes wood, straw, corn stover, biogas, and biofuels. Wood from forest waste or wood industries is burned to produce heat, representing 14% of global energy consumption. Biogas comes from the fermentation of organic waste. Its combustion produces heat and also electricity through cogeneration. Biofuels come from cultivated plants (sunflower, beet, rapeseed...): the most common are biodiesel (or fatty acid methyl ester, FAME), ethanol, and its derivative, ethyl tert-butyl ether, or ETBE. [19].

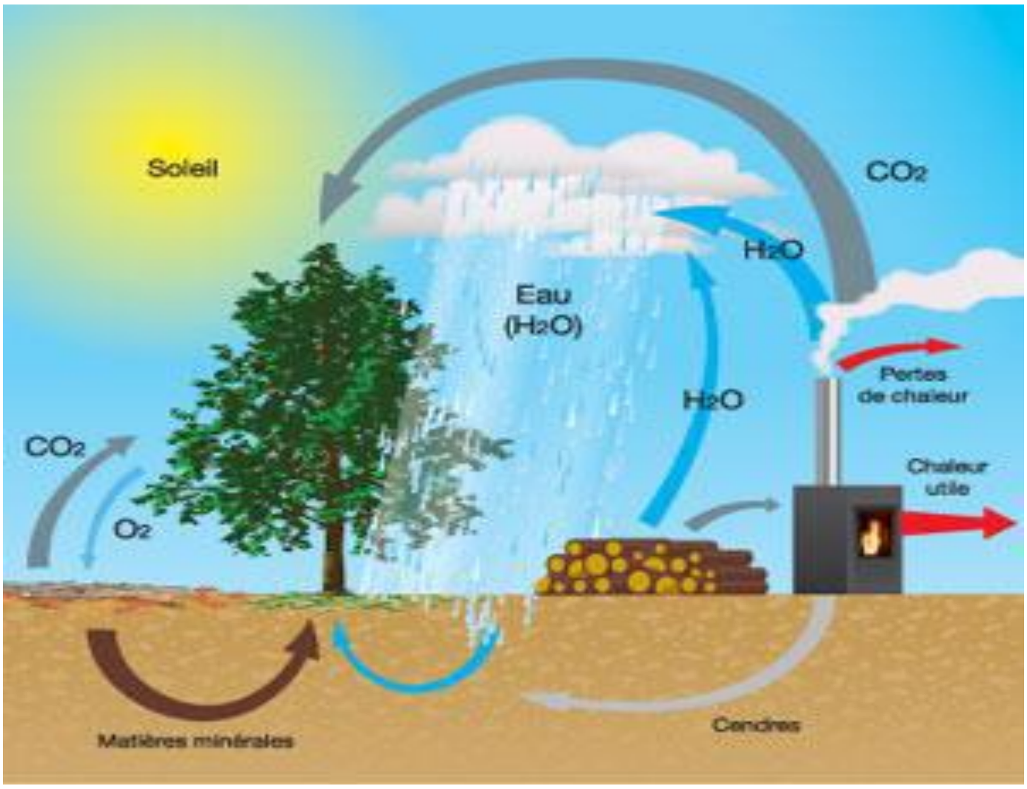


Figure 09 : *Biomass principle [20]*

4.9 Biomass renewable energy from plants and animals

Biomass is renewable organic material that comes from plants and animals. Biomass contains stored chemical energy from the sun that is produced by plants through photosynthesis. Biomass can be burned directly for heat or converted to liquid and gaseous fuels through various processes

Biomass was the largest source of total annual U.S. energy consumption until the mid-1800s. In 2022, biomass accounted for nearly 5% of U.S. total primary energy consumption. Biomass is used for heating and electricity generation and as a transportation fuel. Biomass is an important fuel in many countries, especially for cooking and heating in developing countries.

Biomass sources for energy include:

- Wood and wood processing waste—firewood, wood pellets, and wood chips, lumber and furniture mill sawdust and waste, and black liquor from pulp and paper mills
- Agricultural crops and waste materials—corn, soybeans, sugar cane, switchgrass, woody plants, algae, and crop and food processing residues, mostly to produce biofuels
- Biogenic materials in municipal solid waste—paper products; cotton and wool products; and food, yard, and wood wastes
- Animal manure and human sewage for producing biogas (renewable natural gas)

4.10 Biomass can be converted to energy in different ways

Biomass is converted to energy through various processes, including:

- Direct combustion (burning) to produce heat
- Thermochemical conversion to produce solid, gaseous, and liquid fuels
- Chemical conversion to produce liquid fuels
- Biological conversion to produce liquid and gaseous fuels

Direct combustion is the most common method for converting biomass to useful energy. All biomass can be burned directly for heating buildings and water, for providing industrial process heat, and for generating electricity in steam turbines.

Thermochemical conversion of biomass includes pyrolysis and gasification. Both processes are thermal decomposition processes wherein biomass feedstock materials are heated in closed, pressurized vessels called *gassifiers* at high temperatures. The processes mainly differ in the temperatures and in the amount of oxygen present during conversion.

- Pyrolysis entails heating organic materials to between 800° F and 900° F (400° C and 500° C) in the nearly complete absence of free oxygen. Biomass pyrolysis produces fuels such as charcoal, bio-oil, renewable diesel, methane, and hydrogen.
- Hydrotreating is used to process bio-oil (produced by *fast pyrolysis*) with hydrogen under elevated temperatures and pressures in the presence of a catalyst to produce renewable diesel, renewable gasoline, and renewable jet fuel.
- Gasification entails heating organic materials to between 1,400° F and 1,700 F (800° C and 900° C) with injections of controlled amounts of free oxygen or steam into the vessel to produce a carbon monoxide- and hydrogen-rich gas called synthesis gas or *syngas*. Syngas can be used as a fuel for diesel engines, for heating, and for generating electricity in gas turbines. It can also be treated to separate the hydrogen from the gas, and the hydrogen can be burned or used in fuel cells. The syngas can be further processed to produce liquid fuels using the Fischer–Tropsch process.

A chemical conversion process known as *transesterification* is used for converting vegetable oils, animal fats, and greases into fatty acid methyl esters (FAME) to produce biodiesel.

Biological conversion of biomass includes fermentation to make ethanol and anaerobic digestion to produce biogas. Ethanol is used as a vehicle fuel. Biogas, also called *biomethane* or *renewable natural gas*, is produced in anaerobic digesters at sewage treatment plants and at dairy and livestock operations. It also forms in and may be captured from solid waste landfills. Properly treated renewable natural gas has the same uses as fossil fuel natural gas.

4.11 Biomass provided about 5% of U.S. energy in 2022

In 2022, biomass accounted for 5% of U.S. energy consumption, or about 4,930 trillion British thermal units (TBtu). The types, amounts, and the percentage shares of total biomass energy consumption in 2022 were:

Biofuels—2,419 TBtu—49%

Wood and wood waste—1,984 TBtu—43%

Municipal solid waste, animal manure, and sewage—411 TBtu—8%

4.12 The industrial sector is the largest consumer of biomass for energy in the United States

The amounts—in TBtu—and percentage shares of total U.S. biomass energy use by consuming sector in 2022 were:

- Industrial—2,266 TBtu—46%
- Transportation—1,565 TBtu—32%
- Residential—539 TBtu—11%
- Electric power—413 TBtu—8%
- Commercial—147 TBtu—3%

The industrial sector accounted for the most, in terms of energy content and percentage share, of total annual U.S. biomass consumption in 2022. The wood products and paper industries use biomass in combined heat and power plants for process heat and to generate electricity for their own use.

The transportation sector accounted for the second-highest amount and percentage share of biomass (as biofuels) consumption in 2022.

The residential and commercial sectors use firewood and wood pellets for heating. The commercial sector also consumes, and in some cases, sells renewable natural gas produced at municipal sewage treatment facilities and at waste landfills.

The electric power sector uses wood and biomass-derived wastes to generate electricity for sale to the other sectors.

4.13 Cogeneration

Cogeneration is a system that produces two types of energy: heat and electricity. It allows the recovery of excess heat for heating, for example, instead of wasting it. To achieve this, a primary fuel is burned, which can be of fossil origin, such as coal or natural gas, but also biomass, significantly reducing polluting emissions.

The objectives of cogeneration are as follows:

- Reduction of polluting emissions,
- Energy self-sufficiency,
- Economic gain,
- Recovery of free heat,
- Waste recovery.

However, the initial cost of this technology is high. Cogeneration is used to operate engines and turbines. Growing interest in this ecological technology is currently allowing its implementation in small and medium-sized operations.

4.14 Efficiency

Power plants produce roughly twice as much energy as waste heat as electricity. Homes are usually heated with furnaces and also require fuel to generate their heat. Diverting some of the waste heat from electricity generation, saves substantial amounts of money and energy.

Producing the equivalent amount of heat and electricity using a CHP system is much more efficient as heat from electricity production can be usefully applied. The total efficiency of a CHP system is given by the total energy used, both electrical and heat energy, divided by the energy going in. A much smaller portion of the heat is unrecoverable, and still lost as waste heat.

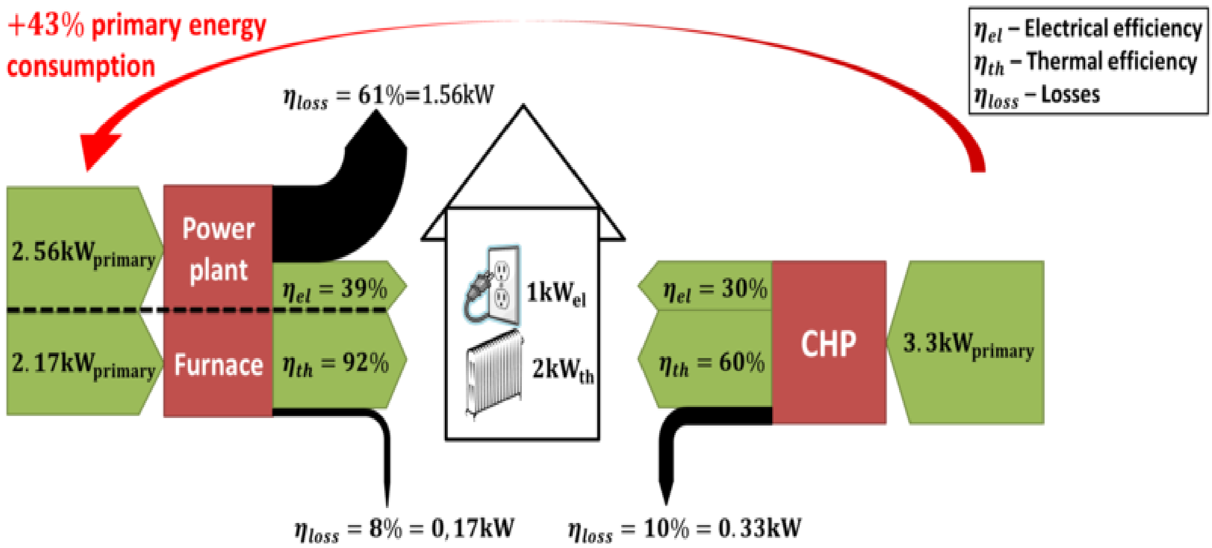


Figure 10: *Energy flow chart comparing the efficiency of separate generation and cogeneration.*

4.15 Efficiency calculations

A household has a specific thermal energy demand and a power demand Wel. The CHP has a thermal efficiency ηth, and an electrical efficiency ηel. Due to combined generation, the CHP efficiency is the sum of these efficiencies.

Types

The electrical output needed will contribute to the system size of the cogeneration unit. Typically, Micro-CHP will output less than 5 kilowatt (kW) while Mini-CHP will be greater than 5 kW and less than 500 kW. Micro-CHP systems are usually installed in homes and are heat demand controlled. This means that they turn on when there is a need for heat to produce the by-product heat while generating electricity.

The different types of Micro-CHP systems include for example:

- Micro gas turbines.
- Internal combustion engines.
- Fuel cells.
- Stirling engines.

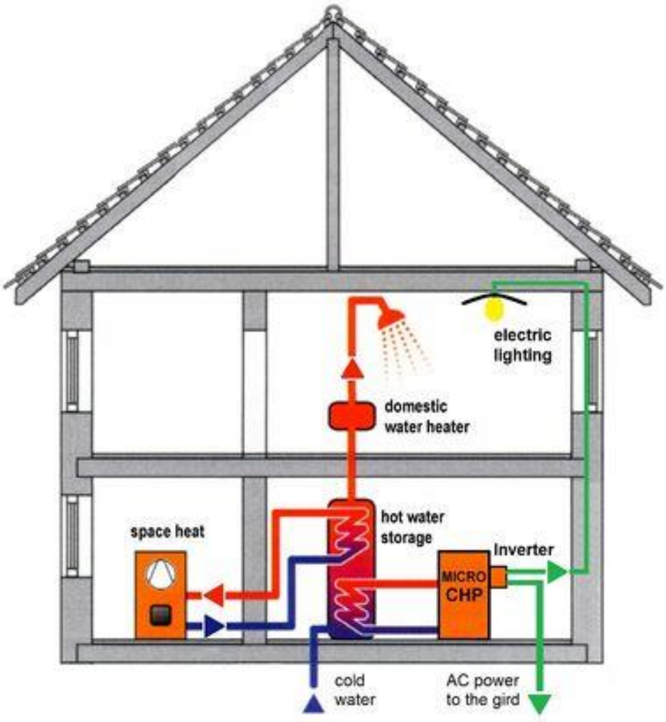


Figure 11: *Schematic view on a grid-connected residential cogeneration generation unit.*

4.16 Integrating CHP in the electricity grid

To integrate a CHP system onto the grid, it must first be connected to an inverter to convert DC electricity to AC electricity. This allows the generated electricity to be used by others on the grid. A high penetration rate of micro-CHP systems in homes has the potential to cause instabilities to the electrical grid. This is due to the difficulty in forecasting when these systems will generate electricity as they must be producing heat in the home in order to obtain the electricity required for the load. At peak hours when the electricity consumption is high, there is a greater need for additional electricity on the electric grid than in off-peak hours. Areas of interest addressing this issue include heat storage which may effectively make the CHP become electricity demand controlled instead of heat demand controlled. The system would generate electricity as required by the grid and store excess heat for use at another time.

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