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Ziane Achour University of Djelfa
جامعة زيان عاشور الجلفة

Faculty of Sciences and Technology
كلية العلوم والتكنولوجيا

Department of Mechanical Engineering
قسم الهندسة الميكانيكية

Course

Thermal and hydraulic machine technology

For L3 level Industrial Maintenance

Realized by:

Dr. AZIZI Hakim

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Teaching objectives

This program aims to give the student the fundamental bases of thermal and hydraulic machine technology, understand their operating principles, learn how to model and dimension them.

Recommended prior knowledge

MDF, Physics, Thermodynamics and Mathematics of L1 and L2, the student must be able to make calculations regarding thermodynamics, basic laws of heat transfer, Fourier's law, thermal conductivity and orders of magnitude for materials and fluids

Thanks

I would like to thank Mr. Mohamed CHEBOUT, Class A lecturer at Ziane Achour University of Djelfa and Mr. Naamane MOHDAB, Class A lecturer at the University of Jijel, for both taking the time to read this modest work and their valuable comments.

PREFACE

This handout aims to quickly present the widest possible range of basic knowledge on thermal and hydraulic machine technology. It is intended for third-year industrial maintenance (MI) students and all those who want to learn the operating principle of thermal and hydraulic machines.

The support developed respects the university program adopted for the training of License in MI in its content as well as in its educational architecture. This course is broken down according to the CANEVAS into seven (07) chapters:

Chapter I. Heat exchangers

- Types of exchangers.
- Evaluation of thermal performance.
- DTLM method
- NUT method.
- Exchanger technology.

Chapter II. Design of exchangers

- “Condenser” phase change exchanger.
- “Evaporator” phase change exchanger.

Chapter III. Boilers

- Coolant.
- Features.
- Types of boilers.
- Driving and maintenance.

Chapter IV. Steam turbine

- Functioning.
- Action turbines.
- Jet turbines.
- Centripetal turbines.

Chapter V. Turbine sizing

- Yields.
- Consumption.
- Regulation and safety devices.

Chapter VI. Gas turbine

- Cycles.

- Turbomotors and turbojets.

Chapter VII. Hydraulic turbines

- Kaplan turbine.
- Pelton turbine.
- Francis turbine.

The ideas of this course were mainly inspired by a large number of sources, the most relevant of which are cited in the bibliographical references section.

At the end of this course, exercises without solutions so that the student learns how to solve a problem in thermal and hydraulic machines and to enrich their skills and help them get closer to the industrial applications of the different installations studied during the training.

I hope that this modest work can help our students to fully understand and assimilate the principle of thermal and hydraulic machines.

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Chapter I: Heat exchangers

Chapter II: Design of exchangers

Chapter III: Boilers

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Chapter I: Heat exchangers

I.1. Introduction

A heat exchanger is a device for transferring thermal energy from one fluid to another, without mixing them. The heat flow crosses the exchange surface that separates the fluids. Most of the time, this method is used to cool or heat a liquid or gas that is impossible or difficult to cool or heat directly, for example the water in a primary cooling circuit of a nuclear power plant [1].

The functionalities of heat exchangers are extremely diverse and varied: the main ones are as follows:

- Preheater or cooler of a liquid or gas (air for example) for which many examples could be recalled and which is characterized by a simple function: controlling the temperature of the fluid at a particular point in the process.
- Thermal recuperator (figure I.1) which makes it possible to introduce the recent notion of valorization of the thermal energy of a process. The function of this exchanger is then to ensure the transfer of maximum thermal capacity in order to allow maximum recovery of thermal rejection based on energy and economic criteria.

Figure I.1.Example of thermal recovery

- Refrigerants (and air-refrigerant when the cooling vector is air, refrigerant on water) which ensures the dissipation of non-recoverable thermal energy from a process to the external environment, an essential function in many processes.
- Thermal sensors or transmitters whose equipment has the function, respectively, of associating reception of thermal energy and transmission to the use. The most common

examples are solar thermal collectors (figure I.2) as well as domestic radiators that provide thermal comfort in a building.

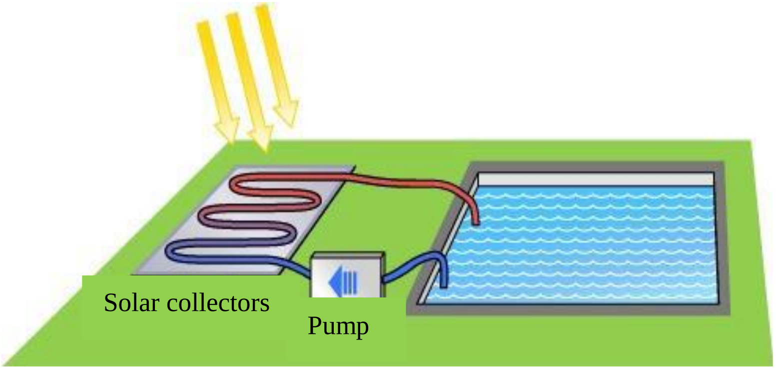


Figure I.2.Solar thermal collector

- Humidifiers (figure I.3) or partial condensers which ensure the condensation of a vapor mixed with a non-condensable gas to obtain, at the end of the operation, a gas depleted in vapor: the example frequently encountered is the dehumidifier of humid air which ensures control of the humidity of the air leaving the Air Handling Unit (CTA). Other industrial examples can be cited such as the capture of organic vapors in cryo-condensers or mist condensers frequently encountered in chemical engineering installations.

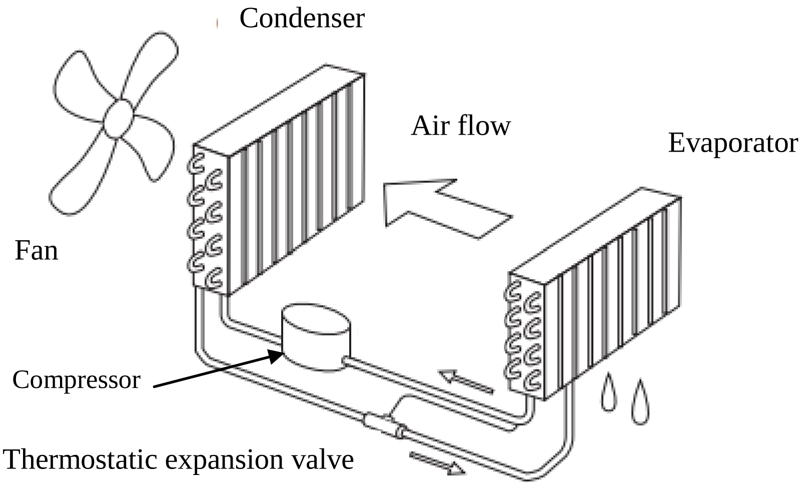


Figure I.3.Operating principle of a condensation humidifier according to Dantherm.

- Evaporators which ensure the complete or partial evaporation of a liquid in different processes, notably mechanical energy production (Rankine, Hirn engine cycle) and refrigeration production: compression cycle (PAC), refrigerator. Condensers which ensure the complete or partial condensation of a gas (steam), again for example for the production of mechanical and refrigeration energy

- Equipment which allows the freezing and melting of a liquid or vapor phase thanks to a wall cooled below the triple point of the fluid. These devices are used to ensure the separation of several bodies, provide thermal energy storage (ice storage or MCP storage), and produce a solid phase for various uses.
- The heat pipe, a true two-phase thermal system, which notably ensures the dissipation of the heat generated by the electronic elements (figure I.5) (Microprocessor or on-board electronics), the recovery of energy, the maintenance in stable and uniform temperature [2].

Figure I.4.Computer processor heat sink with copper heat pipe.

I.2. Fundamentals

The heat exchanger is a piece of equipment that ensures heat transfer from a hot fluid to a cold fluid without direct contact between the two fluids. The same fluid can retain its physical state (liquid or gas) or appear successively in the two phases: this is the case for condensers, evaporators, boilers, or cooling towers. In principle, for the most common exchangers in the industry, the two fluids flow in spaces separated by a wall or partition with low thermal inertia through which the exchanges take place by conduction. Indeed, the heat that one of the fluids transfers to the wall by convection along the contact surface is transferred by conduction and is transferred to the other fluid by convection along the other face [3].

Radiation only intervenes significantly if there are very significant temperature differences between a fluid and the wall [3].

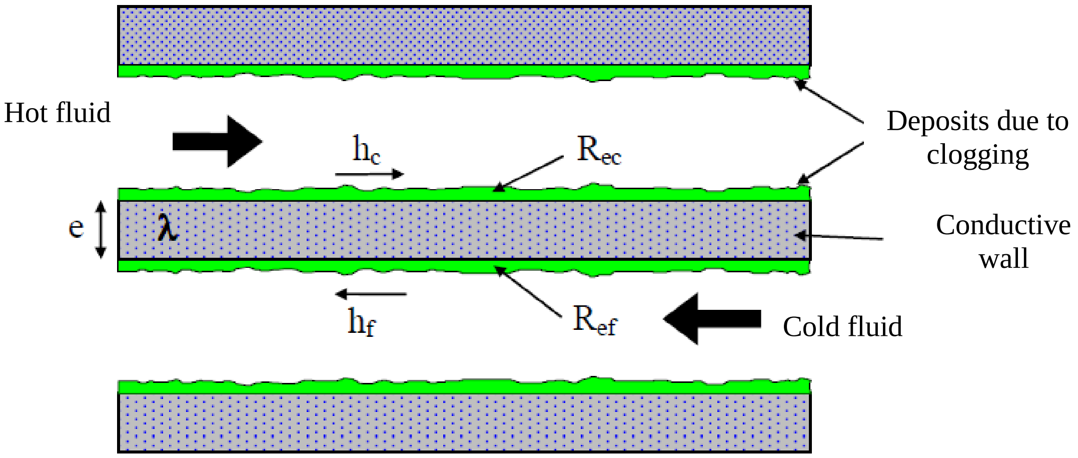


Figure I.5. Principe de fonctionnement d'un Echangeur

I.2.1. Why are exchangers used? [4].

- ➢ Each time we need to heat or cool a fluid using another fluid (hot or cold coils, evaporator or condenser, cooling tower, etc.).
- ➢ When two fluid distribution networks must be separated for health problems (solar water heater; etc.).
- ➢ When two fluid distribution networks must be separated for pressure problems (district heating).

I.2.2. General operation of a heat exchanger

There are many heat exchanger technologies, but they all operate following the same physical exchange processes, that is to say [5]:

- ➢ Conduction which represents exchanges through the walls (most often metallic),
- ➢ Convection which represents the exchanges between the fluids and the walls,
- ➢ The radiation which represents the radiative exchanges between the fluids and the walls (mainly infrared) although the latter is often negligible (because only taken into account for operation at high temperature).

We also distinguish three different flow modes:

- ✓ That with co-currents: parallel flows of fluids and in the same direction.
- ✓ Countercurrent: parallel flows of fluids but in opposite directions.
- ✓ That with cross currents: perpendicular flows between the two fluids.

I.2.3. The different types of heating

There are two types of heating [6]:

- Anti-methodical heating: parallel current exchanger in the same direction.
- Methodical heating: parallel current exchanger in opposite directions.

I.3. Classification of exchangers

There are several classification criteria for different types of exchangers. Let's list the main ones [7].

I.3.1. Contact type

- Direct contact exchangers: The simplest type includes a container or pipe in which the two fluids are directly mixed and reach the same final temperature.
- Indirect contact exchangers: the two fluids flow in spaces separated by a wall.

I.3.2. Classification according to types of exchange

a. Exchanger without phase change

Heat exchangers without phase change correspond to exchangers in which one of the fluids cools to heat the second fluid without there being a phase change. The temperatures of the fluids are therefore variable, all along the exchanger. [8].

b. Exchanger with phase change:

Exchanges with phase change are characterized by three different cases [8]:

- One of the fluids condenses while the other vaporizes: these exchangers are found in refrigerating machines.
- The secondary fluid vaporizes by receiving heat from the primary fluid, which does not undergo a change of state. They are called evaporators.
- The primary fluid condenses by giving up its latent heat to the colder secondary fluid, which does not undergo any state transformation.

I.3.3. Classification according to the arrangement of the flows

In separate fluid exchangers, the modes of fluid circulation can be divided into two categories [8].

- Same meaning “co-currents”.

- Opposite direction “counter-current”.
- Cross flow exchanger the movement of fluids is crossed

I.3.4. Functional classification

The passage of fluids in the exchanger can be carried out with or without phase change; depending on the case, we say that we have a single-phase or two-phase flow. We encounter [8].

So the following different cases:

- Both fluids have single-phase flow;
- A single fluid flows with phase change, in the case of evaporators or condensers;

I.3.5. Classification according to the compactness of the exchanger

Compactness is defined by the ratio of the area of the exchange surface to the volume of the exchanger. An exchanger is considered compact if its compactness is greater than $700 m^2/m^3$; this value is likely to vary from 500 to 800 m^2/m^3 [8].

I.3.6. Classification according to the nature of the material of the exchange wall

We will consider two types of wall: metallic exchangers made of steel, copper, aluminum or special materials: superalloys, metals or refractory alloys [8].

- Non-metallic exchangers made of plastic, ceramic, graphite, glass, etc.

I.3.7. Technology ranking

The main types of exchangers encountered are the following [8]:

- Tubes: monotubes, coaxial or multitubular;
- With plates: with primary surface or secondary surface;
- Other types: direct contact, heat pipes or fluidized bed.

a. Tubular exchangers

For economic reasons, exchangers using tubes as the main constituent of the exchange wall are the most widespread. We can distinguish three categories depending on the number of tubes and their arrangement, always made to have the best possible efficiency for a given use [8]:

- Single-tube exchanger, in which the tube is placed inside a tank and generally has the shape of a coil;
- Coaxial exchanger in which the tubes are most often bent; Generally, hot fluid or high pressure fluid flows into the inner tube;
- multi-tubular changer, available in four forms:
  - ✓ Separate tube exchanger: inside a tube of sufficient diameter are placed several tubes of small diameter held apart by spacers. The exchanger can be either straight or rolled,
  - ✓ Close tube exchanger: to maintain the tubes and obtain sufficient passage for the fluid outside the tube, a ribbon wound in a spiral is placed around some of them. The tubes lean on each other via ribbons,
  - ✓ Finned tube exchanger: these tubes improve the heat exchange coefficient.
  - ✓ Tube and shell exchanger: this is the most common exchanger currently;

b. Plate exchangers

These exchangers were originally designed to meet the needs of the dairy industry. Depending on the channel geometry used, we distinguish between primary surface exchangers and secondary surface exchangers [8].

Figure. I.6. Example of a plate heat exchanger

Primary surface exchangers are made up of corrugated plates (figure I 6), ribbed or pimpled. The design of the plate profile can be quite varied but it always has a dual role of intensifying heat transfer and resisting pressure.

I.4. The different types of exchangers

I.4.1. Spiral exchanger

A spiral exchanger (Figure I.7) consists of 2 metal plates wound helically to form a pair of spiral channels. The diameter of the exchanger is relatively large, with a maximum exchange surface of approximately 450 m2 for a diameter of 3 m2, which places it in the category of non-compact exchangers. The heat exchange is not as good as that of the plate exchanger, because the exchange surface does not generally have a profile, but for the same exchange capacity, a spiral exchanger requires 20%. less exchange surface than a tube bundle exchanger. It can be used for viscous liquids or liquid-solid mixtures and has a self-cleaning capacity guaranteeing reduced clogging compared to the tube bundle exchanger. It can only work with limited temperature and pressure differences [9].

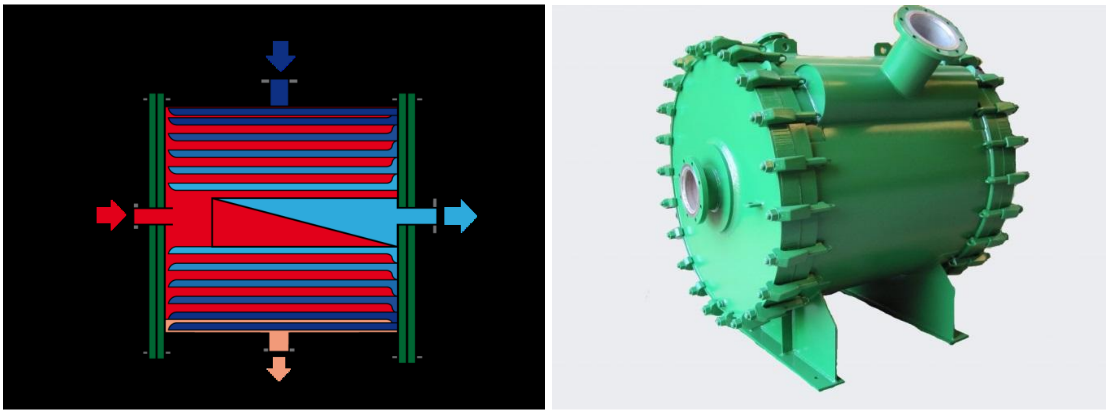


Figure I.7. Example of a spiral heat exchanger

I.4.2. Block exchanger

The block exchanger (figure I.8) is a type of heat exchanger reserved for particular applications. It consists of a block of thermally conductive material pierced with multiple channels in which the two fluids circulate. The block is most often composed of graphite sometimes added with polymers to improve the mechanical properties of the exchanger. The block is placed in a structure which ensures the distribution of liquids in the channels [9].

The block can have different shapes: cylindrical or cubic. It can also be composed of a single block or of several parts stacked so as to allow fluids to pass from one part to another. The advantage of this type of heat exchanger is mainly its chemical resistance to corrosive liquids as well as its modular capacity: the block can easily be replaced in the event of leaks. The fact that the ratio of free volume for the passage of fluids/volume of the block is very small creates great inertia in the case of temperature changes: the block acts as a reservoir and can smooth out temperature differences.

The blocks are, however, fragile both to shocks and to large temperature variations (problem of non-uniform expansion which can lead to cracking of the block). The price is relatively high compared to other types of exchangers and the heat transfer is generally average: the thickness of the exchange wall is greater than for a metal exchange surface due to fragility, this which increases the resistance to transfer [9].

Figure I.8. Block Exchanger

I.4.3. Bouhy column

An excellent alternative to plate exchangers in compressed air dryers, the Bouhy column (figure.9) is in fact a pinhead exchanger to which a centrifugal air/water separator has been added in the lower part. The device has two coaxial exchangers, the first serving to bring the air below its dew point, the second serving both to bring the air back to a temperature suitable for its use and above all to increase the efficiency of the cooling. This type of exchanger is characterized by a very low pressure loss [9].

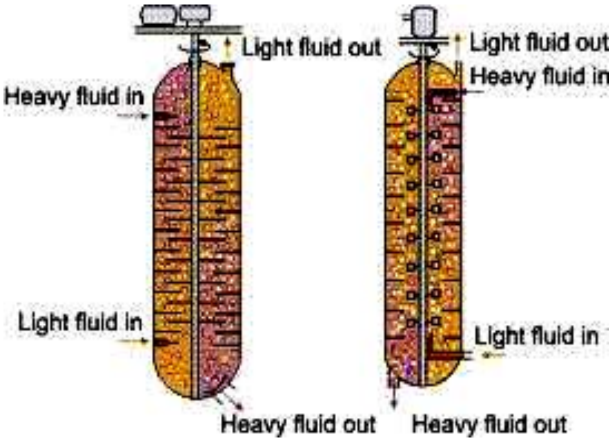


Figure I.9. Bouhy column

I.4.4. Finned exchanger

A finned exchanger (figure I.10) is a relatively simple exchanger: it consists of a cylindrical or rectangular conduit to which metal blades of different shapes are fixed. The cooling fluid is generally ambient air. Heat is transferred from the hot fluid circulating in the main conduit to the metal blades by thermal conduction; these blades cool on contact with air. This type of exchanger is used for heating in buildings: water is heated in the heating installation and circulates in radiators which are finned exchangers [9].

This type of installation is also used to cool car engines or engines of all kinds. In the latter case, the heat due to friction and magnetic induction (case of an electric motor) is directly transferred to the external protection of the motor which has fins fixed to its surface.

Heat transfer is limited, particularly on the cooling fluid side, due to the lack of a circulation system: the air circulates mainly by natural convection around the exchanger. This limitation can, however, be removed by adding a ventilation system. This exchanger is very simple and can take particular shapes, which makes it interesting in electronics.

Figure I.10. Finned heat exchanger

I.4.5. Cooling tower

Air-refrigerating towers or TAR (fig.11), also called cooling towers, are used to cool a liquid, generally water, using a gas, generally ambient air. This is a special case of a heat exchanger where heat transfer takes place by direct or indirect contact between the flows. Cooling towers are common equipment, present in air conditioning installations, or in industrial and energy processes (power plants, combustion installations, sugar factories, chemicals, etc.) [9].

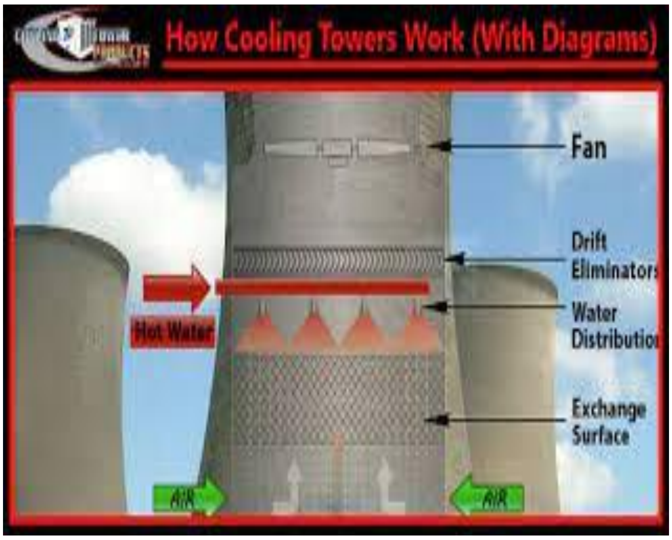


Figure I.11. Represents an air-cooling tower

a. Closed interchanges

In these exchangers, the fluid to be cooled remains confined in layers of pipes. The cooling air is renewed by natural convection or is supplied by fans. These exchangers make it possible to avoid pollution of the liquid to be cooled by dust present in the cooling air. Likewise, they avoid air pollution when the liquid to be cooled presents chemical or bacteriological risks. Another advantage of this construction is that it allows high pressure fluids to be cooled. On the other hand, these exchangers are quite sensitive to frost.

The pipes, however, hamper this type of exchanger, both because of their cost and their role as a heat shield. To improve the efficiency of these exchangers, pipe watering systems are sometimes added, the evaporation of which allows cooling to the wet bulb temperature.

b. Open interchanges

Hot water (whose temperature depends on the equipment to be cooled, generally 25 to -40°C) is sprayed towards the top of the TAR. The air induced naturally by draft, or mechanically by ventilation, allows the water to be cooled by evaporation. The surface area of the air/water exchange is increased by the presence of structures, the “shelves” or the “packing”, generally in the shape of honeycombs. The air rejected by the tower is loaded with water vapor due to evaporation (plume), and fine water droplets. The cooled water (between 5 and 10°C lower than the temperature of the hot water) is collected in a basin before being pumped to the equipment to be cooled.

This water falls by gravitation inside a flow of fresh air rising in the tower. This air circulation makes it possible to cool the water by vaporizing part of the sprayed water.

Inside a cooling tower, the water to be cooled is sprayed into fine droplets at the distribution ramps. The water flows over an exchange surface, the shelves, which, due to their structure, split the water drops and increase their residence time. The cooled water is collected in a retention basin at the bottom of the tower before returning to the exchanger or the process to be cooled. The air is, for its part, set in motion by a fan (forced draft) or by a current of air (natural draft). This air flow is loaded with humidity and carries water droplets. A droplet separator is sometimes placed at the top of the tower in order to limit the entrainment of droplets outside the tower as much as possible.

The water falls into a cold water basin (we also find the term “warm water”) where it is recovered and returned to the installation to be cooled. Depending on the air ejection speeds, the geometric design of the tower, the effectiveness of the droplet guards, etc., the aerosols produced may be in greater or lesser quantities in the rejected air.

In order to compensate for the loss of water caused by evaporation, additional treated water makes it possible to maintain a constant level in the water table or the tower tank.

I.4.6. Horizontal tube bundle exchanger

As their name indicates, tubular exchangers are made up of tubes whose wall forms the exchange surface. They comprise either a single tube (coil), or two coaxial tubes (twin-tube exchangers), or a bundle of tubes enclosed in an envelope called a shell [9].

a. Floating head exchangers

One of the tubular plates is fixed (figure I.12), the second plate, of a smaller diameter, carries the return box and can slide freely from inside the cover which closes the grille.

These devices allow the thermal expansion of the beam as well as its mechanical cleaning, constitute almost all of the exchangers used in refineries [9].

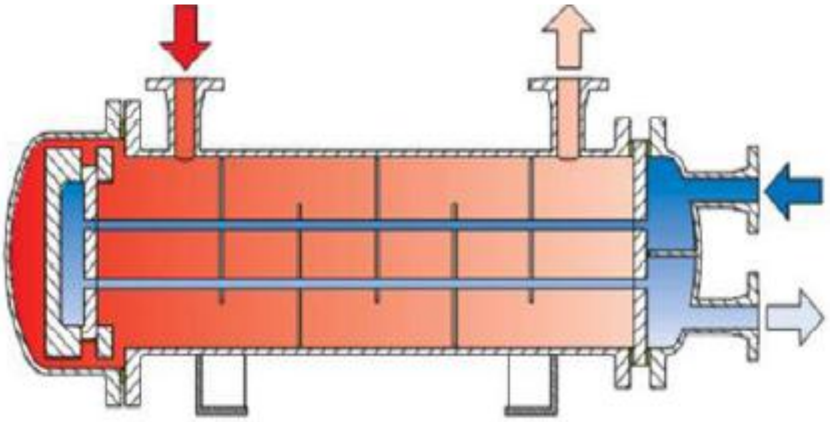


Figure I.12. Floating head exchangers

b. U-tube exchangers

The use of elbow tubes eliminates a tube plate (figure I.13), while retaining the expansion properties of the floating head. The saving made by the cost of a tube plate is offset by the impossibility of cleaning mechanics of the interior of the tubes, these bundles will be mainly used in steam reboilers [9].

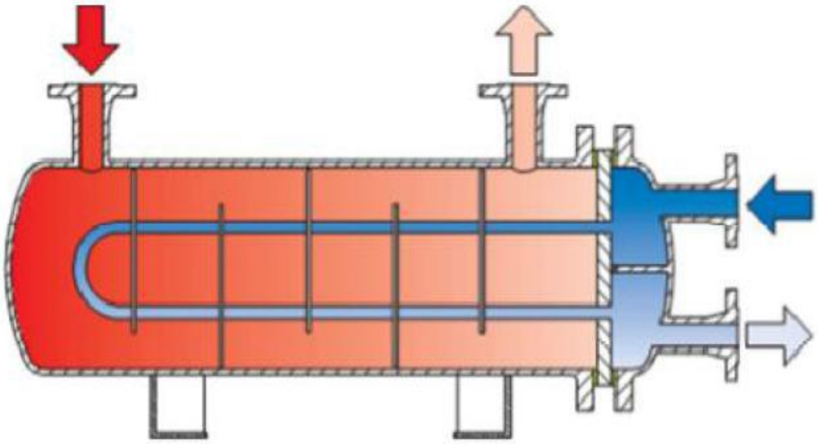


Figure I.13.U-tube exchanger

c. Fixed tube plate exchangers

Welded on the calender (figure I.14), they can only be used if the temperature difference between the hot and cold fluids is sufficiently low for the expansion of the beam to be acceptable [9].

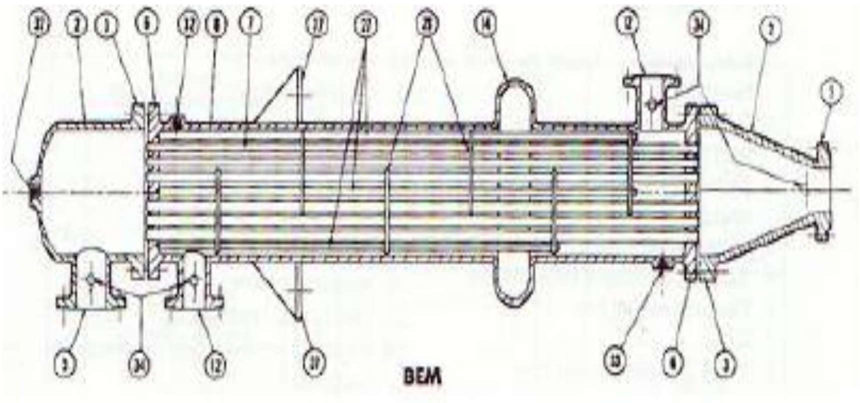


Figure .I. 14.Fixed tube plate exchanger

I.4.7. Beam and calender exchangers

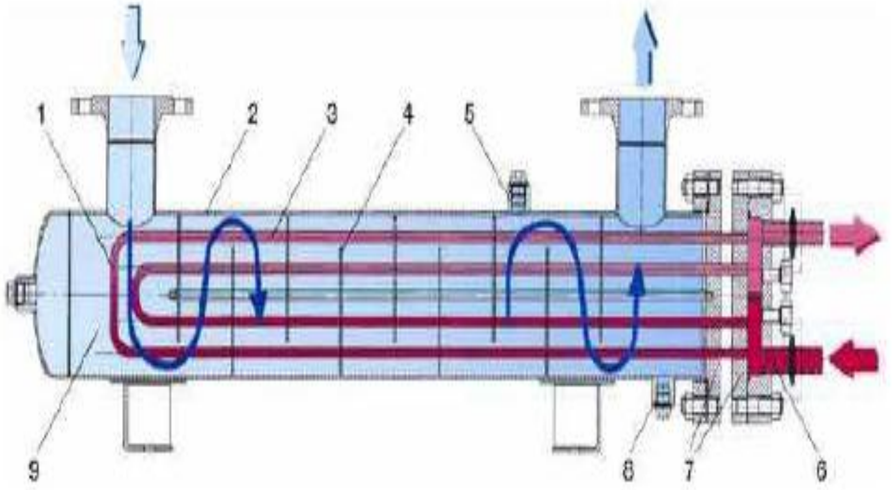


Figure I.15. Typical diagram of a shell and tube exchanger

1. Tube bundle
2. Envelope (grille)
3. Interior tube 4. Baffle
5. Vent connection
6. Interior water box
7. Tube plate
8. Drain connection
9. Interior envelope

This type of exchanger is by far the most common in processing units in the chemical and petrochemical industries. A bundle of tubes is located inside a calender (figure I.15) in which the second fluid circulates. This design is also found in condensers, reboilers and multi-tube furnaces [10].

- **The grille**

This is the metal casing surrounding the tubular bundle. Carbon steel is the most commonly used material for grille construction. At each end the flanges which will carry the cover and the distribution box are welded. The inlet and outlet pipes are welded with reinforcement plates, depending on the operating pressure. Finally, the grille can be equipped with lifting rings and will carry the device's identity plate.

- **Tubular plates**

These are pierced plates (figure 16) supporting the tubes at their ends, their thicknesses vary between 5 and 10 cm. The tubes are generally fixed by: mandling, dudgeon swimming, and by welding in high pressure applications [10].

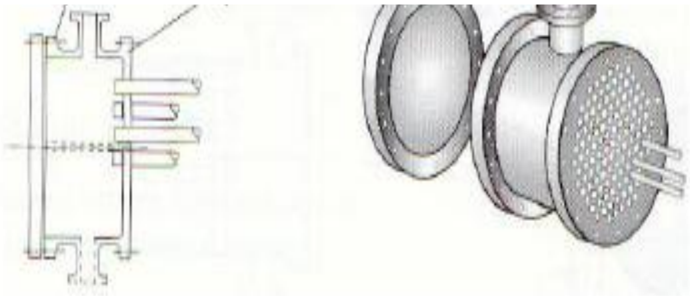


Figure I.16.Tube sheets

- **The beam**

This is the set of tubes constituting the bundle (figure 17). The tube thicknesses are standardized according to the BWG (Birmingham wire Gage). The perforation of the holes in the tube sheets is standardized; it is carried out according to an arrangement either in square pitch or in triangular pitch. The pitch is the center-to-center distance of two neighboring tubes.

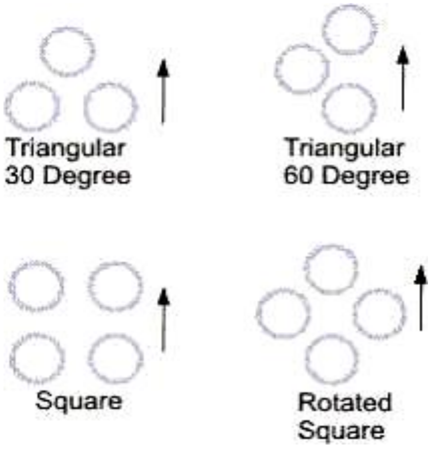


Figure I.17. Tube layout

The triangular pitch allows approximately 10% more tubes to be placed than the square pitch on a tubular plate of a given diameter, but in return, the arrangement of the tubes makes it impossible to clean them externally by inserting scrapers or scrapers through the bundle. For these devices, chemical cleaning must be used and their use reserved for clean fluids [10].

- **The chicanes**

Baffles can have two roles [10]:

- ✓ Increase the rigidity of the beam, to avoid vibration phenomena
- ✓ Increase fluid velocity

There are two types of baffles:

- **The transverse chicanes**

Are generally made up of a disc having a diameter slightly smaller than that of the calender and comprising a free segment whose surface represents 20 to 45% of the total section (figure I.18). These baffles are intended to lengthen the path of the fluid circulating in the calender, and thus improve the transfer outside the tube. In the case of horizontal exchangers, a notch is provided in the lower part of the baffles to facilitate emptying and cleaning and to prevent clogging by stagnation in the lower part [10].

The transverse baffles ensure the rigidity of the tubular bundle, they are attached to the fixed tubular plate by means of tie rods and spacers which occupy the place of standard tubes (TEMA) impose a number of tie rods between 4 to 10.

- **Longitudinal baffles**

Are generally made up of a simple sheet inserted in the middle of the beam, this arrangement forces the fluid to go back and forth in the calender [9].

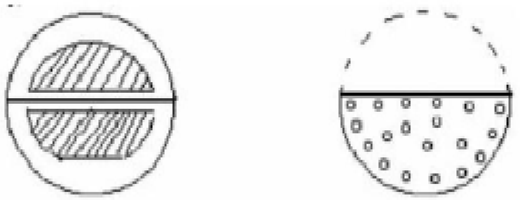


Figure I.18. Baffle type

- **Distribution boxes or distribution chambers**

The distribution chamber or distribution boxes (figure I. 19) allows the fluid to be distributed in order to carry out 1, 2, 4, 6 or 8 passes. The number of passes is generally limited by the admissible pressure loss. The second limiting factor is if the temperature difference at the inlet and outlet is large; for a difference of 150 °C a single pass is required [9].

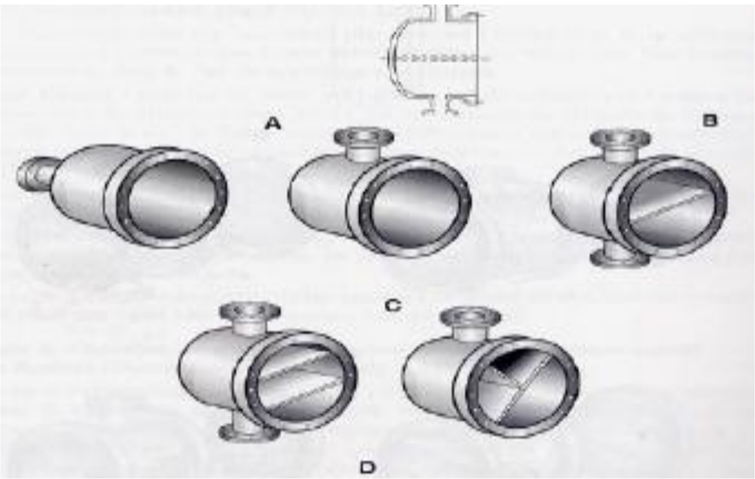


Figure I.19. Distribution chamber type

- **Deflectors or beam protection plate**

To avoid or at least minimize erosion of the beam tube, protective deflectors (figure I.21) can be installed facing the fluid inlet pipes on the calender side, the obligation for their installation is defined in the standards (TEMA) depending on the nature, the state of the fluid and the product ρu2 (ρ: density, u speed of the fluid) these deflectors, with a thickness of around 1/2in, are circular, square or rectangular, welded on tie rods or spacers [9].

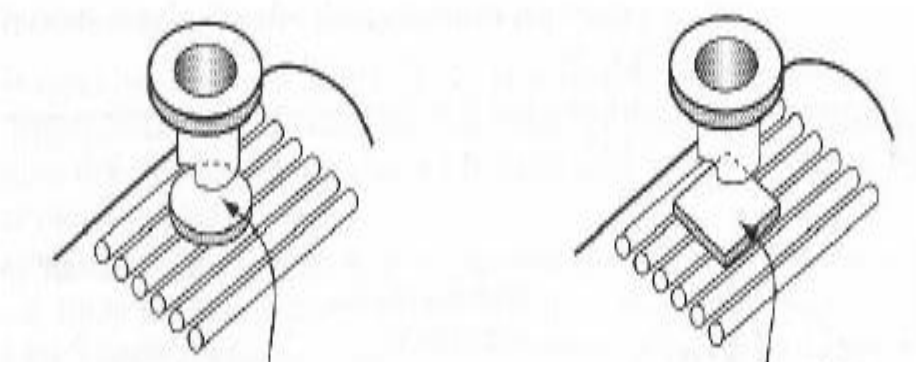


Figure I.20. Harness protection plate

- **The passes**

In the simplest arrangement, tube-side and shell-side fluids enter at one end and exit at the other. We then say that there is only one pass (a single pass) on the tube side and the calender side. Fluids can enter on the same side, (co-flow) or on opposite sides (counter-flow) [10].

Heat transfer is improved when the speed and agitation of the fluid increases. It often happens that with a single pass arrangement the fluid velocity is too low. To increase this speed while maintaining the same number of tubes (same exchange surface), we resort to multiplying the number of passes: on the tube side, we make the fluid travel along the exchanger in one direction in certain tubes, in the other direction in other tubes, etc. We thus construct exchangers having 2, 4, 6, 8 passes on the tube side. This is achieved by installing properly compartmentalized distribution boxes at the ends of the tube bundles.

The exchange coefficient increases at speed 0.8 while the pressure loss increases at speed 2. The pressure loss therefore increases much faster than the heat exchange and in practice we recommend speeds in the tubes higher than 1m/ dry but less than 3m/sec.

On the calender side, we adjust the speed of the fluid in the calender by installing transverse baffles as a priority which will also ensure the support of the tubes. Multiple passes can also be established by installing longitudinal baffles. However, this solution is often not adopted because it makes cleaning the bundle between the tubes more difficult.

All elements used in the construction of these exchangers have been subject to standardization, both by TEMA (Tubular Exchangers Manufacturer's Association) and ASME (American Society of Mechanical Engineers) or API (American Petroleum Institute). .In order to classify the multitudes of devices, the American Association of Tubular Exchanger Manufacturers has defined a symbolism according to which each type of inlet box, calender and return box is characterized by a letter. Thus, any exchanger is defined by three letters [11].

I.5. Conclusion

Heat exchangers are used mainly in the industrial sectors (chemicals, petrochemicals, steel, agri-food, energy production, etc.), transport (automobile, aeronautics), but also in the residential and tertiary sectors (heating). , air conditioning, etc.).

The choice of a heat exchanger for a given application depends on numerous parameters: temperature and pressure range of the fluids, physical properties and aggressiveness of these fluids, maintenance and size. It is obvious that having a well-adapted, well-sized, well-made and well-used exchanger allows a gain in efficiency and energy in the processes.

Chapter II: Design of exchangers

II.1. Introduction

The design of a two-fluid heat exchanger aims to recover waste heat. The problem of thermal sizing in an industrial installation begins first of all with the selection of the type of exchanger adapted to the problem posed, then comes the thermal sizing phase itself; it is intended to fix by calculating the exchange surface necessary for the transfer of power on the fluids considered [12].

The first analysis method used is the average logarithmic temperature difference method DTLM, it makes it possible to determine the energy parameters of this equipment, according to the inlet and outlet temperatures of the two fluids. These fundamental dimensional parameters take into account the thermal and physical properties of the fluids and the heat exchanger material.

The method of the number of transfer units NUT is the second method applied, makes it possible to calculate the overall exchange coefficient of the exchanger R, as well as the desired efficiency E. However, the NUT method is used for the sizing of the refrigeration installations or outlet temperatures are not known [12].

II.2. Sizing and calculation of an exchanger

In any heat exchanger calculation, the goal is to obtain the recovery of a certain quantity of heat under optimal economic conditions which is a compromise between investment costs and operating costs [12].

There are two methods of calculating and sizing heat exchangers:

- Analytical methods: such as the DTLM method, and the NUT method.
- Numerical methods: finite volume method and the enthalpy-temperature diagram method.

II.2.1. Thermal quantities

In order to successfully explain the phenomena of heat transfer from one medium to another, and more generally of heat conservation in isolated systems, it is necessary to define a certain number of physical quantities. For a given quantity of matter, the addition of a quantity of heat induces a change in its temperature or a change in the state of the matter. Temperature for its part is a physical quantity which characterizes an energy level of matter. These different notions will be explained below [13].

II.2.1.1. Temperature

Hot and cold are appreciated by sensations, hence an irrational evaluation of these quantities. Temperature characterizes the level at which the heat is found in a body, thus making it possible to say that one body is more or less hot than another [13].

II.2.1.2. Temperature field

At any point in space where matter is found, we define a scalar temperature function, T (x, y, z, t) as a function of the coordinates of the point as well as time.

The set of instantaneous temperature values throughout space is called “temperature field” [13].

II.2.1.3. Heat flux

Heat flows under the influence of a temperature gradient from high to low temperatures. The quantity of heat transmitted per unit of time and per unit of area of

the isothermal surface is called heat flux density φ [13]:

$$\varphi = \frac{1}{S}\frac{dQ}{dt} \qquad \text{(II.1)}$$

We call heat flow φ the quantity of heat transmitted on the surface S per unit of time

II.2.1.4. The heat

Heat is a form of energy (energy of movement of molecules) that goes from a hot spot (higher temperature) to a cold spot (lower temperature) [13].

II.2.1.5. Specific heat

By definition, the specific heat CP corresponds to the quantity of heat that must be supplied to a material of a given mass for its temperature to rise by one degree. That is to say the quantity of heat exchanged between two bodies respectively at temperature T_1 and T_2 ($T_1>T_2$) is expressed by [13]:

$$C_P = \frac{1}{S}\frac{dQ}{dT} \qquad \text{(II.2)}$$

II.2.1.6. Thermal conductivity

Thermal conductivity is a physical quantity characterizing the behavior of materials during heat transfer by conduction. This constant appears in Fourier's law. It represents the quantity of heat transferred per unit area and per unit time under a temperature gradient. Conductivity mainly depends on:

- The nature of the material,
- Temperature.
- Other parameters like humidity and pressure.

Therefore, the thermal conductivity λ characterizes the ability of the material to transmit heat [14].

II.2.1.7. Contact resistance

The contact between two solids is only uniform on a macroscopic scale. At a more local level, for example on the scale of roughness, the contact is discontinuous. This discontinuity in thermal conductivity at the section level generates a discontinuity in the temperature profile. This phenomenon can be modeled by introducing the contact resistance RC defined by the following relation [14]:

$$R_C = \frac{1}{h_C} \tag{II.3}$$

Where:

h_C is the heat exchange coefficient

II.2.2. Physical quantities

II.2.2.1. Density (ρ)

It is the ratio of the mass of a material per unit volume. Also called density [15].

II.2.2.2. Viscosity (μ)

It is the property of a fluid which tends to prevent its flow when subjected to the application of a force. The more viscous the fluid (high viscosity) the more difficult its movement is [15].

II.2.2.3. The flow

It is the quantity of fluid that flows or is supplied per unit of time. There are two types of flow rates, mass flow and volume flow [15].

II.2.2.4. The Reynolds number

The REYNOLDS number is the ratio of inertia forces to viscosity forces given by the following formula [15]:

$$R_e = \frac{U.L}{V} = \frac{\rho.U.L}{\mu} \tag{II.4}$$

It characterizes the fluid flow regime.

The REYNOLDS experiment relating to flow in a cylindrical pipe highlighted two flow regimes characterized by a parameter (REYNOLDS number).

For low flow rates, the regime is said to be laminar. Otherwise, it is turbulent (figure II.1).

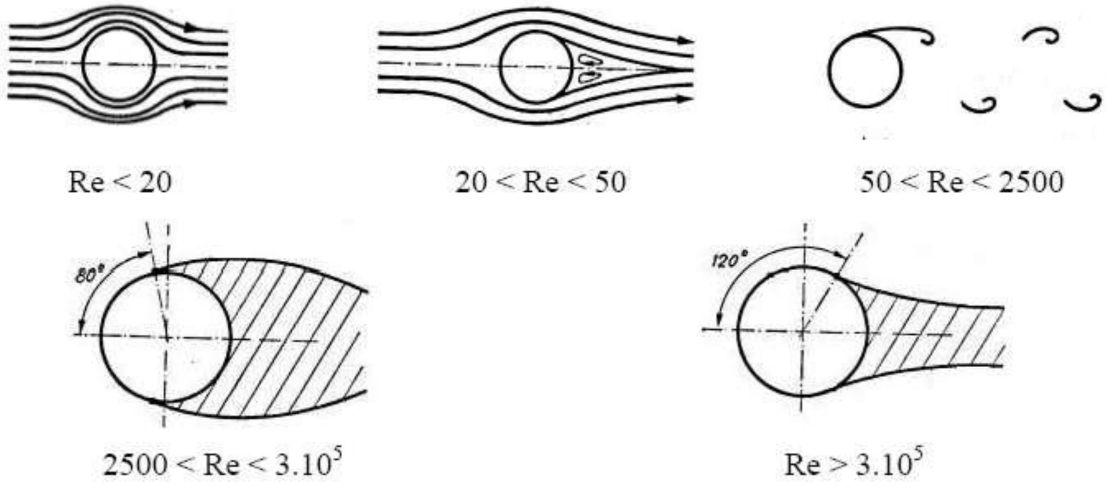
a.Laminar regime

The fluid streams are parallel, exchanges take place between the layers which are of molecular origin (conduction). The flow remains laminar as long as the REYNOLDS number remains below 2300 [16].

b. Turbulent regime

The flow is disturbed, the movement of fluid particles is random and three-dimensional. The flow regime is considered turbulent if the REYNOLDS number reaches or exceeds 10000.

The regime corresponding to the REYNOLDS number between 2300 and 10000 is said to be transient [16].



$Re < 20$ $\quad 20 < Re < 50$ $\quad 50 < Re < 2500$

$2500 < Re < 3.10^5$ $\quad Re > 3.10^5$

Figure II.1. Flow regimes

II.2.2.5. Nusselt number

This dimensionless number specifies the relative importance of the heat flow actually transmitted by convection with respect to a reference conductive heat flow for the problem [16].

$$N_U = \frac{h.L}{\lambda_f} \tag{II.5}$$

h: Local or global exchange coefficient depending on the cases considered.

In forced convection, the Nusselt number is linked to the Reynolds number and the Prandtl number.

II.2.2.6. Prandtl number

It characterizes the influence of the nature of the fluid on heat transfer by convection [16]:

$$p_r = \frac{C_P.\mu}{\lambda} \tag{II.6}$$

II.2.3. Heat transfer modes

II.2.3.1. Thermal conduction

Conduction (figure II.2) is mainly the transfer of heat from hot parts to cold parts, of the same body or two bodies in contact without apparent movement of the material. This mode can be carried out in solids and fluids. The conduction phenomenon is reacted by Fourier's law [17]:

$$\phi = -\lambda.\overrightarrow{gradT} \tag{II.7}$$

Then if a body at temperature T_1 is connected to a body at temperature T_2 via a thermal body of section S and thickness e. The heat flux which flows between the two bodies is given by the relation:

$$\phi = \lambda.S.\frac{(T_1 - T_2)}{e} \tag{II.8}$$

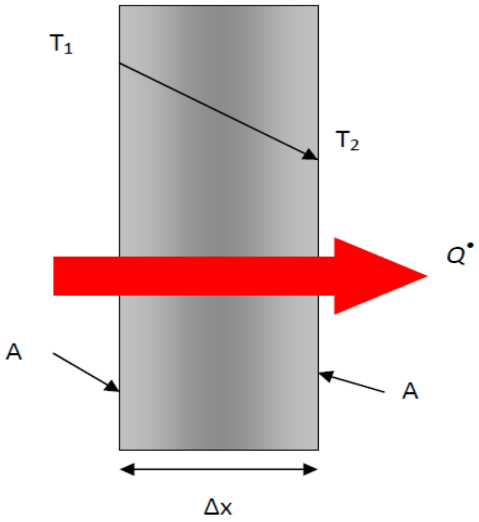


Figure II.2. Conduction de chaleur à travers une paroi

Figure II.2. Heat conduction through a wall

II.2.3.2. Thermal convection

The term convection (figure II.3) is used to describe the transfer of energy between a solid surface and a fluid moving relative to this surface. For this transfer, energy transport by conduction always takes place, however the dominant mode is that due to the movement of fluid particles [17].

$$\phi = h.S.(T_1 - T_2) \qquad \text{(II.9)}$$

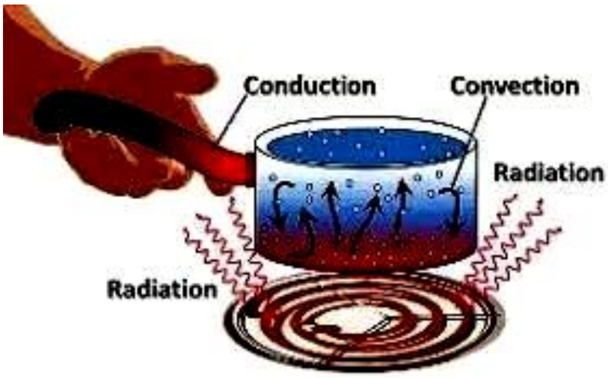


Figure II.3. Thermal convection phenomenon

a. Natural convection

Also called free convection, is caused by mass forces in the fluid due to differences in temperature and therefore density of the fluid.

b. Forced convection

When the movement of the fluid is created by a pressure difference (pump, blower) or an applied speed.

II.2.3.3. Radiation

Along with conduction and convection, thermal radiation is the third mode of heat transfer. Any body whose temperature is greater than 0 K emits thermal radiation. Unlike conduction and convection for which the transport of energy takes place thanks to the presence of matter (in fluid or solid form), the transfer of heat by radiation takes place in the form of electromagnetic waves and can be observed between two bodies placed in a vacuum (figure II.4), it is characterized by the Stephan-Boltzmann law [17]:

$$\phi = \sigma . S . T^4 \qquad \text{(II.10)}$$

$\phi = 5.67 * 10^{-8} \left[N.m^{-2}.K \right]$ Constant of Stephan Boltzmann.

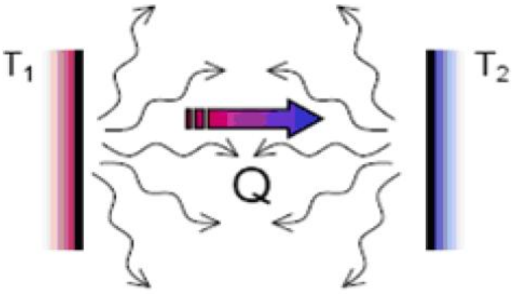


Figure II.4. Thermal radiation phenomenon

II.2.4. Study of an interchange

In the study of an exchanger, we always seek to obtain a given exchange power, with the smallest exchange surface and the least possible pressure losses, in other words best investment and operating costs. Constraints of size, weight, corrosion and standardization come into play, which means that the parameters available are generally much more numerous than the equations, with certain requirements being essentially technological or economic in nature. The complete study of an exchanger therefore calls upon different disciplines (thermal, fluid mechanics, technology, etc.) [18].

In our case, we only addressed the thermal aspect, in other words the evaluation of the thermal performance of the heat exchangers.

II.2.4.1. Overall heat transfer coefficient

The Heat Transfer Coefficient represents the "force" with which the power is transmitted between the wall and the fluid, this coefficient can be small which means that the heat is transmitted in an inefficient way. Likewise, this coefficient can take significant values which leads to a very efficient transfer.

This coefficient is directly affected by the physical properties of the fluids [17], [18].

$$\phi = h.S.(T_C - T_f) \tag{II.11}$$

II.2.4.2. Exchanger sizing methods

The methods intended for sizing and calculating exchangers are analytical or numerical.

a. Analytical methods

There are two calculation methods:

- Mean logarithmic temperature difference method, called DTLM method.
- Method of the number of transfer units, called NUT method, also used in chemical engineering for mass transfer [18].

b. Numerical methods

- Finite volume method
- Enthalpy-temperature diagram method.

II.2.4.2.1.Average Logarithmic Temperature Deference (DTLM)

This method makes it possible to determine the exchange surface S knowing the power exchanged and the inlet and outlet temperatures of the two hot and cold fluids [19]. Consider a simple tubular exchanger made up of two coaxial cylindrical tubes.

One fluid (usually the hot fluid) circulates in the inner tube, and the other in the annular space between the two tubes. The transfer of heat from the hot fluid to the cold fluid takes place through the wall which constitutes the inner tube. The hot fluid enters the exchanger at temperature T_{c1} and leaves at T_{c2} . The cold fluid enters at T_{F1} and exits at T_{F2} .

II.2.4.2.1.1.Study of anti-methodical heating

A section of an anti-method exchanger is made.

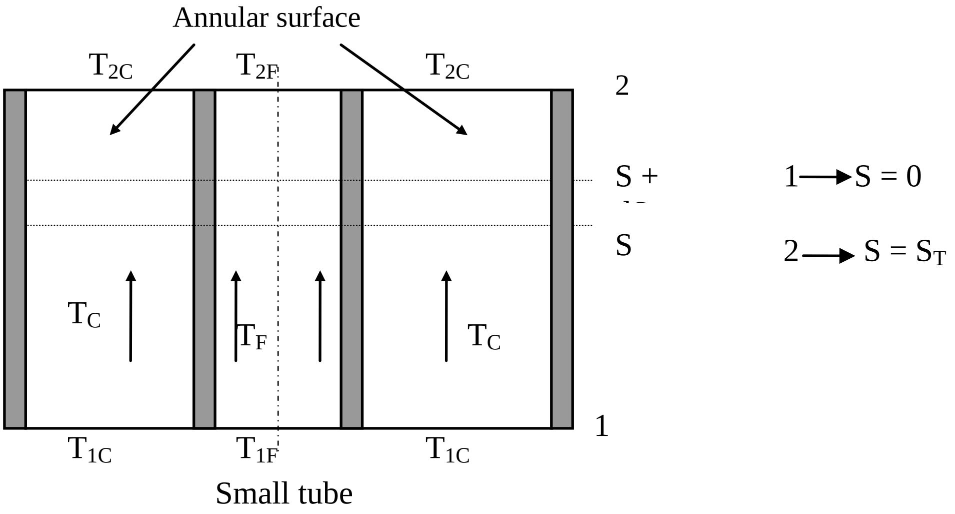


Figure II.5. Section of an anti-method exchanger

a.Calculation assumptions

K: Overall heat exchange coefficient representing the exchanges by convection between the fluids and the wall as well as the conduction inside the exchange surface S.

- ✓ We will assume that this coefficient K is constant.
- ✓ We will also assume C_{PC} and C_{PF} are constant.
- ✓ We will assume that there is no exchange with the outside world.

b. Energy balance

For a given exchange surface S: Φ: Heat flow.

Calorific power received by the cold fluid:

$$\Phi = q_{mF}\, Cp_F\, (T_F - T_{1F}) \tag{II.12}$$

Heat power lost by the hot fluid:

$$\Phi = q_{mC}\, Cp_C\, (T_{1C} - T_C) \tag{II.13}$$

Calorific power exchanged between the 2 fluids:

$$\phi = \int_0^S d\phi = \int_0^S K.\left(T_c - T_F\right).dS \tag{II.14}$$

Order

The fluid heats up.

$$d\Phi = q_{mF}\, Cp_F\, (\, dT_F\,) \qquad (II.15)$$

The fluid cools.

$$d\Phi = q_{mC}\, Cp_C\, (\, - dT_C\,) \qquad (II.16)$$

$$d\phi = \frac{-d\, T_C}{\frac{1}{qm_C\, .\, Cp_C}} = \frac{d\, T_F}{\frac{1}{qm_F\, .\, Cp_F}}\ , \qquad (II.17)$$

We add up.

$$d\phi = \frac{-d\left(T_C - T_F\right)}{\frac{1}{qm_C\, .\, Cp_C} + \frac{1}{qm_F\, .\, Cp_F}} \qquad (II.18)$$

So

$$K.\left(T_C - T_F\right).\, dS = \frac{-d\left(T_C - T_F\right)}{\frac{1}{qm_C\, .\, Cp_C} + \frac{1}{qm_F\, .\, Cp_F}} \qquad (II.19)$$

$$\frac{d\left(T_C - T_F\right)}{T_C - T_F} = -K.\left(\frac{1}{qm_C\, .\, Cp_C} + \frac{1}{qm_F\, .\, Cp_F}\right).\, dS\ , \qquad (II.20)$$

We pose

$$n = K.\left(\frac{1}{qm_C\, .\, Cp_C} + \frac{1}{qm_F\, .\, Cp_F}\right) \qquad (II.21)$$

$$\int_0^S \frac{d\left(T_C - T_F\right)}{T_C - T_F} = \int_0^S -n.\, dS \Rightarrow \ln\left(\frac{T_C - T_F}{T_{1C} - T_{1F}}\right) = -n.\, S\ , \qquad (II.22)$$

We can deduce:

$$T_C - T_F = \left(T_{1C} - T_{1F}\right).\, e^{-n.S} \qquad (II.23)$$

The heat flux at a given S can be expressed as a function of the inlet temperatures.

$$\phi = \int K.\left(T_C - T_F\right).\, dS = \int K.\left(T_{1C} - T_{1F}\right) e^{-n.S}\, .\, dS = K.\left(T_{1C} - T_{1F}\right).\, \frac{1 - e^{-n.S}}{n} \qquad (II.24)$$

Gold

$$-n.S=\ln\left(\frac{T_C-T_F}{T_{1C}-T_{1F}}\right).\Rightarrow e^{-n.S}=\frac{T_C-T_F}{T_{1C}-T_{1F}}\Rightarrow 1-e^{-n.S}=\frac{(T_{1C}-T_{1F})-(T_C-T_F)}{T_{1C}-T_{1F}} \qquad \text{(II.25)}$$

We replace and simplify:

$$\phi=K.S.\frac{(T_{1C}-T_{1F})-(T_C-T_F)}{\ln\left(\frac{T_{1C}-T_{1F}}{T_C-T_F}\right)}, \qquad \text{(II.26)}$$

Si $S = S_T$

$$\phi=K.S.\frac{(T_{1C}-T_{1F})-(T_{2C}-T_{2F})}{\ln\left(\frac{T_{1C}-T_{1F}}{T_{2C}-T_{2F}}\right)} \qquad \text{(II.27)}$$

We set DTLM (logarithmic average of the temperature difference):

$$DTLM=\frac{(T_{1C}-T_{1F})-(T_{2C}-T_{2F})}{\ln\left(\frac{T_{1C}-T_{1F}}{T_{2C}-T_{2F}}\right)} \qquad \text{(II.28)}$$

$$\Phi = q_{mF}\, Cp_F\, (T_{2F} - T_{1F}) = q_{mC}\, Cp_C\, (T_{1C} - T_{2C}) = K.S.\ DTLM \qquad \text{(II.29)}$$

We look at the evolution of temperatures in an anti-method exchanger:

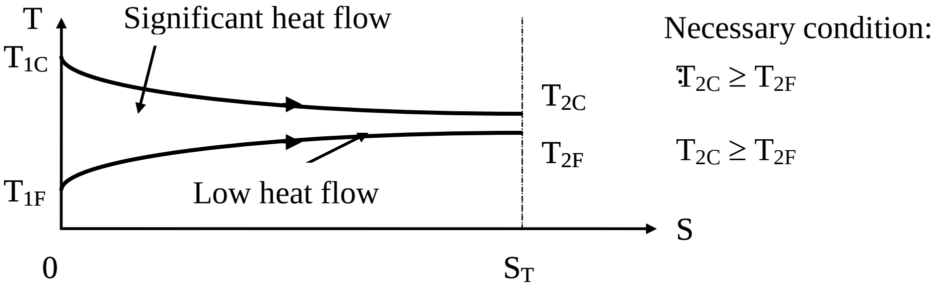


Figure II.6. Evolution of temperatures in an anti-method exchanger

$$DTLM=\frac{(\Delta T_{max})-(\Delta T_{min})}{\ln\left(\frac{\Delta T_{max}}{\Delta T_{min}}\right)} \qquad \text{(II.30)}$$

With:

$$\begin{cases}\Delta T_{max}=T_{1C}-T_{1F}\\ \Delta T_{min}=T_{2C}-T_{2F}\end{cases}$$

II.2.4.2.1.2.Study of methodical heating

In S = 0 Hot fluid inlet and cold fluid outlet

In S = S_T Cold fluid inlet and hot fluid outlet.

In the case of counter-current heating we arrive at the same expression:

$$\mathrm{DTLM} = \frac{(\Delta T_{max}) - (\Delta T_{min})}{\ln\left(\frac{\Delta T_{max}}{\Delta T_{min}}\right)} \tag{II.31}$$

Knowing that :

$$q_{mF}\, Cp_F\, (T_{2F} - T_{1F}) = q_{mC}\, Cp_C\, (T_{1C} - T_{2C}) \tag{II.32}$$

On distingue alors deux cas :

- If $q_{mF}\, Cp_F < q_{mC}\, Cp_C$

We then distinguish two cases:

$(T_{2F} - T_{1F}) > (T_{1C} - T_{2C})$ S

Either :

$T_{2C} - T_{1F} > T_{1C} - T_{2F}$

The evolution of temperatures in this type of exchanger is as follows:

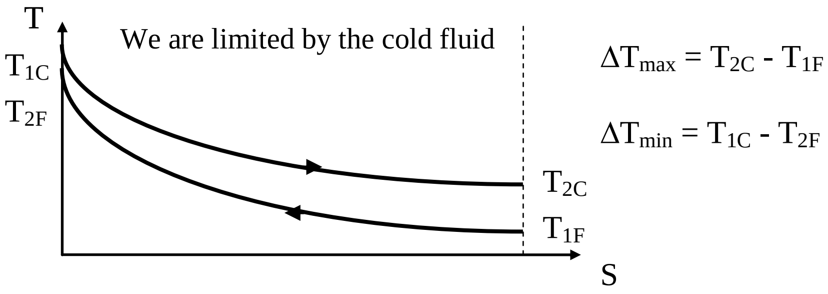


Figure II.7. Evolution of temperatures in a methodical exchanger ($q_{mF}\, Cp_F < q_{mC}\, Cp_C$)

- If $q_{mF}\, Cp_F > q_{mC}\, Cp_C$

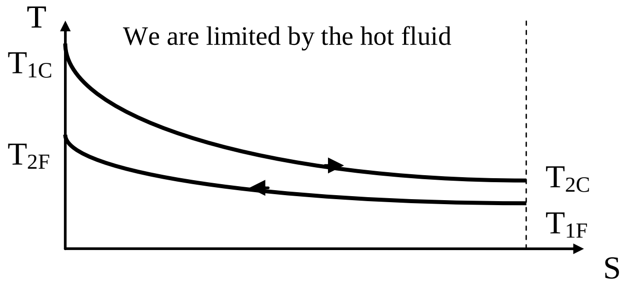
Then

$(T_{2F} - T_{1F}) < (T_{1C} - T_{2C})$

Either :

$T_{2C} - T_{1F} < T_{1C} - T_{2F}$

The evolution of temperatures in this type of exchanger is as follows:



$\Delta T_{min} = T_{2C} - T_{1F}$

$\Delta T_{max} = T_{1C} - T_{2F}$

Figure II.8. Evolution of temperatures in a methodical exchanger (q_{mF} Cp_F > q_{mC} Cp_C)

II.2.4.2.2.Method of useful numbers of transfers (NUT)

The DTLM method requires that the temperatures of the fluids at the ends of the exchanger are known [19].

In practice the fluid inlet temperatures are defined and the average exchange coefficient “K” estimated; it is therefore impossible to know the ΔT

To size a separate fluid exchanger in this case, we will use the NUT method which only integrates the fluid inlet temperatures.

The NUT method provides an elegant and rapid response to most of the problems that arise in engineering studies relating to exchangers. These are divided into two large classes [19]:

- Design problems in which inlet temperatures and an outlet temperature are imposed, the flow rates being known. The question is: select the most appropriate exchanger model, and look for its size, that is to say the exchange surface necessary to obtain the desired outlet temperature. The method to be used consists of determining the NUT then the efficiency to finally calculate the necessary exchange surface.
- Performance problems where the data is the model and size of the exchanger, flow rates and inlet temperatures. It is then a matter of determining the output power and

temperatures. The method makes it possible to calculate NUT from the initial data, from which the efficiency value and the two outlet temperatures are deduced.

- **Efficiency of an exchanger**

We define the efficiency of an exchanger by the ratio between the real flow exchanged and the maximum flow which would have been exchanged by a methodical exchanger of infinite surface with the same fluid temperatures [19].

$$E = \frac{\phi_{reel}}{\phi_{max}} \tag{II.33}$$

With :

$0 < E < 1$

- **Search for efficiency**

The heat capacity of a fluid in W/°C is called the exchangeable power for a degree of difference and evaluated for each fluid: C = qm.Cp. We are looking for the maximum flow for a counter-current exchanger.

$C_C = q_{mC}\ Cp_C$

$C_F = q_{mF}\ Cp_F$

- **Si $C_F < C_C$ $\quad$ $C_{min} = C_F$**

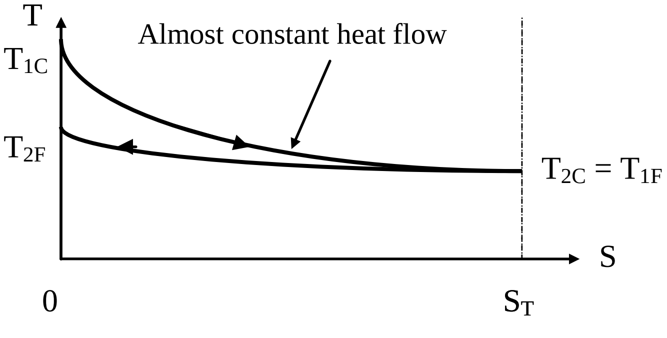


Figure II.9. Evolution of temperatures ($C_F < C_C$)

Maximum flow for: $T_{2C} = T_{1F}$

$$\Phi_{max} = q_{mC}\ Cp_C\ (T_{1C} - T_{2C}) \tag{II.34}$$

- **Si $C_F > C_C$ $C_{min} = C_C$**

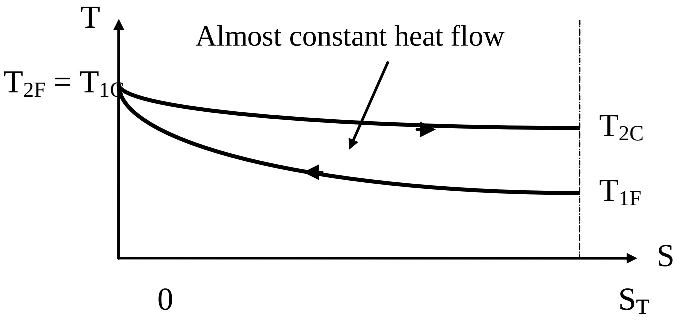


Figure II.10. Evolution des températures ($C_F > C_C$)

In all cases: $T_{2F} = T_{1C}$

$$\Phi_{max} = q_{mF}\, Cp_F\, (T_{2F} - T_{1F}) \qquad \text{(II.35)}$$

$$\Phi_{max} = C_{min}\, (T_{1C} - T_{1F}) \qquad \text{(II.36)}$$

C_{min} , T_{1C} and T_{1F} are often known, Φ_{max} will be easy to determine, on the other hand E is difficult to calculate, nevertheless, using dimensional analysis:

$$E = \frac{T_{2F} - T_{1F}}{T_{1C} - T_{1F}} \qquad \text{(II.37)}$$

$$R = \frac{T_{1C} - T_{2C}}{T_{2F} - T_{1F}} \qquad \text{(II.38)}$$

Also

$$R = \frac{q_{t\,\min}}{q_{t\,\max}} \qquad \text{(II.39)}$$

The idea of the NUT method consists of expressing the efficiency E of the exchanger as a function of the two parameters R and NUT for each exchanger configuration.

We then have a general function independent of particular temperature or flow conditions which makes it possible to quickly calculate the flows involved without knowing the outlet temperatures.

In this case, it is enough to calculate R then the NUT since we know the characteristics of the exchanger and the flow rates.

$$NUT = \frac{1}{1-R}\ln\left(\frac{1-RE}{1-E}\right) \quad \text{(II.40)}$$

Also

$$NUT = \frac{k*\Sigma}{q_{t\min}} \quad \text{(II.41)}$$

The new formula of E' as a function of NUT is

$$E^{'} = \frac{1-e^{1-(R+1)NUT}}{R+1} \quad \text{(II.42)}$$

To size an exchanger we look for NUT = NUT (R, E) to find S the exchange surface.

II.3. Conclusion

To properly size a heat exchanger, it is essential to consider various factors, such as the temperature, flow rate, and type of fluids being used. One common method for sizing heat exchangers is the “rule of thumb,”

Chapter III: Boilers

III.1. Introduction

The production of steam or hot water occupies a dominant place in industrial activities, the principle is to heat water and produce steam, thermal energy can be produced in various ways either by electricity Joules effect , by solid, liquid or gaseous combustion [20].

The boiler is one of the key components of a thermal installation. Its main function is to produce hot water or steam (at low, medium or high temperature) for different reasons such as centralized heating, domestic hot water production or even for the production of electrical energy. . This system is designed to operate over long periods and with incessant, rapid and sometimes significant load variations.

A boiler comprises a heating body with an integrated water circuit which recovers the heat produced by a burner using gas, oil, wood fuel, etc. It presents, due to its fuel, a combustion efficiency. Depending on its size and the different power demands, it will generate production output. This means that a boiler, whether it is a gas boiler, or an oil boiler or a wood boiler, may have different efficiencies depending on the applications it serves. Hence the notion of energy savings and energy efficiency of the said boiler.

The efficiency of boilers is now real. We find the best efficiency with condensing boilers. The latent heat of the fumes is thus recovered on the hot water heating return. The fumes come out colder and the heat is transferred to the heating circuit [20].

Figure III.1. Industrial boiler

III.2. Scientific definition

“System for increasing the temperature of a heat transfer fluid (most generallywater) in order to move thermal energy” [21].

III.3. Historical

The idea of using steam as a driving force dates back to the 1st century AD with the invention of the aeolipile by Heron of Alexandria. But it was only really from the end of the 17th century that engineers developed modern steam engines. In 1800, the American engineer Evans developed the first fire tube boiler which was used in the first locomotives. The need for high steam flow rates and pressures led in 1867 to the development of the water tube boiler by the American engineers Babcok and Wilcox. Since then, these have been constantly improved, allowing yields of 90.0% [21].

- **Years 1955-1970**

Appearance of oil-fired stoves with the first boilers with cast iron elements, and the appearance of new, more efficient boilers after the 1973 oil crisis.

After 1973: central heating boilers with higher efficiencies and reductions in losses from gases burned by radiation as well as when the burner stops.

- **1980s**

Improved yields with water laws, i.e. boilers whose water temperature varies gradually depending on the outside temperature. Appearance of low temperature boilers (boiler whose hot water temperature does not exceed 75°C and which can drop to 40°C)

- **1990s**

Increase in power of the condensing boiler which recovers latent heat from the flue gases. Yields exceed 100% on PCI.

- **2000s**

Mixing of energies with heat pumps and solar. Appearance of the eco-generator, the hybrid boiler (with heat pump).

III.4. Classification of boilers

It is a challenge to want to establish a classification of industrial boilers, it involving too many criteria which are not significant when taken in isolation, too many variants and too many possible combinations.

It is obvious that each boiler model has, by its design and its dimensions in general, a limitation in steam production capacity; but it is very rare to come up against all the limitation criteria at the same time and it is often enough to change one parameter to significantly extend the range of use [22].

So a boiler description is made by classification:

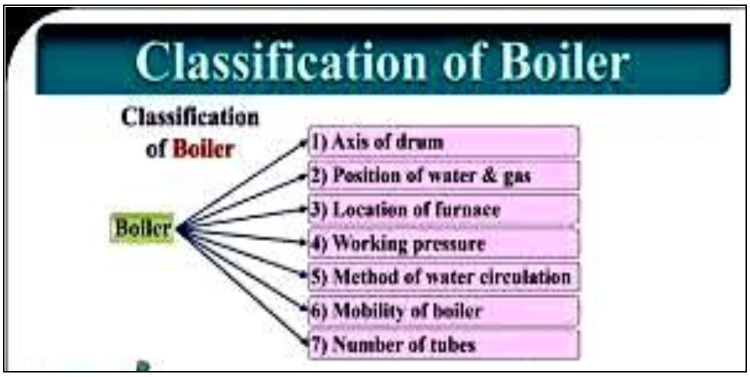


Figure III.2. Classification of boilers

III.4.1. Classification by heat source

III.4.1.1. Electric boilers

Electricity is not strictly speaking a fuel. However, it is a source of energy that is sometimes converted into heat in electric boilers.

There are several heating principles. Resistance boilers heat water using an electrical resistance immersed in the water. Joule effect boilers heat water using electrodes immersed in water. It is then the joule effect of the water which allows the water to be heated or vaporized. Ionic boilers project ions at high speed (280 km/s) using an electric field, causing the heat transfer liquid to heat up [22].

The scarcity of electric boilers is explained by the price of electricity, which is more expensive than most other energies. Electric boilers are found in the field of domestic central heating, in the humidification of premises equipped with air conditioning (small steam boilers used for humidification), but also in industry for powers up to a few tens of MW .

Due to the absence of energy losses through the sensible heat of the flue gases, the efficiency of electric boilers is often close to 100% [22].

Figure III.3. Electric boiler

III.4.1.2. Recovery boilers

A recovery boiler is a boiler which uses the heat from the exhaust gases of the gas turbine; it allows the calories contained in the flue gas to be recovered to produce steam.

The boiler operates in pure recovery mode (without post-combustion), it recovers the energy available in the fumes exhausting the combustion turbine, to produce superheated steam from demineralized water at room temperature. [22].

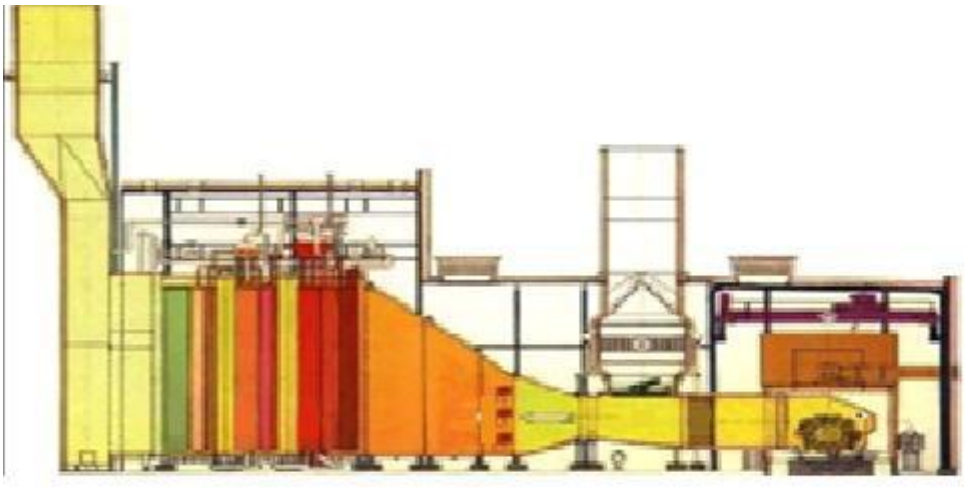


Figure III.4. Recovery boiler

III.4.1.3. Combustion boiler

III.4.1.3.1. Solid fuel boiler

Characterized by hearths, boilers are separated into three solid combustion types according to their hearth [22]

- Grate fireplaces
- Pulverized coal fireplaces
- Fluidized bed hearths

Figure III.5. Hearth boiler

III.4.1.3.2. Liquid or gas fuel boiler

This type of boiler is generally equipped with a burner which takes care of the combustion

a. Gas combustion boiler

Gas operation is a combustion system: the gas is burned in a boiler, with a heating body. This (small radiator) heats water which is then distributed throughout the home through pipes via one or more water pumps. This type of boiler is widely used for domestic use or in industry, it has advantages (very affordable price of gas, excellent energy efficiency, etc.) as well as disadvantages (damage from explosions or poisoning) [22].

b. Liquid combustion boiler

Many homes or industrial factories are equipped with fuel oil; oil-fired boilers have made considerable progress in terms of efficiency, ecology and hygiene [22].

Figure III.6. Combustion boiler (gas)

III.4.1.4. Solar power plant

A “solar boiler” in this case has thermal solar collectors similar to those which supply a solar water heater then distributed by a network of pipes similar to that used in conventional systems, one (or more) device(s) storage of thermal energy (buffer tank, concrete slab) are placed ensuring storage, sending this energy to heat emitters (low temperature radiators, heating slab, etc.) although regulation is essential [22].

A backup system makes it possible to compensate for radiation insufficiencies. It can be completely independent of the solar installation: fireplace, wood stove, electric convectors, etc. It can also be coupled to the solar part of the installation.

Thus, the regulation can manage the switching on and off of the backup, depending on the sunshine, the demand for heating or domestic hot water. In this case, we use a classic boiler (oil, gas, wood, electric).

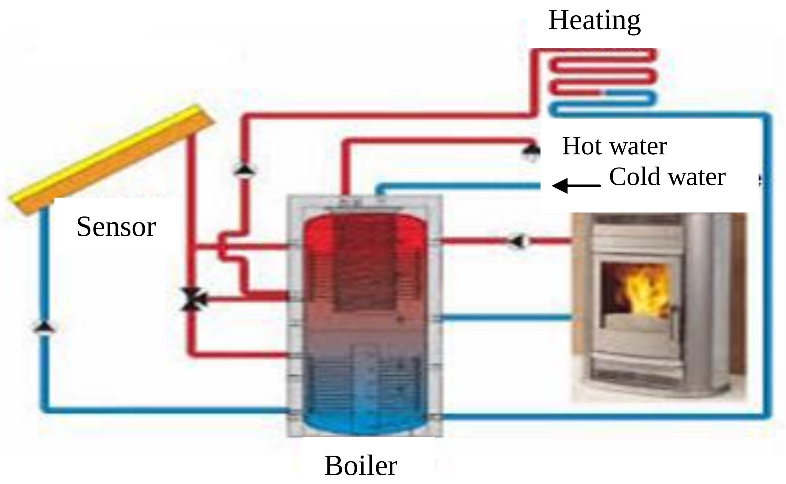


Figure III.7. Solar power plant

III.4.2.Classifications by type of heat transfer fluid

A boiler exchanges thermal energy with different types of heat transfer fluids which then transport it to the point of use [23].

III.4.2.1. Hot water

Is mainly used in heating systems for residential, commercial or industrial premises. In the field of domestic central heating, it is almost the only fluid used

III.4.2.2. Superheated water

Superheated water is mainly used in district heating. It can also be found in industry. Common pressure and temperature are around 20 bars at 180°C with return to 90°C.

III.4.2.3. Saturated steam

Mainly used in industrial processes. The steam produced by the boiler is then used to heat fluids through exchangers. Specific machines like paper machines may also need a steam supply.

III.4.2.4. Superheated steam

The superheated steam is mainly used to turbine, generally with the aim of driving an alternator to produce electricity. This principle is used by thermal power stations. Some industries have waste to eliminate, the latter used as fuel allowing them to produce electrical energy and all or part of the thermal energy necessary for the factory. We then speak of cogeneration [22].

III.4.2.5. Thermal fluid

Generally oils, allowing high temperatures to be reached without requiring high pressures. They are used as thermal energy for example in the chipboard industry. The use of thermal fluid also allows for better precision in temperature regulation. However, the use of thermal fluid generates numerous operating constraints for manufacturers; they are increasingly replaced by steam [22].

III.4.3. Classification by power range

III.4.3.1. Domestic boiler

Used for heating in homes and buildings, its consumption is less than 70 KW [23].

III.4.3.1. Industrial boiler

In industry the use of the boiler has massive importance, it is used in several fields such as (milk milk production, textile industry etc. …….) its consumption exceeds 70 KW [23].

III.4.4. Classification by construction

III.4.4.1. Fire tube boiler

It is historically the first type of construction. The first models used vertical circulation, easier to achieve, due to the convection of gases, but subsequently, boilers were produced with a horizontal arrangement, more suitable for use in railways or navigation. [23].

A smoke tube boiler consists of a large water tank crossed by tubes in which the smoke circulates. The first tube in the smoke path is a tube of larger diameter which constitutes the hearth.

This type of construction is used almost exclusively today for gaseous and liquid fuels. Indeed, the shape of the firebox of fire tube boilers makes it difficult to extract the ashes. When used with solid fuels the hearth is placed outside the boiler itself [23].

In this case, the hearth is a water tube or refractory front hearth. This type of construction is generally reserved for powers not exceeding 20 or 30 MW.

Figure III.8. Smoked tube boiler

III.4.4.2. Water tube boiler

In this construction, it is the heat transfer fluid which circulates in tubes, the hot gases circulating outside them. The advantage of this formula is above all the safety of not having large quantities of water in the boiler itself, which could, in the event of mechanical breakdown, lead to an explosive creation of steam. They also have the advantage of having lower inertia. In this type of boiler, the hearth always has a very large volume. In addition, the fireplace has the possibility of being open in its lower part. It is these two characteristics which mean that they are often used with solid fuels even for powers of only a few MW [23].

III.4.4.3. Compact boilers

It has a cylindrical outer envelope containing two large diameters in which the hearth is placed. The combustion gases exit the hearth tube into a refractory brick chamber and are conveyed through small diameter tubes located on either side of the hearth tube. These tubes represent a large exchange surface for heating the water. The fumes are then extracted from the boiler on the front by an extractor then through the chimney. It is determined by two models [23]:

- Compact two-pass boilers
- Compact three-pass boilers

Figure III.9. Compact two-pass boiler

III.4.4.4. Backfire Boilers

The combustion chamber is dice-shaped and the burner is located in the center. The flame returns to this chamber towards the front of the boiler. The smoke tubes surround the hearth and allow the evacuation of gases through the chimney located at the rear of the boiler [23].

III.5. Principle of operation of a boiler

Whatever model you have, the operating principle of a boiler is based on elements that vary little [24]:

- A boiler needs a fuel, a source of energy: wood, fuel oil, gas, electricity, or more recently, air.
- For combustion boilers, fuel is burned, and it is this action that produces heat.
- For electric or thermodynamic models, there is no combustion, but the use of an “invisible” energy source.
- In all cases, the energy used or released by combustion is used to produce heat, which is then transmitted to circuits connected to heat emitters (radiators, heated floors) and/or to the water supply device hot.
- The vapors released and combustion residues are evacuated, except in condensation models, in which the vapor is reused in the internal circuit [24].

III.6. Conclusion

According to this study we were able to have an idea or a global view on different types of boilers so that in the end we could make our own classification which is divided into three types of boilers using water, boilers using saturated steam and finally those which use superheated steam all this depending on the desired final steam.

Chapter IV: Steam turbine

IV.1. Introduction

Steam turbines are used in many industries to operate boiler fans, fuel boilers and water pumps, process and cooling compressors, blast furnace blowers, paper mill line shafts, sugar mills and generators in a variety of industries and applications [25].

Turbines can be small and simple in design/construction or large, very complex designs/developments involving multiple sections and multiple shafts.

Therefore, it is necessary to determine the required maintenance and overhaul intervals for steam turbines. Consider the design/construction of the turbine and the industry and application in which the turbine will be used. In addition to steam turbine configurations and industries, infrastructure monitoring, operation and maintenance, including specific practices, steam quality can significantly impact steam turbine reliability. industrial or public service steam.

IV.2. History of steam engines

The use of steam to generate work began with the invention of the pressure cooker by Denis Papin in 1681, he invented the boiler to boil water and with a cylinder-piston combination which made possible the mechanical work using steam pressure [25].

At the beginning of the 19th century, steam engines were quite common, but the fundamental physical principles governing their operation were still obscure. Many researchers have struggled with the problem of the efficiency of steam engines.

It was only after two centuries that a major breakthrough was due to the work of the physicist Sadi CARNOT (1796-1832). In 1824, he published the book “Reflections on the motive power of fire and on the machines suitable for developing this power”.

The ideas developed by Carnot are the foundation of thermodynamics, but based on an erroneous premise: Carnot is convinced of the existence of the caloric. He designed an ideal machine, as efficient as possible, reversible, operating with an ideal gas and whose efficiency only depends on the temperatures of the hot and cold sources (according to what we call the Carnot cycle). The Carnot cycle is composed of two reversible isothermal curves and two reversible adiabatic curves. Carnot's book goes unnoticed. It was only ten years later that Emile CLAPEYRON (1799-1864) found a copy and published it [25].

IV.3. Principles of Steam Turbine Operation

Mechanical energy is required to drive the alternator. Any type of "engine" can be used to drive the alternator (eg: a gas turbine, a steam turbine, a water turbine or air turbine), diesel or gasoline engines can also be used [26].

To generate mechanical energy in industrial applications, the motor must be very powerful and have very good efficiency (the size of the motor is less important). Of these machines, the steam turbine is by far the most suitable to meet these requirements. In this case this mechanism worked in which the pressure energy of the steam is transformed into kinetic energy and later in turn is transformed into mechanical energy of rotation of the turbine shaft.

The thermal energy of the steam is converted into mechanical energy using the blades. Expansion is accomplished by a series of stationary vanes that direct steam toward the high-speed jets. These jets contain a lot of kinetic energy, which is converted into shaft rotation by the rotor blades as the steam jet changes direction. The steam jet traveling at the curved surface exerts pressure on the blade due to its centrifugal force. Each row of fixed and moving blades is called a stage. The rotor rotates with the turbine blades, and the guide vanes are arranged concentrically in the circular turbine housing [26].

This series of energy transformation involves the intervention of constraints on the mechanism, which requires a good understanding of the thermal cycles and operations of these machines.

A turbine consists of a rotor and a stator, the rotor consists of a shaft on which the blades are fixed, and the stator consists of a housing with fixed blades, usually divided into two parts mounted on an axial plane. It also includes a segmented inlet ring and a divergent outlet facing the condenser. The role of the fixed deflector is to ensure complete or partial expansion by forming a network of nozzles and changing the direction of flow compared to the previous stage [26].

A steam turbine comprises one or more stages, each performing two functions:

- The expansion of steam which corresponds to the conversion of pressure potential energy into kinetic energy,
- The conversion of kinetic energy into rotational torque of the machine by the oblique profile of the moving blades.

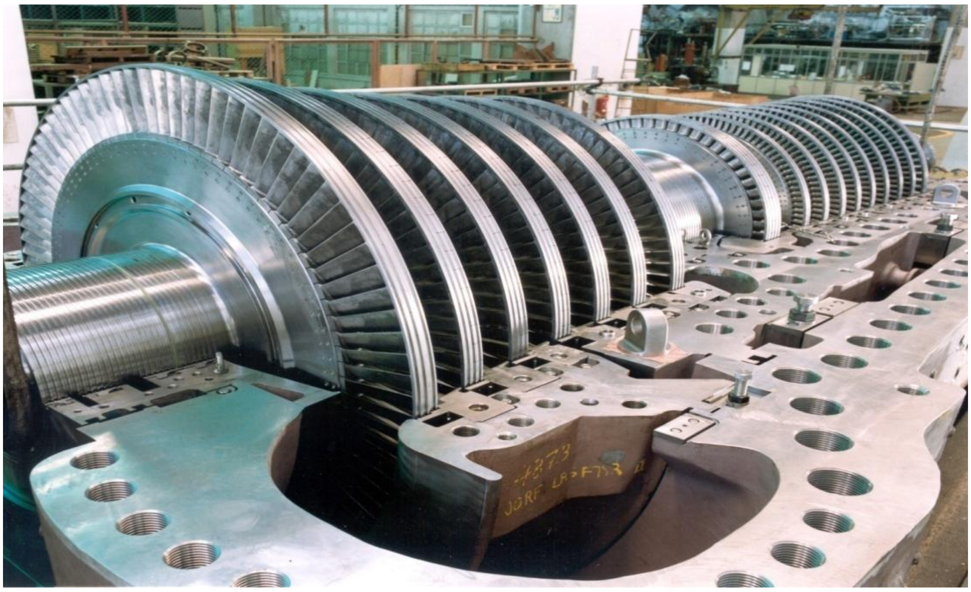


Figure IV.1. Rotor of a steam turbine.

The water used requires treatment to avoid any consequences that could cause disruption to the turbine, such as corrosion and clogging of the boilers.

The water treated by passing through the treatment stations feeds the food tanks of the power plant and the unit, then it undergoes physical and chemical degassing (using products that eliminate oxygen) and finally to the boilers, the steam turbine is placed between the hot source (steam generator) and the cold source (condenser) it ensures the transformation of the available energy of the steam into mechanical rotational energy with the minimum possible loss.

The superheated steam arrives at the turbine at medium pressure to expand, then in a condenser which is crossed on the other side by cold water, the steam condenses and the condensed water is discharged by the pump towards the generator following a closed circuit [26].

IV.4. Use of steam turbines in industry

Due to their characteristics, steam turbines are widely used in medium and high power steam thermal power plants. They are used in cogeneration applications (waste incinerator and district heating, industrial process). It is also necessary to report their use in combined cycles where they make it possible to convert heat into electricity gas turbine exhaust [27].

Steam turbines are also used in the field of naval propulsion, particularly for larger vessels (oil tankers, aircraft carriers) but they are more and more often replaced by diesel engines or gas turbines. The machine drive function is also in disappearing in favor of electric motors.

IV.5. Specification of nuclear turbines

The steam cycle of nuclear power plants is unique. Indeed, in the currently widespread pressurized water reactors, the heat from fission is evacuated from the core by a primary circuit of superheated water at around 150 bars and 300°C. This heat produces saturated steam in the secondary circuit. At the high pressure stage outlet, the steam undergoes drying (separation of liquid droplets) and moderate overheating (by steam leaving the steam generator). Due to the limited temperature of the hot source, and therefore the steam created, the efficiency of the cycle remains low at around 30%. Nuclear power plants have very powerful turbo-generator units that can reach 1400 MW [28].

IV.6. Classification of steam turbines

There are several criteria for the classification of the steam turbine [26]:

IV.6.1. Depending on use

A. Condensing turbine

In which the steam pressure at the outlet is very close to vacuum (0.03 to 0.055 bars) this pressure corresponds to the temperature of the saturated steam at the outlet of the turbine and it depends on the temperature of the cold water which passes through the condenser. Condensing turbines are used for the simultaneous production of electrical energy and heat, for example for district heating, they drive boats, turbochargers and turboblowers.

B. Counter pressure turbine

In which the pressure at the outlet is much higher than atmospheric pressure, produces electricity, and the exhaust steam is used for the different technological lines (paper factories, textiles, etc.).

IV.6.2. According to the shape of the steam vein

A. Axial turbine

The flow of steam takes place in a cone having the same axis as the turbine, this is the most used turbine.

B. Radial turbine

The flow of steam is in all directions perpendicular to the axis of the turbine.

IV.6.3. Depending on the number of rotor stages

A. Elementary turbine

This turbine has a single impeller or single stage.

B. Multiple element turbines

This multi-wheel or multi-stage turbine.

IV.6.4. Depending on the method of construction

A. Single-body turbine

Is built for low or medium powers up to 20 MW.

B. Multi-body turbine

Or high power for high power thermal power plants, it includes two or three bodies (high pressure (HP), medium pressure (MP), low pressure (LP)).

Modern steam turbines are all axial, multi-stage (with the exception of those driving small auxiliary machines).

IV.6.5. According to the mode of action

A. Action turbine

An action turbine consists of a series of fixed nozzles and a rotating wheel (rotor) (figure IV.2) working at constant pressure in which expansion occurs only in the fixed blades. They are well suited to high pressure stages and lend themselves better to varying the flow rate and therefore varying the power of the turbine. Their construction is more expensive and reserves their use for the first stages of the turbine

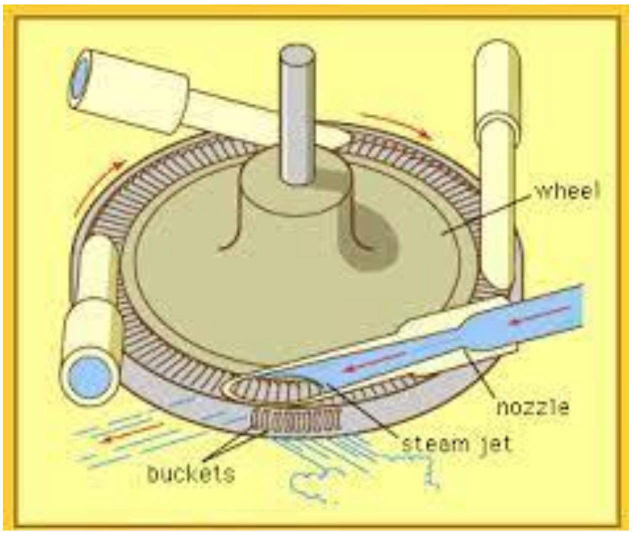


Figure IV.2. Laval turbine (1883)

B. Jet turbine

Reaction turbines in which the expansion is distributed between the fixed and movable blades. The degree of reaction is defined by the distribution of the expansion between the blades. They are better suited to low pressure stages and their cost is lower[26].

When the degree of reaction of a stage is 50%, the shape of the fixed and mobile blades is the same, which reduces the number of molds required for manufacturing. On the other hand, to achieve the same expansion, the reaction turbine will require more stages, which increases the length of the shaft line.

The production of turbines requires the use of highly alloyed steels (Cr-Ni-V) to resist thermal, mechanical (centrifugal force) and chemical (steam corrosion) stresses, see the use of Ni-based superalloys. The first two constraints limit the diameter and therefore the admissible flow rate at the last stages. Thus blades of more than one meter in length already pose serious production problems.

In addition, the radial heterogeneity of the speeds imposes a variable incidence of the blade which then presents a left shape whose machining is complex and whose mechanical constraints limit good performance.

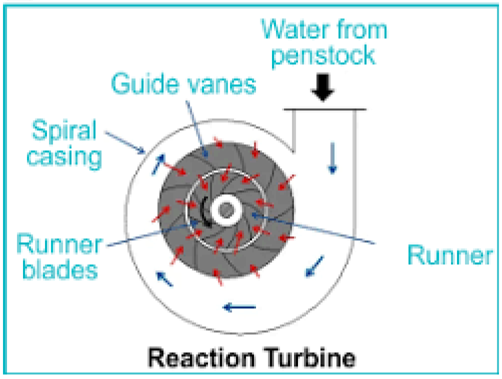


Figure IV.3. Jet turbine

In practice the temperature is limited to 550 to 580°C and the maximum implemented is 650°C. The pressure is around 180 bars and reaches 250 bars for supercritical installations.

As a result, high power turbines generally include on the same axis: A high pressure turbine, Several (2 or 3) low pressure turbines with withdrawals. It is thus possible to reach powers of more than 1,000 MW with a cycle efficiency slightly exceeding 40%.

At the other end, the smallest turbines have powers of a few tens of kilowatts. They generally have a single stage and are used to drive machines in industry or on ships. Between the two, there is a whole range of more or less complex turbines adapted to specific industrial uses (withdrawal, counterpressure, etc.). But there are also many small turbines fitted to vehicle turbochargers. The smallest turbines are certainly the Dental Turbines. [26]

Electric generation: Due to their characteristics, steam turbines are widely used in medium and high power thermal power plants. In the power range is 1 to 10 MW.

IV.7. The main components related to a steam turbine

IV.7.1.Boiler

The role of the steam generator is to extract the heat energy from the fuel to transfer it to the water and produce steam at fixed parameters. It constitutes the hot source of the thermodynamic cycle. This steam will be used by the turbine to provide mechanical energy [29].

IV.7.2.Food pump

The KSB very high pressure pump is a multistage centrifugal pump. It includes a suction body, a discharge body and a certain number of stages or cells assembled by tie rods. The water, coming from the food tank at the pump, has a pressure energy and a kinetic energy which will be increased in the moving turbines to supply the steam generator (boiler) with the necessary quantity of water to maintain the normal level [29].

IV.7.3. Transformers

IV.7.3.1. Main transformer (PT)

The evacuation of the energy produced by the alternator is evacuated on the high voltage network through a main step-up transformer: 13800V/63000V, a 63 KV circuit breaker (52 circuit breaker), three underground oil pressure cables and a line overhead three-phase [29].

IV.7.3.2. Withdrawal transformer (TS)

The group's auxiliaries are supplied via a step-down withdrawal transformer (TS): 13800V/6300V in normal service and a step-down starting transformer (TD): 63000V/6300V as emergency [29].

IV.7.4. Alternator

The alternator is an electrical machine of the alternating current generator type which transforms mechanical energy into electrical energy. It is driven by the turbine [29].

IV.7.5.Condenser

In order to maximize the efficiency of the steam turbine, the pressure and temperature of the steam outlet must be as low as possible. To do this, the steam leaving the turbine is directed to the condenser where it is cooled and condensed. The condenser is a heat exchanger with thousands of tubes through which the water in the cooling circuit circulates. The steam circulates over the tubes and condenses on contact with them. The water in the cooling circuit then extracts heat from the steam [29].

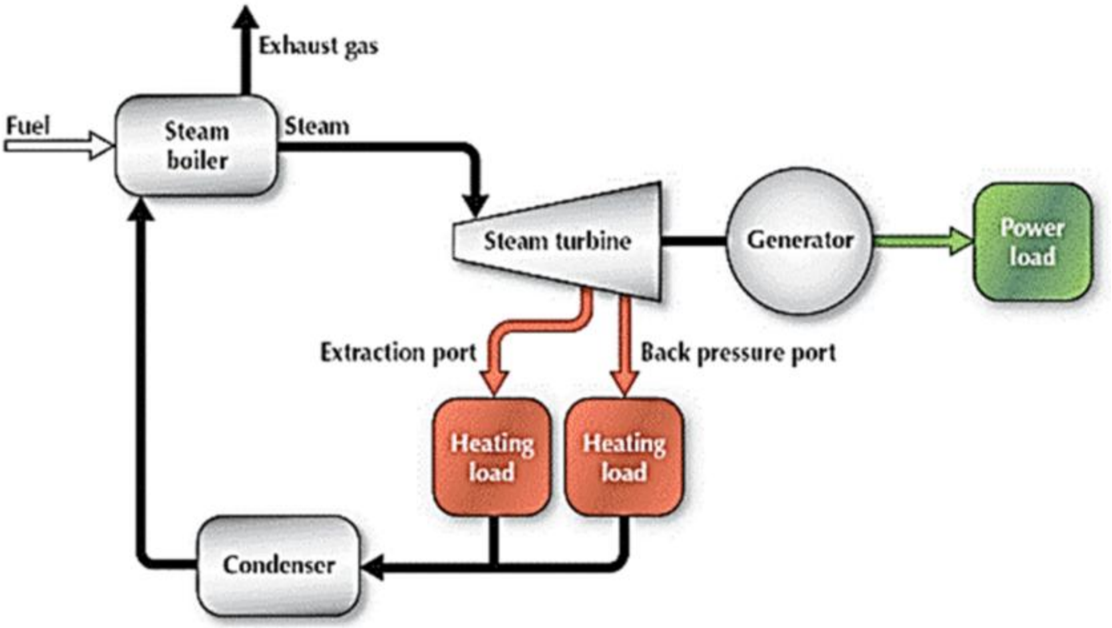


Figure IV.4. Diagram of the main components related to a steam turbine.

Although steam turbines are constructed according to two different principles (action or reaction), their essential elements are similar. They consist of nozzles or jets, and blades. The steam flows in the nozzles, in the as it expands. Thus, its temperature decreases and its kinetic energy increases [29].

The moving steam exerts pressure against the fins, causing them to rotate. The arrangement of the jets and blades, fixed or stationary, depends on the type of turbine. At the exit of the last condenser (heat exchanger), the water can be vaporized again and superheated.

The exiting water or steam is then returned to the boiler and the food pump, which compresses the water into a liquid state. This is an auxiliary turbine integrated into the thermodynamic cycle of the main turbine using steam drawn from it.

However, steam turbines have additional equipment necessary for their operation. Of this, a journal bearing supports the shaft and a thrust bearing positions it axially. An oil system ensures bearing lubrication; seals reduce steam losses throughout its journey.

Finally, a sealing system prevents steam from escaping outside the turbine and air from entering. The rotation speed is controlled by valves located at the machine's intake inlets and controlled by electronic or mechanical regulation systems. Reaction turbines develop considerable axial thrust, due to the pressure drop on the moving blades. This thrust is generally compensated by the use of a balancing piston.

The steam turbine uses thermodynamic principles. When steam expands, its temperature and therefore its internal energy decrease. This reduction in internal energy is accompanied by an increase in kinetic energy in the form of acceleration of the vapor particles. This transformation makes a large part of the energy available.

Thus, a reduction of 100 kJ in the internal energy, due to expansion, can cause an increase in the speed of the steam particles of the order of 2,800 km/h. At such speeds, the available energy is significant. When the pressure of the water vapor leaving the turbine is equal to atmospheric pressure, the turbine is said to be condensing.

Today, steam turbines are generally limited to a maximum temperature of 580°C in the first stage, and a maximum inlet pressure of 170 to 180 bar

IV.8. Characteristics of steam turbines

IV.8.1. Component Size

Given the increase in volume linked to the expansion of steam in the different stages of a turbine, the size of the openings through which the steam passes must increase from one stage to another. In practical turbine design, this increase is achieved by extending the blades from one stage to the next, increasing the diameter of the drum or impeller on which the blades are mounted, and adding two or more turbine sections in parallel [30].

Consequently, a small industrial turbine can have a more or less conical shape, with its smallest diameter on the high pressure, or inlet, side, and its largest diameter on the low pressure, or exhaust, side. A large turbine for a nuclear power plant may have four rotors consisting of a high-pressure double-flow section, followed by three low-pressure double-flow sections.

IV.8.2. Specific floors

Action turbines typically use a pressure stage called a Râteau turbine (named after the French engineer Auguste Râteau), in which the compression ratio at each stage is virtually uniform [30].

Older action turbines used a Curtis speed stage, developed by American Charles Gordon Curtis. This stage has two sets of movable troughs, with an intermediate set of fixed fins following the nozzles. The stage separation of a reaction turbine is sometimes called Parsons separation, named after its inventor, the British Charles Parsons.

A reaction turbine often has a first acting stage which allows adjustment of the system; an action turbine generally has a reaction degree close to 50% in its final stages.

IV.9. Applications

Steam turbines are used in particular in the production of electricity from thermal energy or for the propulsion of boats. In cogeneration systems - that is to say using both process heat (that used during an industrial process) and electricity - the steam is brought to high pressure in a boiler and then extracted of the turbine at the pressure and temperature required by this process. In this case, the turbine is said to be counter pressure[29], [30].

Steam turbines can be used in combined cycles with a steam generator that recovers the heat. Industrial units are used to drive machines, pumps, compressors and generators. Their nominal power ranges from a few hundred Watts to more than 1,300 MW.

The steam turbine is sometimes associated with a gas turbine. Since the efficiency of the gas turbine is low, it is generally used for peak power generation, with the calories from the gas turbine exhaust used to operate the steam turbine boiler.

IV.10. Main generalities of a power plant

The alternator, the turbine and the fluid that drives the turbine are the main elements of production of a source of electricity. This principle can then be rejected depending on the fluid used, water in hydroelectric power stations, steam in thermal power stations. In the case of steam, there remains the choice between how the water can be heated, using fossil fuels (thermal power plants) or nuclear reactions (nuclear power plants).

All the technical complexity of implementing these principles arises from the need to optimize thermal cycling and implement safety devices. [31]

IV.11. Conclusion

The aim of this chapter was to define the operating principle of steam turbines, the different types of turbines, the characteristics of steam turbines, classification of steam turbines as well as turbine configurations which will be useful in sizing.

The next chapter concerns the sizing of turbines (efficiency, consumption, regulation and safety devices).

Chapter V: Turbine sizing

V.1. Introduction

In the previous chapter we presented steam turbines and these different types, the different characteristics as well as some basic notion of these turbines. However, in the majority of cases, the choice of turbine remains a crucial point in practice [32].

In this chapter and with the previous information we propose to size the hydraulic turbines and determine the selection criteria in a power plant.

To size a turbine, several parameters must be taken into account. Our job is to study the key parameters.

V.2. Turbine sizing

V.2.1. Speed triangle

The construction of velocity triangles is necessary for the analysis of the liquid flow on the blade of the hydraulic turbine. This construction of the velocity triangles is a representation of the characteristic vectors between the liquid and the contact with the blade. In fact, we decompose the vector of the absolute liquid speed at the inlet and outlet of the turbine into two vectors; training speed, and relative speed [32].

The absolute speed is a vector sum of the two vectors, it is given by the following relation:

$$\vec{V} = \vec{U} + \vec{W} \qquad \text{(V.1)}$$

$\vec{V}$: The absolute velocity vector

$\vec{U}$: The training speed vector

$\vec{W}$: The relative velocity vector.

Figure V.1 represents the speed distribution of the liquid flow of a Banki turbine.

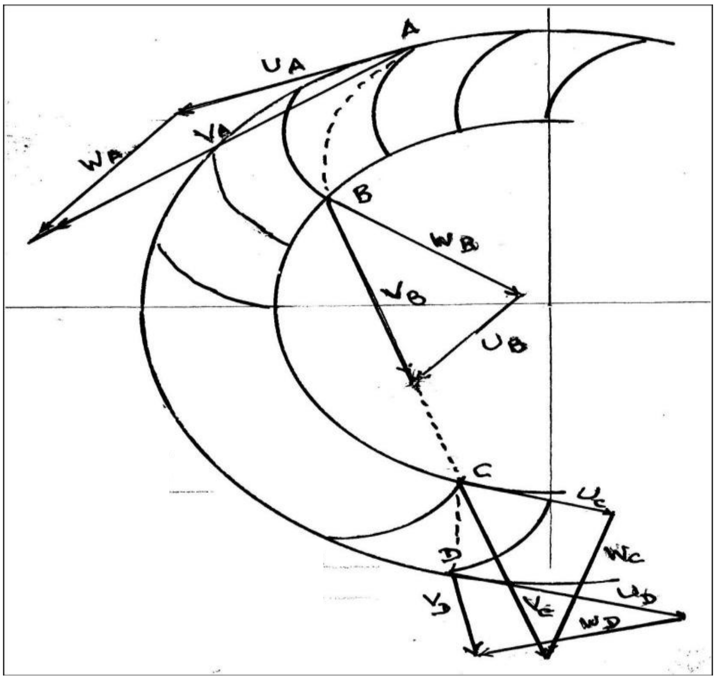


Figure V.1. Speed triangle

V.2.2. Turbine wheel design

The geometric and dimensional parameters of a hydraulic turbine correspond to three essential parameters [32]:

- The speed of rotation.
- The net fall height.
- The flow

The rotation speed that the hydraulic turbine must have is calculated using the following equation:

$$N = \frac{f.60}{P} \tag{V.2}$$

Or

p is the number of pole pairs.

The rotation speed depends on the network frequency and the synchronous speed of the alternators.

- The hydraulic power is given by:

$$P_h = \rho.g.H_b.Q \tag{V.3}$$

Hb: Gross height

Q: Flow

- The mechanical power at the shaft is given by:

$$P_h = \rho.g.H_b.Q.\eta \qquad \text{(V.4)}$$

With :

η : Turbine efficiency

- The number of blades in a turbine wheel is calculated using the following equation:

$$Z = \frac{250}{Ns^{\frac{1}{3}}} \qquad \text{(V.5)}$$

With :

Ns : The specific speed

V.2.3. Specific speed

Among the characteristics of the hydraulic turbine is the specific speed. The latter is determined with different methods; depending on the power of the shaft, the flow [32].

- Depending on the flow rate (Nq)

$$N_q = N\frac{Q^{\frac{1}{2}}}{H^{\frac{3}{4}}} \qquad \text{(V.6)}$$

- Depending on the shaft power (Ns):

$$N_s = N\frac{P_a^{\frac{1}{2}}}{H^{\frac{5}{4}}} \qquad \text{(V.7)}$$

With:

Pa: Mechanical power at the shaft

The speed figure is then:

$$v = \frac{\frac{Q^{\frac{1}{2}}}{\pi}}{2.gH^{\frac{3}{4}}} = 0.00633.N_q \qquad (V.8)$$

According to the specific speed, the choice of turbine is made using the following table [33]:

Turbine type	**Specific speed Ns[tr=min(m^3/s)$^{0.5}$/m$^{0.75}$**
Pelton	1-20(with a throw)
Turbine-Pump	25-120
Francis	20 - 140
Kaplan	100 - 300
Bulb	150 - 400

Table V.1. Le choix de la turbine à l'aide de vitesse spécifique

Table V.1. The choice of turbine using specific speed

V.3. Cavitation phenomenon

Cavitation is a physical phenomenon that affects liquids. This is a change in total liquid phase due to a drop in static pressure at constant temperature. The formation of vapor pockets in the turbine wheel liquid is the consequence of a local increase in flow velocity when the local pressure drops below the vapor pressure of water at constant temperature.

Once the vapor cavities are created, they return to the liquid state in a very short time. [34] This phenomenon in hydraulic turbines causes harmful effects in particular

- The drop in performance.
- Abnormal noises.
- The vibrations.
- Erosion

Figure V.2 shows the damage to the wheels due to this phenomenon:

Figure V.2. Wheel damage

V.4. Cavitation coefficient

The cavitation coefficient is one of the key turbine sizing parameters. It is calculated with the following expression [34]:

$$v = \frac{\frac{P_{atm} - P_v}{\rho} + \frac{v^2}{2} - g.H_S}{gH} \qquad \text{(V.9)}$$

With:

P_{atm}: Atmospheric pressure [Pa]

Pv: Vapor pressure of water [Pa]

ρ: Density of water [Kg/m3]

g: Acceleration of gravity [m/s2]

V: Average output speed [m/s]

H: Net fall [m]

H_s: Suction height [m]

V.5. Suction height

In a horizontal axis reaction hydraulic turbine, the suction height is the distance between the downstream water body and the axis of the turbine wheel.

It takes two values; positive or negative. If the turbine is above the downstream water level then it will be positive, otherwise it will be negative. The suction height is calculated according to equation [34]:

$$H_{sth} = H_a - H_v \tag{V.10}$$

Or

H_{sth}: The theoretical suction height.

H_a: Atmospheric pressure.

H_v: The vapor pressure of water.

V.6. Turbine selection criteria

For the choice of the turbine, several criteria must be followed among these criteria we are interested in; net head, flow rate, and runaway velocity [33]

V.6.1. The net fall

After calculating the net head with the previous equations, we return to the following table for the choice of the hydraulic turbine [33]:

Turbine type	**Height H**
Pelton	50 à 400m
Crossflow	10 à 150m
Francis	5 à 100m
Kaplan	2 à 10m

Table V.2. The choice of turbines according to the head

V.6.2. The flow

In a hydraulic power plant, it is necessary to know the variation in flow to choose the type of turbine and the number of machines. The following table shows us the choice according to the variation of flow and head [33]:

Turbine type	**Ability to respond to flow variations**	**Ability to respond to drop variations**
Pelton	High	Low
Francis	Average	Low
Kaplan	High	Average
Helix	Low	Low

Table V.3. The choice of turbines according to the variation in flow and head

V.6.3. Runaway speed

The runaway speed in a hydraulic turbine is given by the following relationship:

$$V = \frac{\eta_{\max}}{\eta} \tag{V.11}$$

After calculating it, we return to the following table for the choice of turbine:

Turbine type	**Runaway speed**
Kaplan simple adjustment	2.0-2.6
Kaplan dual adjustment	2.8-3.2
Francis	1.6-2.2
Pelton	1.8-1.9
Turgo	1.8-1.9

Table V.4. The choice of turbines according to the head

To summarize the criteria for choosing the hydraulic turbine that we have cited, we have made this table which allows us to make a first classification to identify the types of turbines suitable for micro hydroelectric power plants [34]:

Name	**Pelton**	**Cross flow**	**Francis**	**Kaplan**
Kind	Turbine action: The water is put at maximum speed in the injector. All the energy in the jet causes the rotation of the wheel and the water comes out as rain (kinetic energy)		Reaction turbine: The water is guided by the distributor to enter the wheel without shock. This goes into maximum speed when it leaves the wheel. This machine uses both kinetic energy and pressure difference	
Speed	20 to 1000 L/sec	20 to 7000 L/s	100 to 6000L/s	300 to 10000 L/s
Height	50 to 400m	10 to 150 m	5 to 100m	2 to 10m
Rotation speed	500 to 1500 rpm	Weak	Until 1000rpm	Weak
Features	Water supply adjustable by the injectors which allow good yields. Reduced size by direct turbine generator connection	Construction simple but effective weak. Multiplier bulky between turbine and generator	Excellent performance if the flow rate varies between 60 and 100% of its nominal flow rate. Operation without multiplier.	Good performance. To be used for high flows and low falls.

Table V.5. The choice of turbine using specific speed

Thus the following figure V.3 summarizes the areas of use of turbines on flow rate, head and power curves [33]:

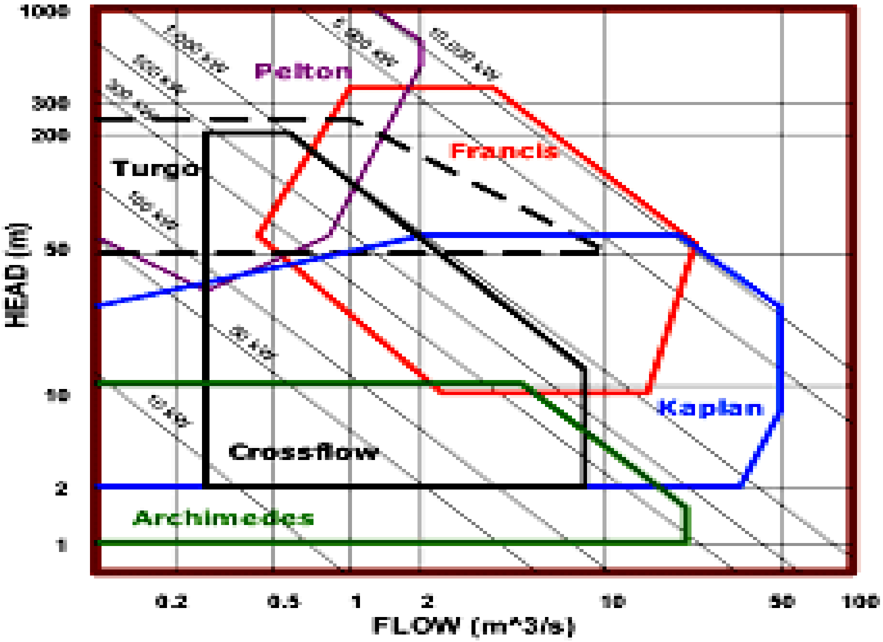


Figure V.3.Areas of use of turbines

V.7. Conclusion

This chapter is devoted to the sizing of the turbine. We started by citing the key parameters of the turbine, such as the speed triangle, the specific speed, and the cavitation phenomenon. Then a design of the turbine wheel was made. Finally, we cited the criteria for choosing the turbine based on flow rate, head, and turbine parameters.

Chapter VI: Gas turbine

VI.1. Introduction

Gas turbines are widely used to drive mechanical loads due to their large power, smooth operation and high performance. Twin-shaft turbines are commonly used in industrial centers because they have two mechanically independent impellers.

The gas turbine can be considered a self-sufficient system because it compresses atmospheric air in its own compressor, increases its energy output in its combustion chamber and converts this power into useful mechanical energy during the expansion process that occurs in the turbine section. This mechanical energy is transmitted to a receiving machine via a coupling, producing the power needed for industrial processes.

The thermal efficiency of a simple gas turbine without exhaust heat recovery is between 16 and 28%, while with exhaust heat recovery it can reach between 26 and 30%. However, the thermal efficiency remains much lower than that of gas engines [35]

VI. 2. History of gas turbines

The first gas turbines appeared on the market in the late 1940s; they were generally used in railways and had the advantage of burning liquid fuel, even at low quality (due to the limitation of refining processes). The MS3001 turbine built by GE, with a power of 3,312 MW, was specifically used for the locomotive service.

Advances in materials technology and in-depth combustion research have allowed rapid improvements in the performance of these machines, in terms of specific power and efficiency, obtained by increasing the maximum temperatures in the thermodynamic cycle [36]. .

In this area, three generations can be classified, distinguished by the maximum temperature intervals (in °C) of the gases at the inlet of the first stage of the turbine rotor:

- **1st generation:**760<Tmax<955.
- **2nd generation:**955<Tmax<1124.
- **3rd generation:**1149<Tmax<1288.

Obviously, the increase in the inlet temperature to the first turbine had the effect of an increase in the thermodynamic efficiency, which went from values lower than 20% in the first machines, to current values higher than 40% (turbine with LM6000 gas).

VI. 3. Definition of a gas turbine

The gas turbine is an internal combustion engine, the role of which is the reconversion of thermal energy due to the combustion of a hydrocarbon into mechanical energy (mechanical torque on the turbine shaft).

The gas turbine takes atmospheric air and compresses it in its own compressor, increases the energy output of the air in its combustion chamber and converts this power into useful mechanical energy during the expansion process that takes place in the turbine section . The resulting mechanical energy is transmitted via a useful power coupling to a receiving machine (alternator, centrifugal pumps, gas compressor, etc.). [37]

VI. 4. Areas of use of gas turbines

Gas turbines have a very great use in industry. They can be used to drive [38]:

- Electricity generators.
- Compressors.
- Pumps.

But also as a thrust generating system, particularly in:

- Railway.
- Maritime propulsion.
- Aviation.

VI. 5. The elements of a gas turbine

The main elements that make up a gas turbine [39]:

VI. 5. 1. Compressor

The compressor is located at the front of the gas turbine and is used to compress the ambient air before it is routed to the combustion chamber. It generally consists of several stages of rotors and stators, which increase the air pressure [39].

Figure VI.1. Compressor rotor

VI. 5. 2. Combustion chamber

The combustion chamber is where fuel is mixed with compressed air and burned. The heat produced by combustion is used to turn the turbine. Modern combustion chambers are designed to maximize combustion efficiency and minimize pollutant emissions [40].

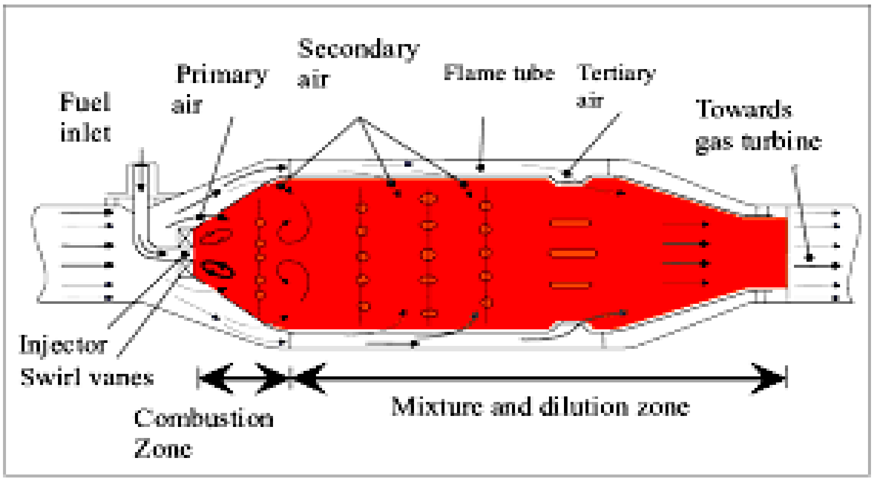


Figure VI.2. Presentation diagram of a combustion chamber.

VI. 5. 3. Turbine

The turbine is the central element of the gas turbine. It is driven by hot combustion gases escaping from the combustion chamber. The turbine generally consists of several stages of rotors and stators, which convert the energy of the gases into mechanical energy.

VI. 5. 4. Cooling system

Gas turbines can reach very high temperatures, which can cause damage to components. To avoid this, modern gas turbines are equipped with sophisticated cooling systems that keep temperatures at acceptable levels [41].

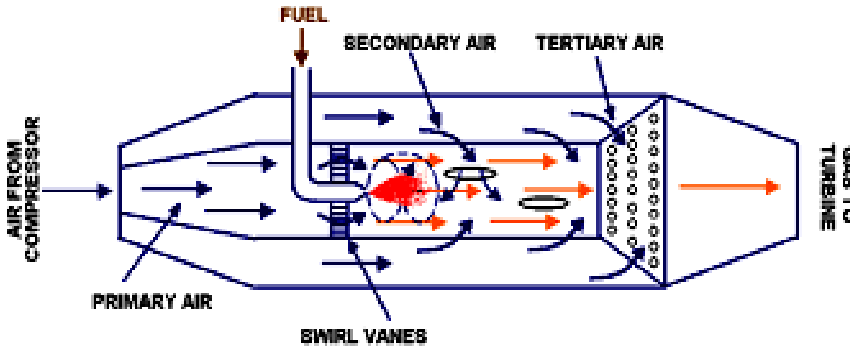


Figure VI.3. Cooling air in the combustion chamber.

VI. 5. 5. Exhaust system

The exhaust system is located behind the gas turbine and is used to remove combustion gases. Modern exhaust systems are designed to minimize noise and polluting emissions.

VI. 5. 6. Generator

The generator is the element that converts the mechanical energy produced by the turbine into electrical energy. Gas turbines are often used in power plants to produce electricity.

VI. 5. 7. Control system

Modern gas turbines are equipped with sophisticated control systems that monitor and regulate the temperature, pressure and speed of the turbine. This optimizes turbine performance and minimizes fuel consumption.

VI. 6. Classification of gas turbines

Gas turbines can be classified based on several criteria, such as their duty cycle, configuration, application, etc. Here are some common classifications:

VI. 6. 1. By the method of construction

The choice of gas turbine type depends on the purpose for which it will be used. In the industrial field, there are two common types of gas turbines: single-shaft turbines, also called single-shaft, and two-shaft turbines, also called twin-shaft.

A. Single-shaft turbine

The compressor and the turbine sections are mounted on the same shaft which allows the assembly to rotate at the same speed. This type is used for applications that do not need speed variations such as driving generators for electricity production. Figure VI.4 below illustrates a single-shaft turbine diagram. [42]

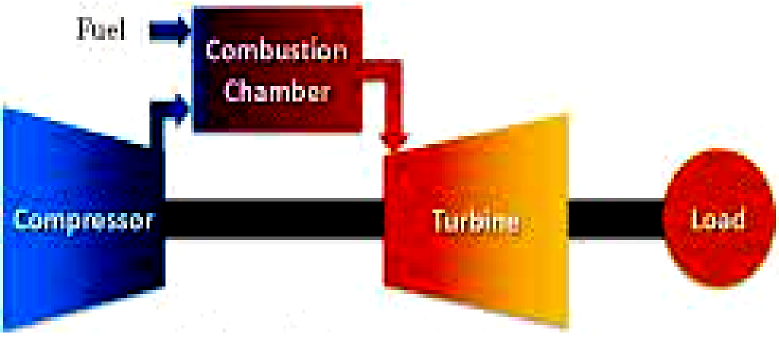


Figure VI.4. Single shaft turbine diagram.

B. Twin-shaft turbine

The gas turbine consists of two mechanically independent turbine wheels. The HP turbine wheel drives the axial compressor rotor and accessories, while the second stage LP wheel serves to drive the receiver unit.

The purpose of unconnected turbine wheels is to allow the two wheels to operate at different speeds to meet the variable load requirements of the receiving body. Figure VI.5 below illustrates Schematic of a twin-shaft gas turbine. [42]

BP:*Low pressure.*

HP:*High pressure*

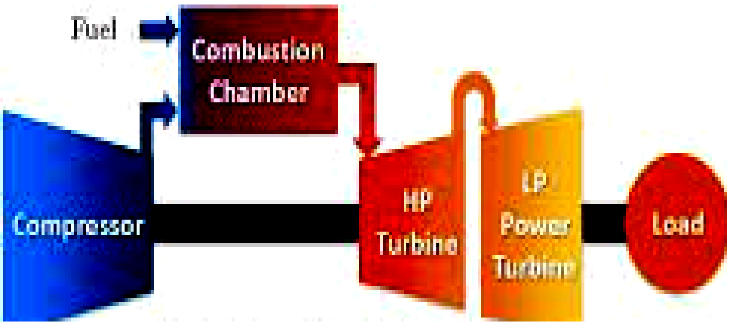


Figure VI.5. Twin-shaft turbine diagram.

VI. 6. 2. By the way of working

There are two types of turbine:

A. Action turbine

Where thermal energy is transformed completely into kinetic energy in the directrix. The evolution of the gases in the wheel takes place without variation in static pressure P1>P2=P3. [42]

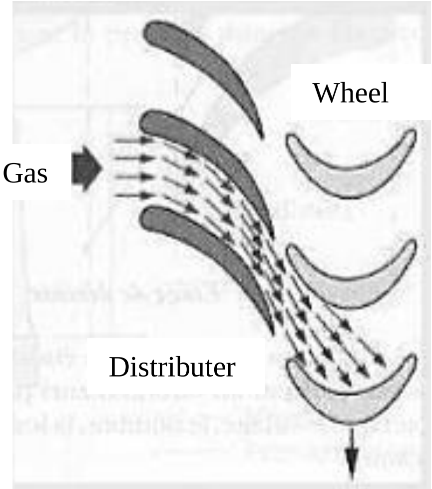


Figure VI.6. Action turbine.

B. Jet turbine

Part of the thermal energy is transformed in the wheel into kinetic and mechanical energy. The evolution of the gases in the wheel takes place with variation of the static pressure P1>P2>P3. The reaction rate ε will characterize the % of total thermal energy. [42]

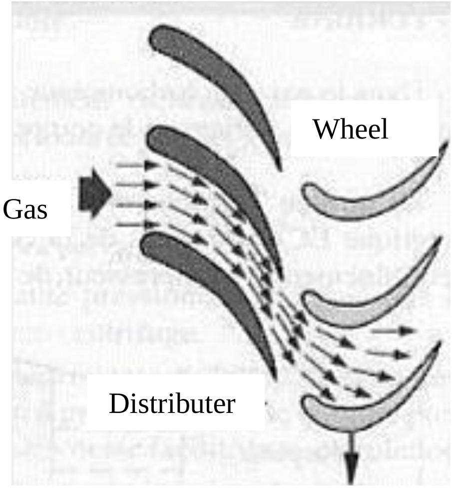


Figure VI.7. Jet turbine.

VI. 6. 3. By the thermodynamic mode of operation

There are two thermodynamic cycles:

A. Closed cycle gas turbine

In which the same fluid is taken up after each cycle.

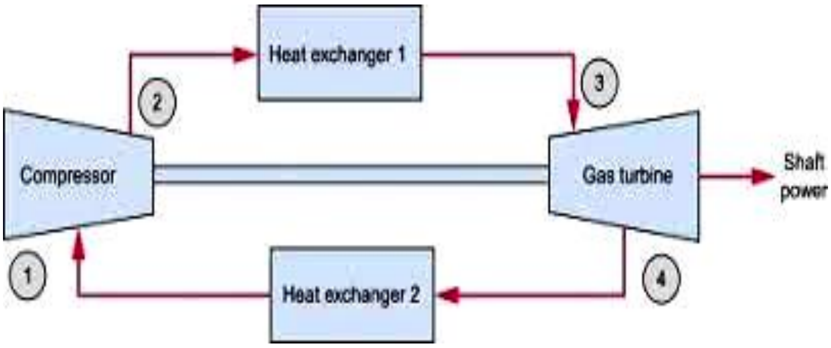


Figure VI.8. Irreversible cycle closed.

B. Open cycle turbine

It is a turbine whose suction and exhaust take place directly into the atmosphere

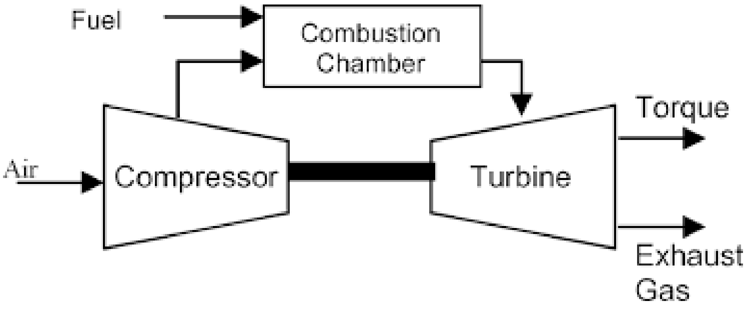


Figure VI.9. Open cycle.

This type of turbine, which is the most widespread, is divided into two classes:

- **Single cycle turbine**

It is a turbine using a single fluid for the production of mechanical energy, after expansion the gases still having energy potential are lost to the atmosphere through the exhaust.

- **Regenerated cycle turbine**

It is a turbine whose thermodynamic cycle involves several driving fluids in order to increase the efficiency of the installation.

VI. 7. Types of gas turbines

There are several types of gas turbines, including [43]:

VI.7.1. Industrial gas turbines

Are used in power plants, petrochemical industries and natural gas production plants. They generally have powers between 5 and 100 MW.

Figure VI.10. Industrial gas turbine

VI.7.2. Aeronautical gas turbines

Are used to propel planes, helicopters and missiles. They are designed to be light, compact and have a high thrust.

Figure VI.11. Aeronautical gas turbine

VI.7.3. Marine gas turbines

Are used for the propulsion of ships and boats. They generally have powers between 1 and 80 MW.

Figure VI.12. Marine gas turbine

VI.7.4. Cogeneration gas turbines

Are used in cogeneration plants to produce electricity and heat simultaneously. These turbines recover heat from exhaust gases to produce steam, which can be used for electricity generation or heating.

Figure VI.13. Cogeneration Gas Turbine.

VI.7.5. Micro gas turbines

Are used for small applications, such as telecommunications equipment and residential installations. They have powers ranging from a few kilowatts to around 300 kW.

Figure VI.14. Micro gas turbine

VI. 8. Principle of operation

We chose MS5002B gas turbine as an example to understand its working principle. In general, industrial gas turbines have the same operating principle, only their difference lies in slight variations, whether for a single or dual axis turbine.

The rotor of the HP turbine (axial compressor) reaches 20% of its nominal speed thanks to a launching device. Air is drawn from the atmosphere and then compressed in the axial compressor up to 6 bar. It is then delivered using a pipe to the combustion chambers where the fuel (fuel gas) is injected by injectors into the 12 chambers.

Ignition is done using two spark plugs placed inside chambers 1 and 12 where the flame propagates into the rest of the chambers through the interconnecting tubes. [44]

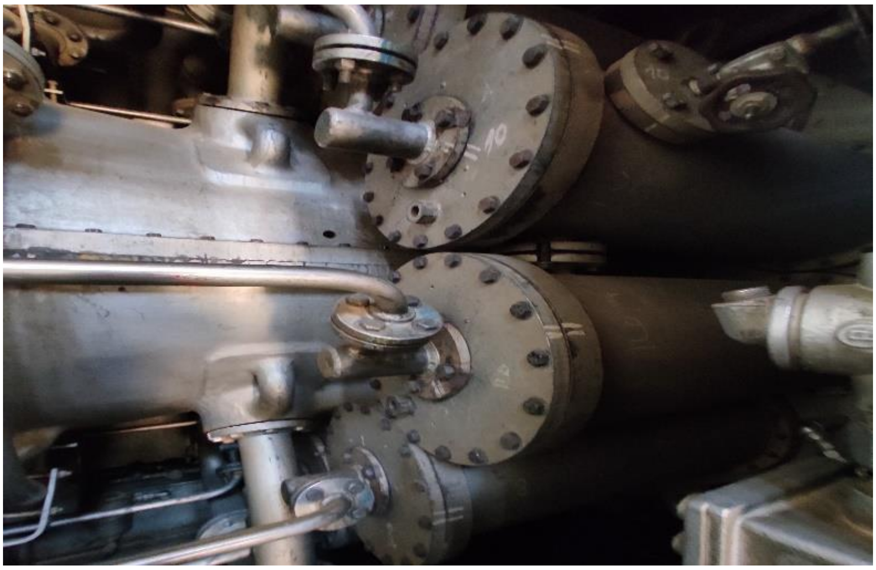


Figure VI.15. Combustion chambers of a gas turbine

The expansion of the gases passes through the fixed director which directs it towards the HP wheel which itself drives the axial compressor up to 60% of its nominal speed where there will be a disconnection between the launch turbine and the axial compressor.

The compressor speed continues to increase up to its nominal value using the (IGV) which regulates the flow rate of the air sucked in by the compressor.

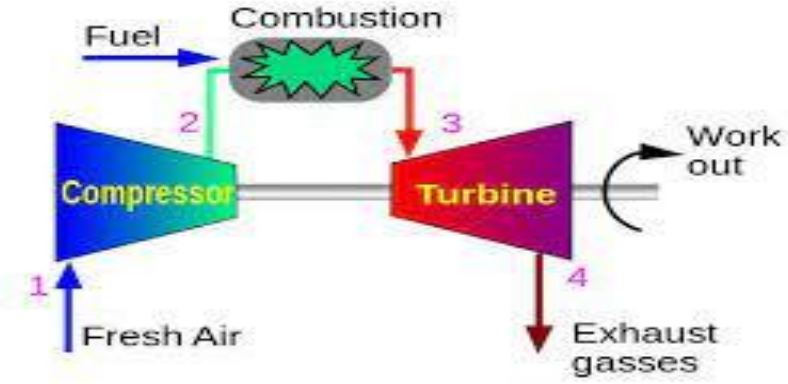


Figure VI.16. Principle of operation of a gas turbine

The gases leaving the impeller (HP) pass through the diaphragm to be directed by the variable vane director and rotate the impeller (LP) at an appropriate speed. The latter drives the centrifugal compressor [45].

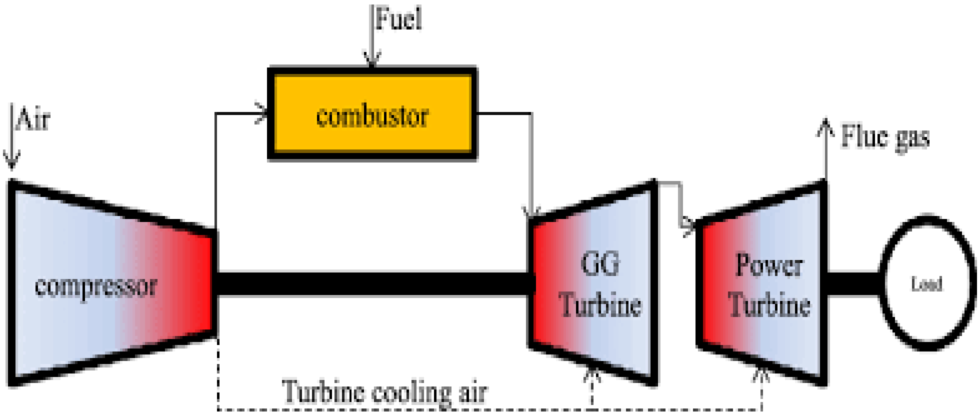


Figure VI.17. Diagram of a gas turbine with 2 shaft lines.

The hot gases are discharged to the atmosphere through an exhaust box.

VI. 9. The theoretical cycle of gas turbine installations

The cycles of the gas turbine plant are diverse, according to the use of the working fluid in the cycle, we first distinguish between the closed cycle and the open cycle [45].

In the open cycle gas turbine installation the working fluid after having done the work escapes into the ambient environment (as in internal combustion engines) and on the contrary, in the closed cycle gas turbine installation the working fluid (air or other gas) constantly circulates in the contour and completes the closed cycle.

The simplest gas turbine installations include the following: fuel feed pump, air compressor, combustion chamber and gas turbine.

The gas turbine and the compressor are on the same shaft, the compressor sucks in atmospheric air, compresses it then sends it to the combustion chamber, in this chamber at constant pressure the pulverized fuel burns and the working fluid receives an amount of heat, the temperature of the gases increases, then these gases enter the gas turbine and during the expansion of the gases, the thermal energy is transformed into kinetic energy and this in turn is transformed into mechanical energy.

Let us consider the thermodynamic cycle of IT G without taking into account the losses in the turbine and in the compressor. Such a cycle is called a theoretical cycle.

The compressor draws in and compresses the air and then heat is supplied to the combustion chamber at constant pressure.

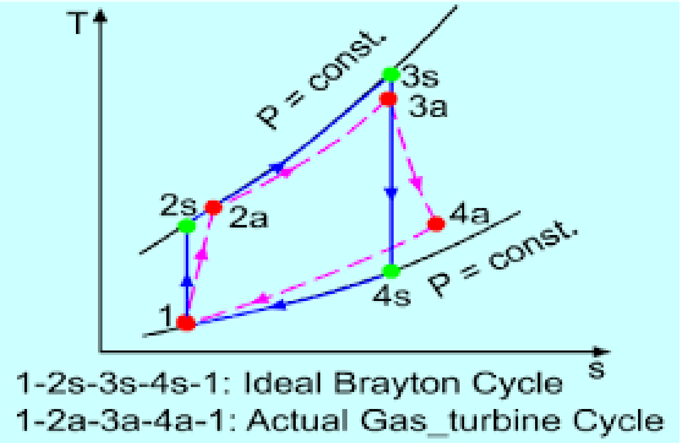


Figure VI.18.TS diagram of a turbine.

1-2: Isentropic compression.

2-3: Isobaric combustion.

3-4: Isentropic expansion.

4-1: Exhaust.

The gas temperature increases in the combustion chamber from T2 to T3, after which the gases expand adiabatically in the turbine from pressure P3 to atmospheric pressure P4.

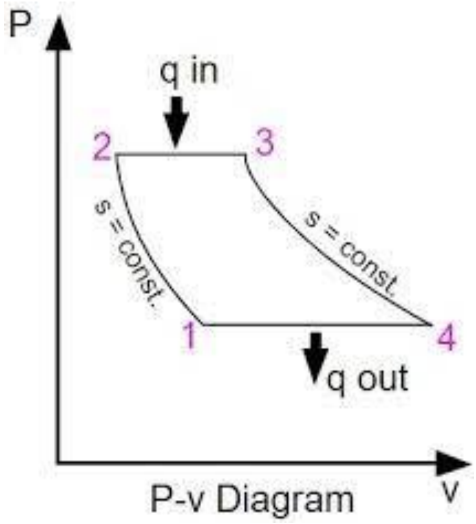


Figure VI.19.PV diagram of a turbine.

During the expansion of the gases in the turbine the potential energy is transformed into kinetic energy and then in the moving blades the kinetic energy is transformed into mechanical energy, i.e. in rotational energy of the turbine rotor.

VI. 10. Gas turbine technology

The technological particularities of the gas turbine are essentially linked to the very high temperatures reached at the expansion turbines (from 800 to more than 1300°C depending on the type). This poses problems with resistance to creep, fatigue and corrosion of the blades in particular. Possible filtering of the air sucked in by the compressor would add erosion as an additional constraint.

Gas turbines are characterized by the high quality of the materials used, they have the advantage of being refractory materials based on nickel or cobalt with added chromium. Fins obtained by oriented solidification casting or single crystal casting. This constitutes part of the solutions provided to remedy possible anomalies which may be generated by thermal stress due to the high temperature of the gases at the turbine inlet.

Another solution consists of diverting part of the air flow (10 to 15%) leaving the compressor (which is at a temperature much lower than that entering the turbine) to cool the fins from the inside and to obtain a thin film of (fresh) air between the fins and the hot gases so as to limit the temperature of the gases reaching the high pressure turbine to around 800°C [45].

VI. 11. Comparison of gas turbine with other power generation technologies [46].

VI.11.1. Gas turbine vs steam turbine

- The gas turbine uses a thermodynamic Brayton cycle, while the steam turbine uses a Rankine cycle.
- The gas turbine has a shorter start-up time and can reach rated power within minutes, while the steam turbine takes longer to reach rated power.
- The gas turbine is more efficient at partial loads than the steam turbine.

VI.11. 2. Gas turbine vs solar power

- Thermodynamic solar power plants can use a gas turbine as a backup system to produce electricity when there is insufficient sunlight.
- Solar power generation is more sustainable and renewable than gas turbine power generation, which uses fossil fuels.

VI.11.3. Gas turbine vs wind turbine

- Wind turbines have a higher initial cost than gas turbines, but have lower operating and maintenance costs.
- Wind turbines are more environmentally friendly than gas turbines because they do not produce greenhouse gases.

VI.11.4. Gas turbine vs nuclear power plant

- Nuclear power plants produce electricity using heat generated by nuclear fission, while gas turbines produce electricity by burning fossil fuels.
- Nuclear power plants are more expensive to build and maintain than gas turbines, but they are more stable and reliable.
- Nuclear power plants are more environmentally friendly than gas turbines because they do not produce greenhouse gases.

VI. 12. Advantages and disadvantages of gas turbines [47]

VI. 12. 1. Advantages

- High power in a small space in which a diesel unit of the same power could not be accommodated.
- With the exception of starting and stopping, power is produced continuously.
- Easy starting even in very cold weather.
- Diversity of fuel for operation.
- Possibility of operation at low load.

VI. 12. 2. Disadvantages

- Below approximately 3000KW, installation price higher than that of a diesel group.
- Much longer start-up time than a diesel unit; as an indication: 30 to 120 s for a turbine, 8 to 20 s for a diesel unit.
- Lower efficiency than a diesel engine (simple cycle). As an indication: 28 to 33% for a 3000 KW turbine, 32 to 38% for a diesel unit.

VI. 13. Conclusion

Gas turbines are machines that have revolutionized the energy industry, used to generate electricity, power planes and ships, and for industrial applications such as gas compression. The key parts of a gas turbine include the compressor, combustion chamber, turbine and cooling system.

Gas turbines are expensive to purchase, but offer high-energy efficiency, reliability and a relatively low carbon footprint. Gas turbines continue to evolve to meet future energy needs.

Chapter VII: Hydraulic turbines

VII.1. Introduction

Hydraulic turbines transform the potential energy associated with height into mechanical energy. Until the 19th century they used the wheel but after the 19th century the turbine replaced the wheel with a blade. Modern hydraulic turbines are the result of several years of progressive development. The efficiency of the turbine is approximately 85%, which is strictly higher than that of the water wheel which is approximately 20%. The turbine contains fixed, mobile, and adjustment members [48].

The fixed and adjusting part are used mainly to direct the water onto the wheel in the best conditions. Concerning the mobile part, it is used to produce motor torque on the shaft while transforming the available power into mechanical power.

The objective of this chapter is:

- The presentation of the turbine and its components.
- Mention the different types of hydraulic turbines, and inverted pumps which operate in turbine mode and pump mode.
- A summary of the common parameters in the different turbines and the choice of number of injectors for a turbine in a hydraulic power plant.
- Quote a simplified model of the hydraulic turbine and a small conclusion.

VII.2. Definition of hydraulic turbine

A hydraulic turbine is a rotating machine that produces mechanical energy from moving (stream or tide) or potentially moving (dam) water. It constitutes the essential component of hydroelectric power stations intended to produce electricity from a flow of water. It was invented by Benoît Fourneyron in 1832 [48].

Figure VII.1. Hydraulic turbine

VII.3. The components of a hydraulic turbine

A turbine is active if the pressures at the inlet equal the pressures at the outlet of the impeller. On the other hand, in a reaction turbine, the pressure at the inlet is greater than the pressure at the outlet. A turbine contains the following elements [49]:

- A fixed distributor which gives the water sufficient speed and an orientation which allows the wheel to be approached at the correct angle because small deviations can lead to significant losses in efficiency.
- A moving wheel equipped with fins or buckets (spoon shape) which has the role of transforming hydraulic energy into mechanical energy.
- A diffuser vacuum cleaner which recovers the kinetic energy of the water at the outlet of the wheel by evacuating this water into the downstream reach. This device creates a depression at the exit of the wheel so that we benefit not only from the majority of the kinetic energy but also from the geometric height between the wheel and the downstream level.

VII.4. Categories of hydraulic turbines

Hydraulic turbines are divided into two categories [50]:

VII.3.1. Action turbine

The action turbine is rested by the fact that the energy of the blade is completely converted into kinetic energy. The pressure remains constant between the water and the blades (atmospheric pressure). The turbine wheel is unwatered and spins in the air.

A jet drives the buckets by exerting a force to set them in rotation. This movement is transformed into torque and mechanical power on the turbine shaft. The most used turbine for this category is the Pelton turbine.

In the case of an action turbine the speed of the water depends only on the fall. The rotation speed of the turbine does not depend on flow. The latter depends on two parameters; the speed of the water and the section of the jet.

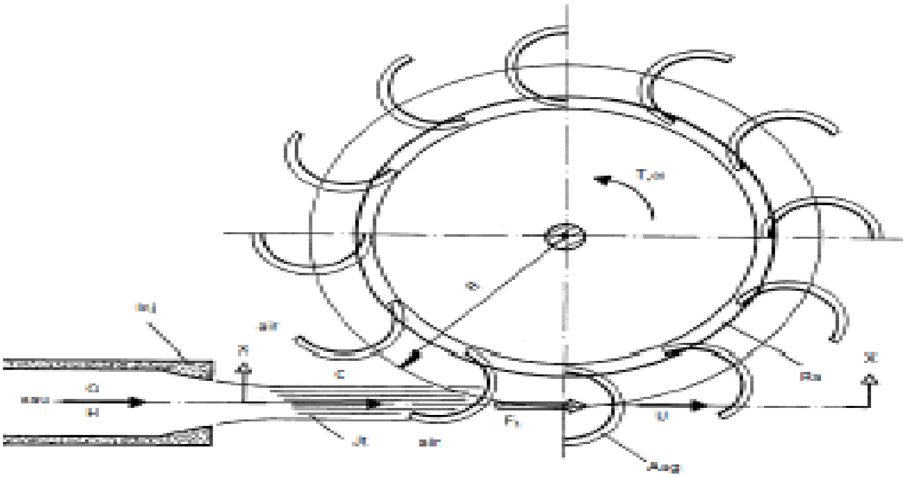


Figure VII.2.Action turbine

VII.3.2. Jet turbine

The reaction turbine is a closed machine. It uses two energy sources; a kinetic energy which is the speed of the water, and a second energy which is the pressure difference. The working principle of this type is that the water pressure creates a force on the surface of the impeller blades, over time the water passes through the turbine, the pressure decreases, so the energy will be transformed into mechanical energy of rotation and transmitted using the transmission shaft to the generator. The principle is based on:

- Creation of a vortex using a cover, guide vanes, or both at the same time.
- Recovery of the circular movement of the tourbillon by the blades of a rotating wheel which deflect the streams of water to give them a direction parallel to the axis of rotation.

Among the turbines that belong to this category: Francis, Kaplan, and propeller

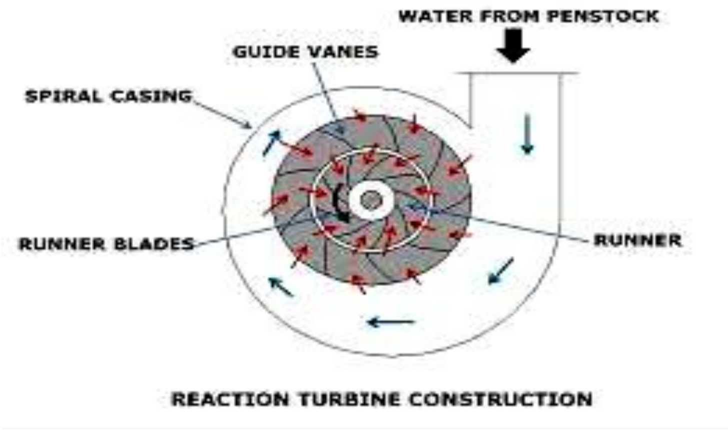


Figure VII.3.Jet turbine

VII.4. The different types of turbines

In the hydraulic field there are several types of turbine. The choice of turbine in a hydraulic power plant is made according to the flow rate and the head. The main types and their characteristics summarized in the following table [51]:

Kind	Drop height (m)	Flow (liters/second)
Kaplan	Low fall	High flow rate up to 100000
Pelton	High falls	Low flow rates
Banki	Wide range of heights from 1 to 200	Wide range of flow rates 20 to 10,000
Francis	Between 40 and 200	30,000

Table VII.1. The different types of hydraulic turbines

VII.4.1. Pelton turbine

This turbine is an action turbine. It is used for head heights greater than 300m and low flow rates. Its wheel is made up of double spoon-shaped buckets which are set in motion by a jet of water coming from an injector, with central notches which ensure optimal progressive penetration of the jet into the bucket. The number of buckets varies depending on the height of fall and the specific speed.

A Pelton turbine can be equipped with several injectors, up to 6. A movable needle inside the injector ensures the adjustment of the flow, which is moved by a hydraulic or electric servomotor. This needle is controlled by the regulation of the turbine.

The Pelton turbine also includes in the majority of cases a deflector which is quickly placed between the injector and the wheel to deflect the jet, this to prevent the turbine from racing in the event of sudden triggering of the generator.

The activation of this deflector does not require an external energy source, it is operated by a spring or a counterweight.

These components are placed in a tarpaulin placed on the turbine leakage channel. Since the wheel turns in the air. The Pelton wheel can be attached with the generator shaft in order to reduce the number of mechanical parts. The advantage of the Pelton turbine is mechanical simplicity, and very good efficiency for the entire flow range.

The rated speed of the turbine varies from 500 rpm to 1500 rpm, which allows direct coupling without a multiplier to the electric generator.

Figure VII.4 presents the main constitutions of the horizontal Pelton turbine [51]

Figure VII.4. Pelton wheel turbine

VII.4.2. Cross flow turbine

The Cross flow turbine is an action machine, the water passes through the impeller twice. The double passage of water through the wheel limits sensitivity to foreign bodies. It has a second name "cross-flow turbine". In 1903, the Australian engineer AGM Mitchell invented the principle of the Cross flow turbine. In 1917, Professor Donat Banki of Hungarian origin published various works on the subject. In 1920, the German firm Ossberger obtained patents for certain technical improvements on these turbines [51].

In 1949, Mockmore and Merryfield of Oregon State University published a comprehensive work on the theory of the Cross flow turbine. In 1982, U. Meier, for SKAT, began drafting plans for the construction of a Cross flow intended for technology transfer to southern countries. Their construction is simple, it is mainly composed of three parts:

- A drum-shaped impeller with profiled cylindrical blades.
- An injector which contains a rotating profiled vane to provide flow adjustment. This injector has a rectangular section. A counterweight which ensures that the turbine stops without external energy, and opening is ensured by a hydraulic cylinder.

- A tarpaulin covered the wheel where the turbine bearings are attached.

To ensure good performance over the entire flow range, a system divides the main components into two sectors, width (1/3) for the turbine, and (2/3) for the wheel and injector.

The impact of water on the cylindrical blades (generally steel blades) is a source of noise and vibration for the machine. When the head is low the turbine is equipped with a vacuum cleaner to recover up to half of the suction height

In general, its rotation speed is low, which justifies the use of a multiplier to couple it to a generator.

Figure VII.5 represents the main components of the Crossflow turbine:

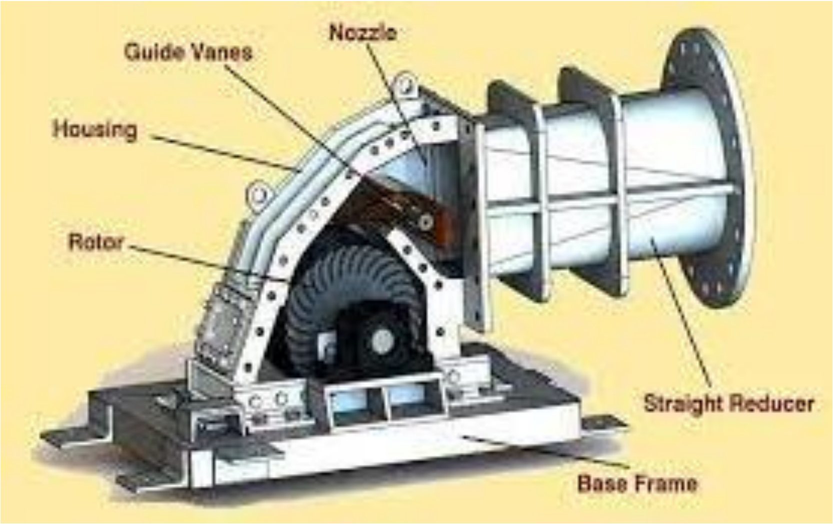


Figure VII.5. The main components of the Crossflow turbine

VII.4.3 Francis Turbine

The Francis turbine is a compact, robust reaction machine. Its wheel is submerged and it exploits both the speed of the water (kinetic energy) and a pressure difference [52].

The Francis turbine is frequently found in old micropower plants. It is used for medium and low heads (40m to 300m) and for low flow variations (average flow rates between 100 ls^{-1} and 6000 ls^{-1}). This turbine is powered by a tarpaulin attached to a penstock. A series of front guides are located at the end of the cover to guide the water towards the distributor.

The distributor is used to regulate the flow, it varies the flow from zero to the maximum value by the turbine and directs the water towards the wheel at an angle to reduce losses. The turbine wheel is placed inside the distributor, it is made up of profiled blades, the number of blades depends on the power of the turbine (8 to 16 blades). The wheel is attached with the generator via a shaft. The latter is guided by the main bearing of the turbine. The Francis turbine is total injection because the wheel is powered over its entire periphery.

For horizontal machines, the wheel can be mounted directly cantilevered on the alternator without an intermediate shaft and bearing. In the case of a fixed flow machine, it is possible to install Francis turbines without a mobile distributor, the coupling being done with the foot valve.

The Francis turbine has good efficiency and a high rotation speed (1000 rpm). Figure 1.6 shows the main components of a Francis turbine:

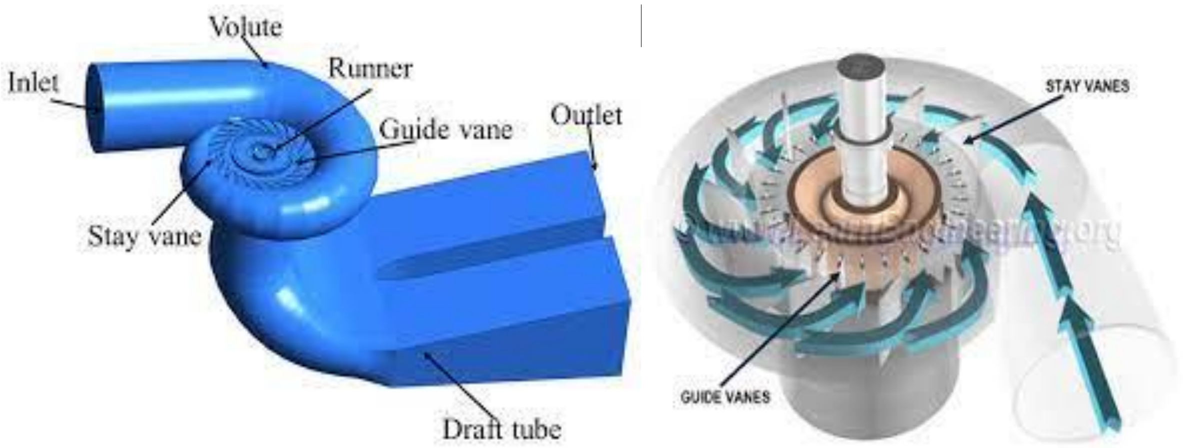


Figure VII.6. The main components of a Francis turbine

VII.4.4. Kaplan Turbine and Propeller

Kaplan and propeller turbines are reaction machines. They are used in low heads (less than 10 m) and high flow rates, and high specific speed [52].

The water supply is similar to a Francis turbine. The turbine wheel in the form of a propeller. There are three configurations depending on the blades:

- If the blades are fixed => Turbine propeller
- If the adjustment of the orientation of the blades is ensured while the turbine is running ==> Kaplan turbine
- If the adjustment of the orientation of the blades is only ensured when the turbine is stopped ==> Variable pitch propeller turbine

The Kaplan turbine is of the "propulsion" type, it was invented in 1912 by the Austrian engineer Viktor Kaplan from whom it takes its name. The first Kaplan turbine installed in

1919 in a demonstration unit in Czechoslovakia, then another, in a textile factory in Austria, with a power of 25.8Kw and a head of 2.3 meters.

In 1922, development of the Kaplan turbine was stopped. In 1926, a Swedish company found a problem on the Kaplan turbine which is the phenomenon of cavitation. The latter can lead to the premature shutdown of the turbine concerned, to be able to carry out heavy maintenance and repair work, and also significant economic consequences (production shutdown, on-site maintenance costs, etc.). This company solves the problem. She called out a power steering device that adjusts the angle of rotation of the blades, before cavitation appears.

The Kaplan turbine is suitable for very high flow rates (70 to 800m3/s), and low heads. The diameter varies from 2 to 11 meters with a rotation range between 50 and 250 rpm.

The advantage of the Kaplan turbine compared to a propeller is that its blades are adjustable, such that the pitch varies during operation, which allows the Kaplan turbine to increase efficiency (90% to 95%) for flow rates variables. The Kaplan turbine is a long-term technical development of the Francis turbine. This development allows the operation of the Kaplan turbine (energy production) when the Francis turbine could not be used.

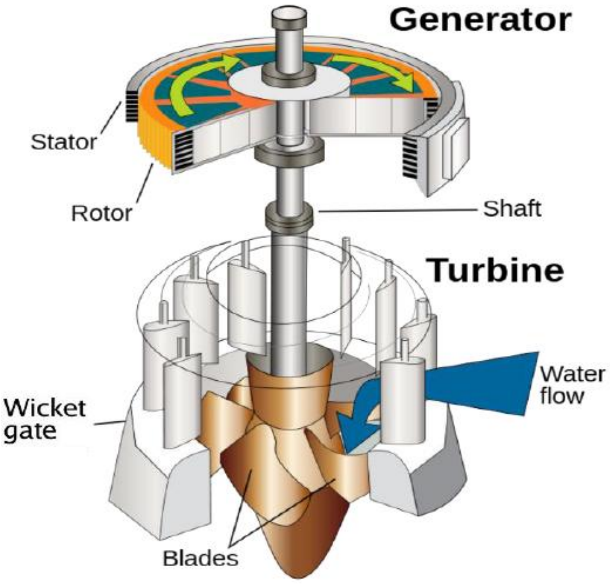


Figure VII.7. Schematic of a Kaplan turbine

VII.5. Reverse push-ups

The reverse pump is a standard pump. Changing the flow direction makes it possible to operate like a turbine (water enters on the pressure side and exits on the suction side). It operates with a fixed flow rate like a “Francis” reaction turbine [52].

The installation of this pump in a hydraulic power plant is very quick, as it is inexpensive. This pump does not require a speed regulator because it operates at a constant speed. This type of machine has several disadvantages:

- Lower efficiency compared to other turbines.
- The efficiency of these machines is 75 to 85%.
- It works with constant flow; a small variation reduces the efficiency of the machine.
- In the event of a network failure, it can cause significant water hammer in the pipes.

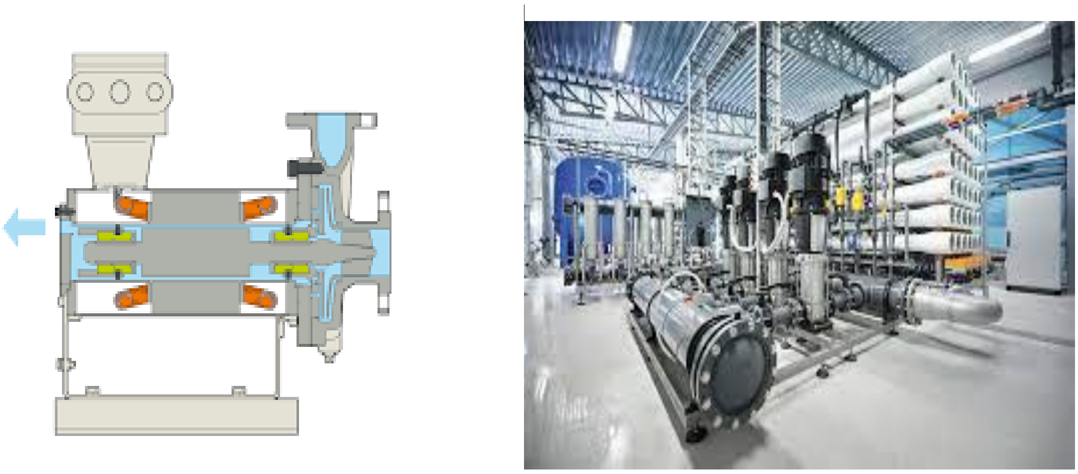


Figure VII.8. Reverse pump

VII.6. Multipliers

When the rotation speed of the turbine is low, below 430 rpm, we then need a multiplier to increase this speed. There are different types of multipliers [52]:

- Bevel gear multiplier.
- Parallel shaft multiplier.
- Belt multiplier

VII.7. Choice of number of injectors

The choice of number of injectors depends on the specific speed. The following table shows us this choice [53]:

Figure VII.9. Multiplier

Ns: The specific speed	Number of injectors
1 to 23	1
20 to 34	2
26 to 40	3
32 to 47	4
38 to 58	5

Table VII.2. Choice of number of injectors

VII.8. Advantages and disadvantages of hydraulic turbines [54]:

VII.8.1. Advantages

- **Renewable Energy Source**

Hydro turbines utilize the power of flowing water, which is a renewable and abundant resource. As long as there is a steady water source, such as a river or dam, the turbines can generate electricity continuously without depleting the resource.

- **Clean and Environmentally Friendly**

Hydroelectric power is considered one of the cleanest forms of energy generation. It produces no air pollutants or greenhouse gas emissions during operation, thereby minimizing the contribution to climate change. It also does not require the burning of fossil fuels, which can contribute to air pollution and acid rain.

- **Reliable and Predictable**

Hydro turbines provide a reliable and consistent source of energy since the flow of water is relatively stable, especially in large dams or rivers. This predictability allows for efficient energy planning and grid management.

- **Long Operational Life**

Hydro turbines have a long operational life, often lasting for several decades. With proper maintenance and regular upgrades, they can continue to generate electricity efficiently for a long time, resulting in a stable and consistent power supply.

- **Flood Control and Water Management**

Large hydroelectric projects can serve multiple purposes, such as flood control and water management. Dams built for hydroelectric power generation can regulate water flow, reducing the risk of flooding downstream. They can also store water during periods of excess flow and release it during dry seasons, helping to meet water demands for irrigation, drinking water, and other purposes.

VII.8.2. Disadvantages

- **High Initial Cost**

Constructing hydroelectric power plants, including the installation of hydro turbines, can be expensive. Building dams, reservoirs, and associated infrastructure requires significant capital investment. The cost can be prohibitive for small-scale projects or in areas with limited water resources.

- **Environmental Impact**

While hydroelectric power is considered clean, the construction of large dams and reservoirs can have a significant impact on the environment. It can lead to the displacement of local communities, loss of wildlife habitats, and alteration of natural water flows. The creation of reservoirs may result in the flooding of large areas, leading to the submergence of forests, farmland, and cultural heritage sites.

- **Limited Suitable Locations**

Hydro turbines require a sufficient and continuous flow of water, making them suitable only in specific locations. Not all regions have access to suitable rivers or dams with the necessary water resources to support hydroelectric power generation.

- **Ecological Disruption**

The construction of dams and reservoirs can disrupt natural river ecosystems. It can affect fish migration patterns, spawning grounds, and aquatic habitats. It may also impact downstream water quality and temperature, potentially harming aquatic flora and fauna.

- **Vulnerability to Droughts and Climate Change**

Hydroelectric power generation relies on a steady supply of water. During periods of drought or reduced water flow, the energy output of hydro turbines can be significantly affected. With the increasing frequency and intensity of droughts and the uncertain effects of climate change, the reliability of hydroelectric power generation can be compromised in some regions.

It's important to note that the advantages and disadvantages of hydro turbines can vary depending on the specific project, scale, and location. Consideration of these factors is crucial when evaluating the feasibility and sustainability of hydroelectric power generation.

VII.9. Conclusion

The hydraulic turbine transforms the water passing through the pipe into rotational (mechanical) energy. The categories of hydroelectric installation in which the turbines are employed are essential factors in determining the shape and characteristics of the hydraulic turbine which we have presented in this chapter. Then we mentioned the different types of turbines and inverted pumps.

The latter can then either directly transmit the mechanical energy to another machine to operate, or, in turn, exchange the mechanical energy with an alternator to transform it into electricity.

TD Series N°. 1

Exercise N°. 1

Use method useful numbers of transfers (NUT)

A counter-current exchanger operates under the following conditions:

$T_{1C} = 350°C$

$T_{2C} = 200°C$

$T_{1F} = 120°C$

$T_{2F} = 290°C$

$Puissance\ \Phi = 415 kw$

1. Calculate the coefficient E and R

2. What is the power exchanged ($Puissance\ \Phi'$) if we make the exchanger work in counter-current mode, with the same flow rates?

3. Determine their percentage by intake a $Puissance\ \Phi$

4. What are the new outlet temperatures?

Exercise N° 2

Use the Logarithmic Average Temperature Difference (DTLM) method

A counter-current or co-current exchanger operates under the following conditions:

$T_{1C} = 350°C$

$T_{2C} = 200°C$

$T_{1F} = 120°C$

$T_{2F} = 290°C$

$Puissance\ \Phi = 415 kw$

1. Calculate the value of DTLM If ($S=S_T$)?

2. Determine the overall exchange coefficient K through the wall as a function of the exchange surface?

TD Series N^o. 2

Exercise N^o. 1

To cool a flow rate of 9.4 kg/h of air from 616 °C to 178 °C, it is passed through the central tube of a two-pipe counter-current exchanger 1.5 m long, 2 cm in diameter and thin.

1. Calculate the heat output to be evacuated. We give for air: C_{pc}= 1060 J / kg K.

2. The cooling fluid is water, which enters the annular section at a temperature of 16°C with a flow rate of 0.6 l/min. Calculate the temperature of this water at the outlet of the exchanger. We will take C_{PF}= 4180 J / kg K.

3. Determine the efficiency of this exchanger (E), then its NUT. Deduce the exchange coefficient k

Exercise N^o. 2

We want to estimate the temperature drop of the fumes in a chimney, considering the conduit as an exchanger in which the fumes constitute the hot fluid, and the ambient air the cold fluid. We assume that the air temperature Ta is constant along the exterior wall of the chimney. We denote by k the overall exchange coefficient through the wall.

1. By adapting the calculation of a co-current exchanger to the particular case above (T_f= T_a = cte), show that the temperature of the smoke in the chimney obeys the law:

$$\frac{T_c - T_a}{T_{ce} - T_a} = \exp\left(-\frac{k}{q_{t\,c}} S \right)$$

2. The duct is cylindrical, of diameter D and length L. Write the smoke outlet temperature T_{cs}.

3. Calculate T_{cs} with the following values: L= 20m; D = 30cm; T_{ce} = 320°C;

T= 10°C; k = 20 W / m^{2}K. For: q_{mc} = 0.5 kg / s; C_{pc} = 1050 J / kg K.

Exercise N^o. 3

The heat transfer between two fluids takes place through a steel tube with internal/external diameters of 18/21 mm.

We give :

- interior side: h=1000 W / m^{2}K; average mixing temperature T_1 = 10 °C
- exterior side: h=2000 W / m^{2}K; temperature T_2 = 25°C
- Steel: λ = 46 W / mK

1. Calculate the overall exchange coefficient k.

2. After one year of operation, we estimate that we have a fouling resistance R =4.10 $^{4-}$ W $^{1-}$ m^2 K.

Determine the new global exchange coefficient.

3. By assigning an efficiency of 1 to the new tube, what happens to this efficiency after one year?

4. What is then the flow exchanged in a tube of length L = 1 m?

Exercise N°. 4

Cold water circulates through a condensing boiler tube. Its inlet temperature is T_{fe} = 18 °C and its flow rate qmf = 400 kg/h. Heating is ensured by condensation of water vapor outside the tube, at the temperature Tc = 104 °C.

We give: internal diameter d = 12.5 mm; external diameter D = 16 mm; length L = 2.4 m; wall conductivity λ_p = 46 W / mK. For water, we will admit in the temperature range considered: v_f =0.7.106 m2 / s; P_{rf} = 5.5; C_{pf} = 4180 J / kg K.

1. Calculate the h_f exchange coefficient inside the tube.

2. We give the coefficient h on the steam side: h_c =8000 W / m^2 K

Calculate the overall exchange coefficient k.

3. Calculate the NUT and efficiency of the device.

4. Determine the water outlet temperature T_{fs}, then the quantity of heat Q recovered annually thanks to the condensing device, if we consider that the heating season lasts 150 days and that the boiler operates 5 hours per day.

TD Series N^o. 3

Exercise N^o. 1

A dam power plant is equipped with a hydraulic turbine (Pelton type), whose blades are driven by a jet of pressurized water. The outlet pipe with a diameter of d=2.5m is located at an altitude Z_2=5m. The volume flow q_v=25m3/s. It is assumed that the water level of the dam (Z_1=30m) varies very slowly, and the pressure losses are estimated at J_{12} =32.75 J/kg. The mechanical energy of the turbine is converted by an electrical current alternator (220kV), of which 17% of the electrical energy is lost in the form of heat.

We give:

ρ=1000 kg/m^3

g=9.81 m/s^2.

1. Determine the speed of water flow at the outlet.

2. Determine the power available on the turbine shaft in MW, if its efficiency is 60%.

3. Deduce the electrical power and intensity of the current produced.

Exercise N^o. 2

A flow rate of 900 kg/s of crude oil flows through a pipeline, which constitutes the control volume shown in the figure. The sections upstream and downstream of the pumping station are respectively:

S_1=0.400m2 and S_2=0.200m2; with heights: Z_1=9m and Z_2=30m and pressures: P_1=140kPa and P_2=1MPa.

The horizontal lengths: L_1=50m and L_2=250m and the coef. Ks=0.5 of the two 90° elbows.

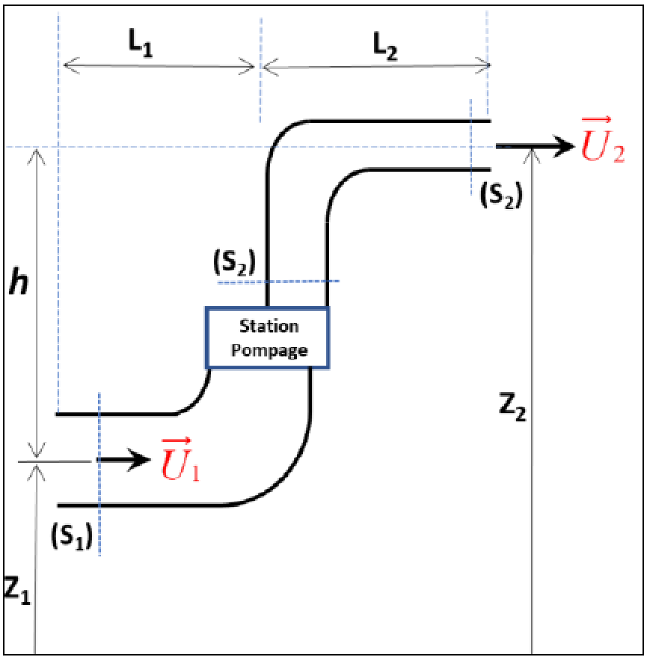
We give :

The density of oil 0.9

The dynamic viscosity is 0.261Pa.s and g=10m/s^2.

1. Determine the linear and singular pressure losses of the pipeline system.

2. Deduct the useful power supplied by the station, considering that the pump has an efficiency of 70%



Exercise N°. 3

A wheel with the following characteristics:

We give:

U=160m/s

The absolute speed C_1=270m/s; φ_1=30°

The absolute speed C_2=160m/s; φ_2=30°

1. Draw the velocity triangles
2. Calculate the speeds w_1, w_2
3. Calculate the head of this wheel

TD Series N^{o}. 4

Exercise

Let k = 0.9, β2=165°, and K= 0.1. Hence, A= 1.869 and ν= 0.475. Typical performance of a Pelton turbine under conditions of constant head and speed is shown in figure 1 in the form of the variation of overall efficiency against load ratio. As a result of a change in the load the output of the turbine must then be regulated by a change in the setting of the needle valve to keep the turbine speed constant. The observed almost constant value of the efficiency over most of the load range is the result of the hydraulic losses reducing in proportion to the power output.

However, as the load ratio is reduced to even lower values, the windage and bearing friction losses, which have not diminished, assume a relatively greater importance and the overall efficiency rapidly diminishes towards zero.

Exemple

A Pelton turbine is driven by two jets, generating 4.0 MW at 375 rev/min. The effective head at the nozzles is 200 m of water and the nozzle velocity coefficient, KN =0.98. The axes of the jets are tangent to a circle 1.5 m in diameter.

The relative velocity of the flow across the buckets is decreased by 15% and the water is deflected through an angle of 165°.

Neglecting bearing and windage losses, determine

- The runner efficiency.
- The diameter of each jet;
- The power specific speed.

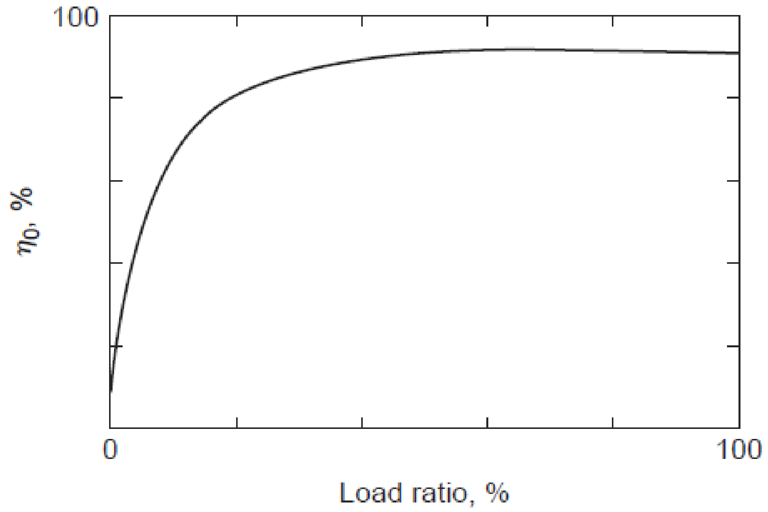


Figure 1 Pelton Turbine Overall Efficiency Variation with Load Under Constant Head and Constant Speed Conditions

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