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DEPARTMENT OF MECHANICAL ENGINEERING

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Major: Mechanical Engineering

1st Year Master

SPECIALTY: ENERGETICS

Polytechnic course material for teaching the subject (version II)

Thermal Machines

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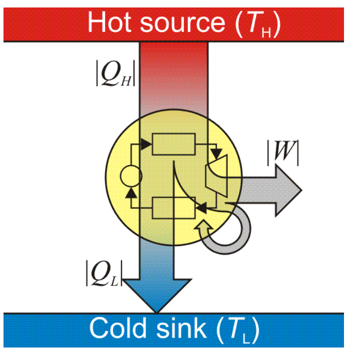

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Table of Contents

Foreword

This course handout for the teaching of thermal machines is intended for first-year master's students in energy, as well as students in master's and bachelor's programs in the field of science and technology in higher education who may be interested in this discipline.

The manuscript consists of lessons that cover the fundamental concepts of applied thermodynamics. It aligns with the curriculum of the subject titled "Thermal Machines" as approved by the ministry. Its didactic presentation is the result of several years of the author's pedagogical experience.

The content of the manuscript is derived from the study of numerous books and documents, most of which are cited in the bibliographic references.

Chapter I: Technical Thermodynamics Review

I.1. Introduction

Thermodynamics is the science that studies and describes the behavior of matter or systems, based on the concepts of temperature (T), energy (heat Q, work W...), and entropy. S.

The object of thermodynamics is to study the operation and energy balance of thermal machines, as well as the exchanges or transfers of heat within a system or between two systems.

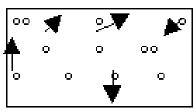
- In thermal machines, we observe a conversion of energy from one form to another (heat -> work or vice versa)
- In heat exchanges, heat is transferred due to a temperature difference within the system or between two systems.

ex1: In thermodynamic machines (TD), work is produced by converting heat into work (such as in thermal engines, thermal or nuclear power plants, etc.)

ex2: In dynamo-thermal machines (DT), on the other hand, there is a transfer of heat from a cold source to a hot source by supplying work (such as in refrigerators, heat pumps, liquefiers, etc.)

Concept of Temperature: Temperature is related to the degree of molecular agitation of matter.

If the velocity (vi) of molecules, and therefore their kinetic energy (Ei), increases, the degree of thermal agitation in the medium is greater. At a temperature of 0 K (absolute zero at -273°C), atoms or molecules are frozen and have minimal thermal motion.



- Molecules move within the enclosure in a completely random manner with velocities **(vi)**

Fig. I.1: Gas in an enclosure

Temperature **T** is defined by the relation:

$$1/2\ mv^2 = 3/2\ kT \tag{I.1}$$

This relation defines the absolute temperature scale **T** in degrees Kelvin (**K**).

Concept of Pressure: Pressure is caused by the numerous collisions of atoms or molecules with the walls of the container.

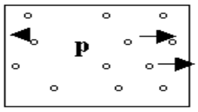


Fig. I.2:"Pressure in an enclosure."

- In the enclosure, there are N molecules in constant agitation, so n' = N/V is the number of molecules per unit volume.

Pressure is defined by the relationship: $p = 1/3\ n'mv^2$ (I.2)

Energy exchanges:

Energy exchanges in the form of heat (Q) or work (W) are interpreted at the microscopic level as a manifestation of molecular agitation in a disordered (Q) or ordered (W) form.

Units:

- MKS System (or SI System):

- Time in [s]
- Temperature in degrees [K], where T [K] = t °C + 273
- Pressure in Pascal [Pa] or [N/m²]
  $p = [Pa] = [N/m^2]$ and 1bar = 10^5 Pa = 750 Torr
- Energy in Joules [J], where 1 Cal = 4.184 Joules
- Power P in Watt [W], where 1 W = 1 J/s

- Thermicians' System (TS) :

- Time in [h]
- Energy in [kcal]
- Power in [kcal/h]

Other units of pressure :

1 atm = 1,013 bar = 760 Torr

1 Torr = 1,333 mba

1 bar = 750 Torr

1 mbar = 100 Pa = 0,750 Torr

1 atù = 1 kg/cm^2 = 0,980 bar

A distinction is made between absolute pressure and relative pressure, or total pressure and partial pressure of a fluid, and energy.

Frigorie [fg] with 1 fg = 1 kcal

kWh (kilowatt-hour) 1 kWh = 3.6 MJ = 860 kcal

1 kcal = 1.16 Wh

In Anglo-Saxon countries, different units are used: energy is expressed in BTU (British Thermal Units) and temperature in degrees Fahrenheit [°F], with:And

1 BTU = 1 055,05585 joules

T(°C) = 5/9t(F) – 32

I.2. Thermodynamic system and equilibrium state

I.2.1 Definition of a system

To thermodynamically describe a system, it is necessary to consider both:

- Defining the system by establishing its boundaries in relation to the external environment.
- Determining the state of the system defined by its variables.

The system is defined as a portion of matter (with a given mass) delimited with respect to the external environment. The external environment is the remaining space surrounding the system.

The system can be classified as open or closed, adiabatic (thermally isolated) where

Q = 0, or rigid (undeformable) where W = 0.

Table I.1: Exchange of mass and energy between the system and the external environment

System	Matter exchange	Energy exchange
Isolated	Non	Non
Closed	Non	Yes
Open	Yes	Yes

In a closed system, there is no transfer of mass, and in an isolated system, there is no exchange of work or heat.

I.2.2.State of the system

The state of the system is defined or described by its macroscopic variables (m, p, V, T, n, etc.), also known as state variables. A given system is associated with a whole set of possible states.

It is said that a system is in a state of thermodynamic equilibrium if its state variables have well-defined and constant values. Depending on the situation, we distinguish between :

- Thermodynamic or heat-related variables (p, V, T) or calorimetric variables (U, H, W, Q, S).
- Extensive variables, which are proportional to the amount of substance, such as (m, V, U...), or intensive variables, which are independent of mass, such as (p,T,concentration...)

  Mass-related quantities are often defined, which are expressed per unit mass of the system, such as:
- Specific volume: $v = V/m$ in [m³/kg]
- Specific internal energy or specific enthalpy: $u = U/m$ or $h = H/m$ in [J/kg]

These quantities are related to each other through relationships, for example:

$m = \rho V$ or $q_m = \rho q_v$(for mass flow rates and volumetric flow rates)

where $q_m = \rho\omega S$ where$\omega$is the velocity of fluid flow

and for steady flow :$\rho_1\omega_1S_1 = \rho_2\omega_2S_2$ (continuity equation)

I.3.Evolution or transformation of the system :

Under the influence of energy exchanges or transfers between the system and the external environment, the system undergoes changes and the state variables of the system are modified. We say that the system undergoes a transformation or changes its state, transitioning from one equilibrium state (1) to another equilibrium state (2).

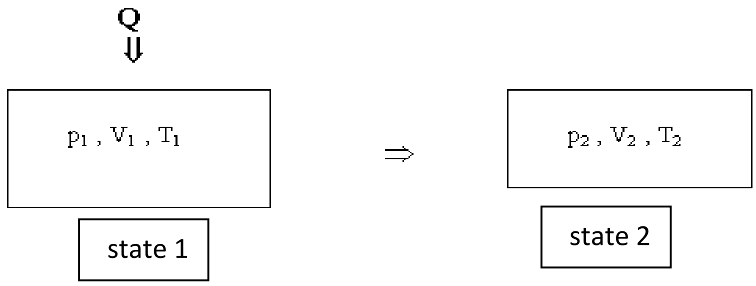


Fig. I.3:Transformation of the system through energy exchange (heat transfer Q).

During a transformation, the state variables of the system change to reach another state of equilibrium. The transition from equilibrium state (1) to equilibrium state (2) typically occurs out of equilibrium.

Then, we distinguish between (see Fig. I.4):

- Reversible transformations (or ideal transformations): These are infinitely slow transformations formed by a succession of equilibrium states.
- Irreversible transformations: These are rapid and abrupt transformations that occur out of equilibrium

The reversibility of a transformation requires the system to pass through an infinite number of intermediate states, including a series of quasi-static equilibrium states. Natural spontaneous transformations are irreversible; they can only evolve in one direction (e.g., the expansion of a gas from high pressure (HP) to low pressure (LP), the flow of heat from high temperature (HT) to low temperature (LT)).

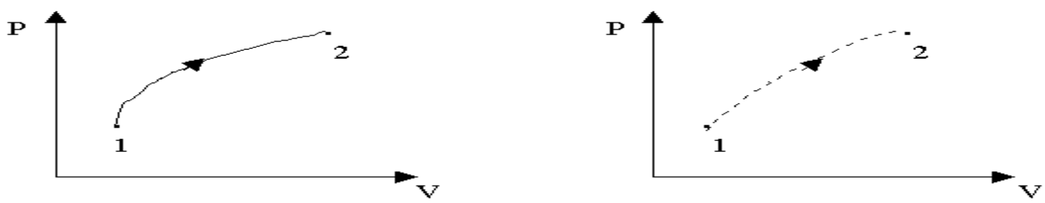


Fig. I.4 :"Transformations a) reversible and b) irreversible."

I.4 Equations of state of the system and state function:

The state variables are not all independent but are related to each other through equations known as equations of state of the form: f (p, V, T) = 0.For example, the equation of state for ideal gases is given by: $pV = nRT$

Here, there are only two independent variables, so we can express it as p = f (V, T),

V = f (p, T), or T = f (p, V)

We distinguish between different transformations that can be easily represented in these previous diagrams (by vertical or horizontal lines), namely:

- Isochoric transformation (V = constant).
- Isobaric transformation (p = constant).
- Isothermal transformation (T = constant) satisfying pV = constantla.
- Isentropic transformation (S = constant) or (Q = 0) governed by: pV^{γ} = cte.
- Polytropic transformation satisfying: pV^{n}= cte with $1 < n < \gamma$.

State Functions:

Often, transformations between state 1 and state 2 can be achieved in different ways, i.e., by following different paths. In general, the variation ΔX of a quantity X depends on the path taken from state 1 to state 2.

However, in thermodynamics, there exist functions F that are related to the state variables and whose variations ΔF during a transformation are independent of the path taken. These quantities or functions are called state functions, and they are characterized by:

- their independence with respect to the path followed by the transformation
- the fact that the differential dF is an exact differential

Then, ΔF12 = F2 - F1, regardless of the path followed

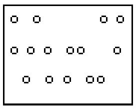
Example:internal energy U, enthalpy H, and entropy S are state functions. However, work W and heat Q are not state functions.

I.5. Energy Exchanges: Work, Heat, Internal Energy

I.5.1Internal Energy U

The internal energy of a system or a body is the energy content of that system. Every system (solid, liquid, or gas) is a collection of objects such as atoms, molecules, etc. These particles are constantly in motion, undergoing continuous and random movements (molecular agitation): vibrations in solids or thermal agitation in liquids or gases.These microscopic movements of the molecules are associated with kinetic energy Ek. Additionally, there can be interaction forces (attraction and repulsion) between these atoms or molecules, which are associated with potential energy Ep.At the microscopic level, the internal energy U of the system is defined as the sum of the kinetic energies Eki and potential energies Epi of all the particles comprising the system

Ex1:A perfect gas is characterized by the absence of interactions between molecules (Ep = 0).



$U = \sum_i E_{ci}$

so, $U = \Sigma_i \ 1/2 m v_i^2 = N.1/2 \ mv^2$

also,$U = 3/2 \ NkT$

where N is the number of molecules in the enclosure.

Example 2: A real gas is characterized by the presence of interactions between molecules (thus $Ep \neq 0$).

$$\text{Therefore, } U = \Sigma_i \ E_{ci} + \Sigma \ E_{pi\_} \qquad (I.3)$$

Properties of internal energy U :

At thermal equilibrium, the internal energy U:

- is an energy expressed in joules [J] or [kcal].
- It has a well-defined value known up to a constant (not known absolutely).
- It is a state function

I.5.2 The Heat Q:

Heat is a special form of energy:

• It is an energy expressed in joules [J] or [kcal].• On a microscopic scale, it is energy exchanged in a disordered form through molecular agitation (i.e., through collisions between moving molecules).• It always flows from a hot source to a cold source.• Heat is not a state function

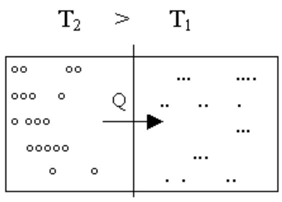


Fig. I.5 : Heat transfer Q through molecular agitation (by removing the adiabatic partition).

We distinguish between two types of heat:

a) Sensible Heat :

- It is related to a temperature change ΔT of the system due to heating or cooling.
- It is proportionalto the mass of the substance and the temperature difference.

  Therefore, for an infinitesimal transformation :

$$dQ = mcdT \tag{I.4}$$

where c represents the specific heat capacity of the material or fluid, expressed in [J/kg·K].

Finite transformation: The heat Q exchanged during a finite transformation between state 1 and state 2 is obtained by integrating equation 3.3, which is valid for an infinitesimaltransformation. Several cases are distinguished based on the value of c:

$$dQ = mcdT$$

The specific heat remains constant (c = constant).

Therefore, Q12 = ∫12 mcdT = mc ∫12 dT = mc(T2 - T1).

So, Q12 = mc∫T = mc(T2 - T1) = mc(t2 - t1) (I.5)

The specific heat varies, average value c = $c_m\Big|_{T_1}^{T_2}$

c varying in the interval [T1, T2], we then take an average value for c = $c_m\Big|_{T_1}^{T_2}$

$$Q = m\, c_m\Big|_{T_1}^{T_2} (T_2 - T_1) \tag{I.6}$$

Where the average value,

$$c_m\Big|_{T_1}^{T_2} = \frac{c_{m0}\Big|_{T_2}^{T_2} - c_{m0}\Big|_{T_1}^{T_1}}{T_2 - T_1} \qquad (I.7)$$

Because, $Q_{12} = Q_{02} - Q_{01}$

=>the average value is calculated from tables that provide $c_m\Big|_0^{T_1}$

the specific heat is a function of T: $c = f(T) = a_0 + aT + bT^2$

Hence,

$$Q_{12} = m\int_1^2 cdT = \int_1^2 (a_0 + aT + bT^2 + ...)dT$$

We generally distinguish between specific heats at constant pressure or constant volume, denoted as c_p or c_v:

- For solids or liquids, we have: $c_p \sim c_v = c$
- But for gases: c_p # c_v et $c_p/c_v = \gamma$

b) Latent Heat:

Latent heat is the heat required for 1 kg of substance to change its state at constant temperature. It is defined by: $Q = mL$ (I.8)

Where L is the specific heat associated with a change of state, this heat is either released (L → V) or absorbed (V → L). We distinguish between latent heats of fusion, vaporization, sublimation, etc...

Note :Phase changes are utilized in Thermodynamic Machines as they release significant amounts of heat. This allows for a significant reduction in the size of heat exchangers and compressors, resulting in material and energy savings.

c) Law of mixtures:

By bringing two bodies at different temperatures into contact or mixing them, there is heat transfer: at thermal equilibrium, both bodies will have the same temperature, T = Tm (final temperature of the mixture).

The temperature of the mixture, Tm, is obtained from the energy balance of the two systems or bodies.

$Q_{am} + Q_{bm} = Q_p$ or, Q_p They refer to the heat losses from a non-adiabatic system.

If the system is adiabatic ($Q_p = 0$), then we have:

$$m_a c_a (T_m - T_a) + m_b c_b (T_m - T_b) = 0$$

$$t_M = \frac{m_a c_a t_a + m_b c_b t_b}{m_a c_a + m_b c_b}$$

The Work W :

Work is another form of energy (mechanical energy):

- it is an energy expressed in [J] or [kcal]
- at the microscopic level, it is an energy exchanged in an orderly manner (through the displacement of the piston, which gives a certain direction to the atoms)
- it is not a state function

We distinguish between volumetric work, technical work, and friction work.

Volumetric Work (Wv) :

Work typically results from a change in volume of a deformable system (non-rigid), for example, the displacement of a piston. This is referred to as Volumetric Work defined by:

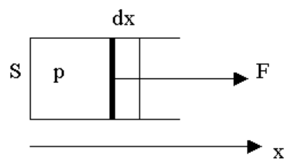


Fig. I.6 : Work transfer

$p = F/S$

$dW_v = Fdx = pS\,dx = pdV$in [Nm] or [J]

Hence, the elemental work is given by:$dW_v = -\,pdV$(I.9)

Noticed :

- the minus sign (-) is imposed by the convention for energy signs
- if the piston moves to the right, then dV increases (dV>0) and work is transferred or provided to the external environment (thus the work is <0)

* Calculation of volumetric work **Wv** for a finite transformation.

To calculate the total work between state 1 and state 2, it is necessary to integrate equation (I.9), resulting in:

$$W_{12} = -\int_1^2 pdV = aire.de.a12b \qquad \text{(I.10)}$$

Several cases can be distinguished in this regard.:

a) Isobaric transformation (p = cte)

So, $W_{12} = -p\int_{12} dV = -p[V_2 - V_1]$ (I.11)

b) Isothermal transformation (T = cte)

So, $W_{12} = -\int_{12} pdV$ or $pV = nRT$

Therefore, $W_{12} = -\int_{12} nRT\, dV/V = -nRT \int_{12} dV/V$

$W_{12} = nRT \ln V_1/V_2 = nRT \ln P_2/p_1$ (I.12)

c) Isochoric transformation (V = cte)

So, $dV = 0$ and the work is zero, $W_{12} = 0$

Technical Work W_t :

Technical work Wt occurs in open systems (such as piston engines, turbines, flowing fluids, etc.), and it is defined by the following relation:

- Elementary transformation :$dW_t = Vdp$(I.13)

- Finite transformation :$W_t = \int_{12} Vdp$

Calculation of the technical work Wt: it is performed by integrating equation 3.11 using the same rules as for volumetric work:

- for an isobaric transformation ($dp = 0$) :we have $W_{t12} = 0$
- an Isochoric transformation ($V = cte$) : $W_{t12} = V(p_2 - p_1)$

Friction work(W_f) :

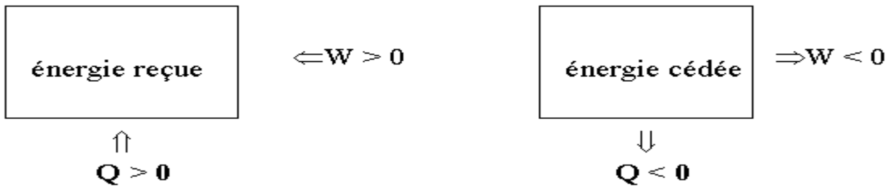
Friction work Wf is the mechanical energy dissipated due to mechanical friction or other processes. Therefore, the overall work of a closed system is given by:

$$W_g = W_v + W_f$$

The convention for the sign of exchanged energies (heat, work...) is as follows:

• The energies (W, Q) received by the system are considered > 0 and assigned the positive (+) sign.

• The energies (W, Q) released by the system are considered < 0 and assigned the negative (-) sign.



I.6. The reversibletransformations :

Reversible transformations of a system are ideal transformations that play a significant role in thermodynamic processes. In these transformations, there is no friction or energy dissipation, making them easily calculable.

The operation of thermodynamic machines is described by a thermodynamic cycle consisting of several successive reversible transformations.

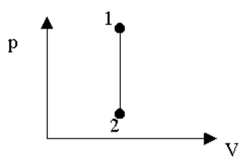
I.6.1 Closed Systems:

In closed systems, the enclosed mass of matter can undergo varioustransformations.

Weconsider the following different simple and reversible transformations:

I.6.1.1 Isochoric transformation (V = cte)

Let's consider an ideal gas confined in a rigid enclosure.(non-deformable, where dV = 0).



Hence,, $\frac{p_2}{p_1} = \frac{T_2}{T_1}$ (I.14)

Fig.I.7 : Isochoric transformation

Work :

We have, dW = -pdV => $W_{12} = -\int_{12} pdV$

the container being non-deformable (dV = 0), $W_{12} = 0$5.2)

Heat :

We have,$\Delta U = W_{12} + Q_{12}$

So, $Q_{12} = U_2 - U_1 = mc_v (T_2 - T_1)$

Internal energy and enthalpy:

We have, $\Delta U = Q_{12} + W_{12}$ (avec $W_{12} = 0$)

So, Internal energy $\Delta U = Q_{12} = mc_v (T_2 - T_1)$ (I.15)

And enthalpy, $\Delta H = H_2 - H_1 = mc_p (T_2 - T_1)$ (I.16)

I.6.1.2Isobaric transformation (p = cte)

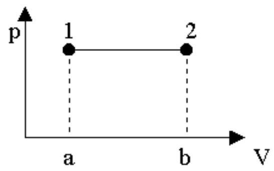


Fig.I.8 : Isobaric trensformation

We have , $\Rightarrow \frac{V_2}{V_1} = \frac{T_2}{T_1}$ (I.17)

Work

$$W_{12} = -\int_1^2 pdV = -p(V_2 - V_1)$$

We have , $W_{12} = -p(V_2 - V_1) = mr(T_1 - T_2)$ = aire(I.18)

Heat

We Have , $dH = dQ + Vdp$ (or $dp = 0$) $\Rightarrow dQ = dH$

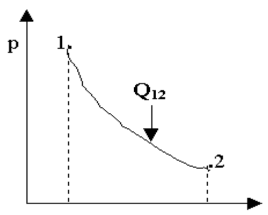
$Q_{12} = H_2 - H_1 = mc_p(T_2 - T_1)$ (I.19)

Internal energy and enthalpy:

We have, $\Delta U = Q_{12} + W_{12}$

And $\Delta U = mc_v(T_2 - T_1)$
$\Delta H = Q_{12} = mc_p(T_2 - T_1)$ (I.20)

I.6.1.3 Isothermal transformation (T = cte)



$p_1V_1 = mrT_1$

$p_2V_2 = mrT_2$

So => $p_1V_1 = p_2V_2$ (I.21)

Fig. I.9 : Isothermal transformation

Work :

$$W_{12} = -\int_1^2 pdV = m.r.T.lin\frac{V_1}{V_2} = m.r.T.lin\frac{p_1}{p_2}$$

$W_{12} = mrTlnp_2/p_1 = mrTlnV_1/V_2$ (I.21)

Heat :

As, T = cte and U = f(T) only we have :

$Q_{12} = - W_{12} = mrTlnp_1/p_2$ (becauseΔ U = 0)5.12)

Internal energy and enthalpy

we have,Δ U = 0 car, U = f(T)

Hence,Δ H = 0 car, H = f(T)5.13)

I.6.1.4 Isentropic transformation Q = O (Reversible adiabatic)

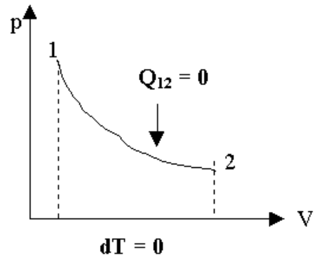


Fig. I.10 : Isentropic transformation

or, dU = dQ + dW (and dQ = 0)

$dQ = dU + pdV = mc_vdT + pdV = 0$ (I.22)

$dQ = dH - Vdp = mc_pdT - Vdp = 0$

So,

$$mc_vdT = -\ pdV$$
$$mc_pdT = +Vdp$$

$$\frac{dp}{p} = -\gamma.\frac{dV}{V}.avec.\gamma = \frac{C_p}{C_v} = \frac{c_p}{c_v}$$

By integrating this relation, we obtain the well-known equation for a gas undergoing an isentropic transformation:

$pV^\gamma = cte \Rightarrow$ or $p_1V_1^\gamma = p_2V_2^\gamma$(I.22)

Relations (p, T) et (V, T) for thermodynamic quantities :

We have the relations: pV = nRT and $pV^\gamma = cte$ (I.23)

- for the pair (p, T): $TP^{\frac{1-\gamma}{\gamma}} = Cst$ (I.24)
- for the pair (V, T): $TV^{\gamma-1} = Cst$ (I.25)

We have the relations : $T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1}$ et $T_1^\gamma p_1^{1-\gamma} = T_2p_2^{1-\gamma}$(I.26)

Work:

$$W_{12} = -\int_1^2 pdV = \frac{p_1V_1}{\gamma-1}\left[(\frac{V_1}{V_2})^{\gamma-1} - 1\right] = \frac{p_1V_1}{\gamma-1}\left[\frac{T_2}{T_1} - 1\right] = \frac{n.r}{\gamma-1}(T_2 - T_1) = \frac{1}{\gamma-1}(p_2V_2 - p_1V_1)$$

So, $W_{12} = mr(T_2 - T_1)/(\gamma - 1) = (p_2V_2 - p_1V_1)/(1-\gamma)$ (I.27)

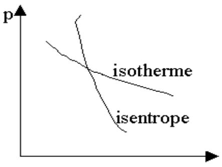
Heat :

adiabatic transformation, $Q_{12} = 0$

Internal energy and enthalpy$\Delta U = mc_v (T_2 - T_1)$5.21)

Or,$\Delta U = W_{12}$ and $\Delta H = mc_p (T_2 - T_1) = \gamma \Delta U$

comparative slopes of isotherms and adiabats:



$$tg.\alpha.(isotherme) = \frac{dp}{dV} = -\frac{P}{V}$$
$$tg.\alpha.(isotropique) = \frac{dp}{dV} = -\gamma\frac{P}{V}$$

And $\gamma > 1$

Fig. I.11:Isotherm and adiabat curves

The slope of the adiabat curve is steeper than that of the isotherm curve.

I.6.1.5 Polytropic transformation (with heat exchange Q ≠ 0):

The polytropic transformation is closer to a real transformation, and its equation of state is given by:$pV^n = cte$ (I.28)

where $1 < n < \gamma$ (**!**:be careful, n is not the number of moles, but a number)

Formula:

We have , $p_1V_1^n = p_2V_2^n$

$$W_{12} = -\int_1^2 pdV == \frac{p_1V_1}{n-1}\left[\frac{T_2}{T_1} - 1\right] = \frac{n.r}{n-1}(T_2 - T_1) = \frac{1}{n-1}(p_2V_2 - p_1V_1) \quad \text{(I.29)}$$

$$\text{et, } \frac{T_2}{T_1} = \left(\frac{V_2}{V_1}\right)^{n-1} = \left(\frac{P_2}{P_1}\right)^{\frac{1-n}{n}} \quad \text{(I.30)}$$

Warning : For a polytrope

$Q_{12} = \Delta U - W_{pol12}$

$$\frac{Q_{12}}{W_{12}} = \frac{n-\gamma}{\gamma-1} \rightarrow W_{12} = m.C_v\frac{\gamma-1}{n-1}(T_2 - T_1) \quad \text{(I.31)}$$

$Q_{12} \neq 0$ and,

$$Q_{12} = mC_v\frac{n-\gamma}{n-1}(T_2 - T_1) \text{ (I.32)}$$

These transformations (except for the polytrope) are ideal approximations that differ from real transformations, but they are very useful for modeling or describing thermodynamic cycles.

The formula pV^n = constant is very general and encompasses all the previous transformations:

- Isochoric (V = constant): $p^{\circ}V = pV_{1}$ /0 = constant, where $n = \infty$
- Isobaric (p = constant): pV° = constant, where n = 0
- Isothermal (pV = constant): pV = constant, where n = 1
- Isentropic (pV_{γ} = constant) : pV^{n} = constant, Where $n = \gamma$

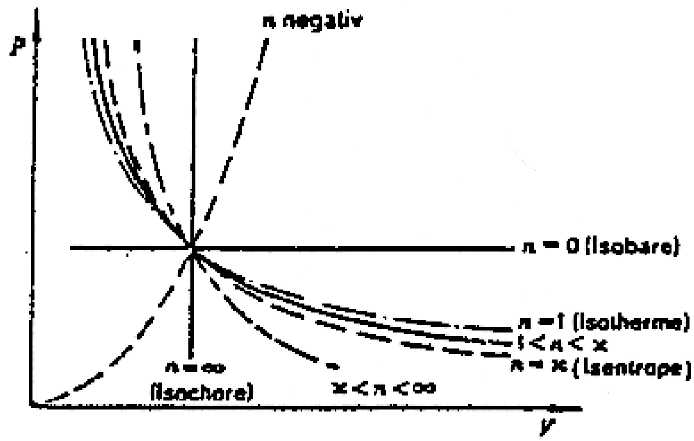


Fig. I.12: The different transformations in (p, V)

Chapter II: Heat Engine Cycles

II.1. Compressors:

II.1.1Introduction :

A compressor is a machine that is designed to increase the pressure of a compressible fluid as it passes through it. Its name reflects the fact that the fluid is compressed, resulting in a decrease in volume, as the pressure increases.

The pressure increase provided by a compressor is used to achieve a specific pressure level required for various processes, such as:

- Chemical reactions (required pressure for the catalyst)
- Storage in cavities
- Liquefaction or separation processes
- Refrigeration cycles
- Supplying compressed air networks…. etc.

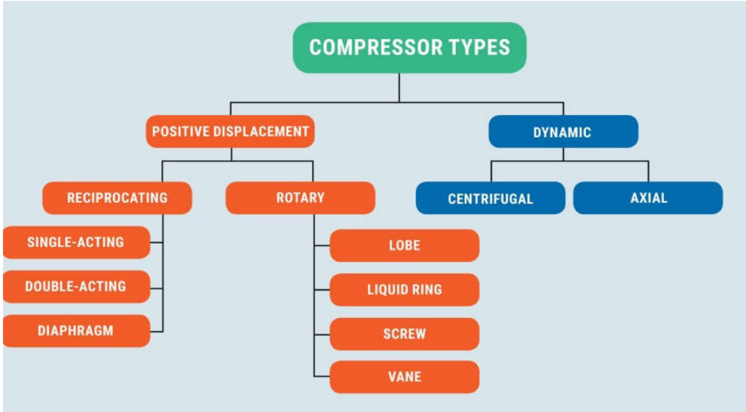
II.1.2.The objective of these devices:

Pressure increase (raising the suction pressure) from low pressure to high discharge pressure.

II.1.3.- Classification of compressors:

Compressors can be classified according to the following characteristics: figureII.1

- Operating principle : volumetric, dynamic
- Movement of moving parts : linear movement, rotary movement
- Air compressors
- Gas compressors



FigII.1.Classification of Compressors.

II.1.3.1- Positive Displacement Compressors:

Positive displacement compressors achieve pressure elevation by reducing a certain volume of gas through mechanical action.

II.1.3.1.a- Operating principle:

The operating principle of these compressors is as follows, as shown in Figure II.2. A fixed mass of gas at suction pressure is trapped in a chamber with variable volume. To increase the pressure, the volume is gradually reduced, following a method that varies depending on the technique used. Typically, the transformation follows a law similar to a polytropic process

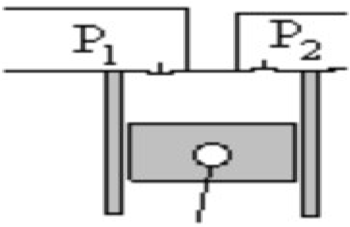


Fig II.2 Operating principle :

II.1.3.1.b- Different types of volumetric compressors:

Volumetric compressors can be chosen based on the mentioned characteristics shown in FigureI.1.

1 - Reciprocating piston compressors:

In a reciprocating piston compressor, the chamber is the volume enclosed by a cylinder, one of its fixed bases, and the other base which is a movable piston in the cylinder bore, driven by a connecting rod-crank system.

At the end of compression, the chamber is connected to the discharge circuit so that the compressed gas at pressure P2 can be discharged. A new mass of gas at pressure P1 is then drawn in from the upstream pipes, and so on, as the operation of the machine is cyclical.

The valves that control the discharge or intake are, in piston compressors, automatically operated by pressure differences between the chamber and the discharge or intake pipes.

The displacement is the volume swept by the piston between its two extreme positions, and the clearance is the minimal volume of the compression chamber. In common designs, the clearance is around 3 to 5%.

Due to the existence of clearance, volumetric compressors have a unique characteristic: their apparent displacement is less than their geometric displacement. Some amount of fluid remains trapped in the compressor at the end of the discharge, thereby reducing the effective volume of the machine. This reduction in displacement is characterized by a parameter called volumetric efficiency.

2- Rotary compressor:

These compressors, like piston compressors, compress gases by reducing the volume. Among the different types of rotary compressors, we can distinguish:

- Vane compressor
- Screw compressor
- Rotary-type compressor
- Spiral compressor

II.1.3.2- Dynamic compressors:

From a fluid flow perspective, dynamic compressors can be divided into axial and centrifugal machines. See Figure II.3.

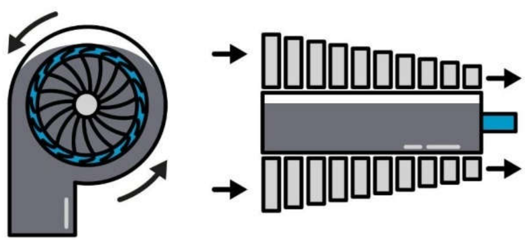


Fig II.3 Dynamic compressors

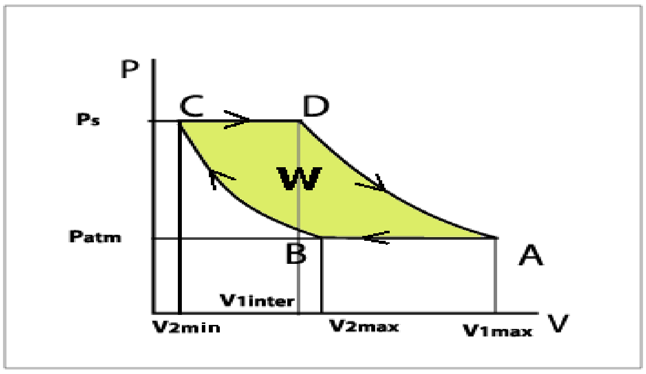
II.1.3.3- Axial compressors :

Axial compressors are receivers with axial flow of the compressible fluid. They are commonly used in high-power turbines and aviation turbojets. They are characterized by a large number of stages and a relatively low compression ratio.

II.1.3.4- Centrifugal compressors :

Centrifugal compressors increase the energy of the compressed gas through the centrifugal force generated by the rotation of the impeller blades.

II.2- Thermodynamic cycle:



II.2.1- Energy balance :

A-B –Isobaric transformation : $P_A = P_B$

$$T_A/V_A = T_B/V_B = \text{constant}$$

-The Internal energy ΔU:

$$\Delta U = nCv\Delta T = nC_v(T_B - T_A)$$

-**The enthalpy ΔH** :

$$\Delta H = nCp\Delta T = nC_p(T_B - T_A)$$

-**Internal work (W_{in}) :**

$$W = -\int PdV = -P(V_B - V_A)$$

-External work (W_{ex}) :

$$W = \int VdP = V(P_B - P_A)$$

-Heat quantity (Q) :

$$Q = \Delta H = nCp(T_B - T_A)$$

B-C – Adiabatic compression transformation :S_B=S_C

$$P_B V_B^{\gamma} = P_C V_C^{\gamma}$$

$$T_B V_B^{\gamma-1} = T_C V_C^{\gamma-1}$$

$$T_B P_B^{\frac{1-\gamma}{\gamma}} = T_C P_C^{\frac{1-\gamma}{\gamma}}$$

- The Internal energy ΔU :

$$\Delta U = nC_v\Delta T = nC_v(T_C - T_B)$$

- The enthalpy ΔH :

$$\Delta H = nC_p(T_C - T_B)$$

- Internal work (W_{in}) :

$$W = \frac{1}{\gamma-1}(P_B V_B - P_C V_C)$$

- Heat quantity (Q):

$$Q_{BC} = 0$$

C-D – Isobaric transformation : PC = PD

$$\frac{T_C}{V_C} = \frac{T_D}{V_D} = \text{constant}$$

- The Internal energy ΔU:

$$\Delta U = nC_v\Delta T = nC_v(T_D - T_C)$$

-The enthalpy ΔH:

$$\Delta H = nCp(T_D - T_C)$$

- Internal work (W_{in}):

$$W = -\int pdv = -P(V_D - V_C)$$

- External work (W_{ex}):

$$W = \int VdP = V(P_D - P_C)$$

- Heat quantity (Q):

$$Q = \Delta H = nC_p(T_D - T_C)$$

D – AAdiabatic relaxation transformation : $S_A = S_D$

$$P_A V_A^{\gamma} = P_D V_D^{\gamma}$$

$$T_A V_A^{\gamma-1} = T_D V_D^{\gamma-1}$$

$$T_A P_A^{\frac{1-\gamma}{\gamma}} = T_D P_D^{\frac{1-\gamma}{\gamma}}$$

-The Internal energy ΔU :

$$\Delta U = nC_v\Delta T = nC_v(T_A - T_D)$$

-l'enthalpie ΔH :

$$\Delta H = nCp(T_A - T_D)$$

- Internal work (W_{in}) :

$$W = \frac{1}{\gamma-1}(P_A V_A - P_D V_D)$$

- Heat quantity (Q) :

Q = 0 (Because it's an adiabatic expansion transformation)

-Calculation of total work(W_T):

The total work is the sum of the suction work + discharge work + compression work.

-The suction work :

$$W_{asp} = P_B.S_C = P_B VB$$

-The compression work (W_{comp}):

$$W_{comp} = \int_{V_B}^{V_C} PdV$$

-The discharge work (W_{dis}):

$$W_{dis} = P_C.S_C = P_C V_C$$

Total work (W_T):

$$W_T = W_{asp} + W_{comp} + W_{dis}$$

$$W_T = P_B V_B - \int_{V_B}^{V_C} PdV + P_C V_C$$

-The efficiency (ε) :

$$\varepsilon = \frac{Q_{BC}}{W_T} = \frac{nC_P(T_D - T_C)}{P_B V_B - \int_{V_B}^{V_C} PdV + P_C V_C}$$

Compression ratio :

-

$$\beta = \frac{Discharge\ pressure}{Suction\ pressure} = \frac{P_C}{P_B}$$

Conclusion:

In general, compression can be imposed by the technical necessity of moving a certain quantity of gas from a system at a certain pressure to another system at a higher pressure.

II.2 Thermal machines; some definitions:

II.2.1 Thermal machine:

A thermal machine is defined as any system that can convert energy transfer from non-thermal sources to thermal energy transfer and vice versa. Commonly, a thermal machine is described as a system that converts work into heat and vice versa. These machines operate in a cyclic manner, meaning that after a certain number of transformations, they return to their initial state.

A thermal machine is composed of several components:

- The essential part is the thermodynamic system responsible for carrying out the transformations. This system is usually a fluid that exchanges mechanical and thermal energy with other components.
- Work reservoirs (such as engines, electrical circuits, etc.) that exchange work only with the system. These are considered to be ideal, meaning that the exchanges are adiabatic and reversible.
- Heat sources, often represented by thermostats, capable of providing or receiving any quantity of heat without changing their temperature.

II.2.2 Types of thermal machines:

There are three types of thermal machines:

- Engine: (S) exchanges heat and provides work. Its efficiency is defined by

$$\eta = \frac{|W|}{Q} < 1$$

- Refrigerator: (S) receives work and transfers heat from the inside to the outside. Its efficiency is defined by $\varepsilon = \frac{Q'}{W} > 1$
- Heat pump: (S) receives work and transfers heat from the outside to the inside. Its efficiency is defined by $\varepsilon = \frac{Q''}{W} > 1$

II.2.3 Conventions :

In the study of thermodynamic machines, we will focus on the system (S), and according to the usual conventions of thermodynamics, we will count the energy received by the system as positive.

II.3 Applications of thermodynamic principles to thermodynamic machines:

II.3.1 Clausius inequality:

Consider the system (S) performing a cycle and exchanging:

- Heat with thermostats
- Work with work reservoirs

The system being isolated, we have $\Delta S \geq 0$ and $\Delta S = \Delta S_e + \Delta S_{th} + \Delta S_W$

Or $\Delta S_e = 0$ since the system undergoes a cycle and $\Delta S_W = 0$ because the work reservoirs are assumed to be ideal

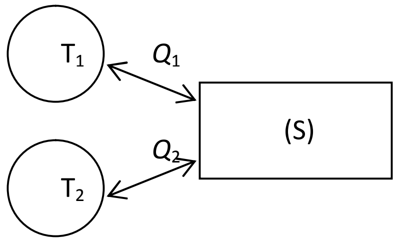
Therefore $\Delta S_{th} = \sum_i \frac{-Q_i}{T_i} = -\sum_i \frac{Q_i}{T_i} \geq 0$

We deduce *the Clausius inequality*:

$\sum_i \frac{Q_i}{T_i} \leq 0$, The equality occurs for a reversible cycle

II.3.2 Other statements of the second law:

a) Statement of Clausius:



On assumes that $T_1 > T_2$

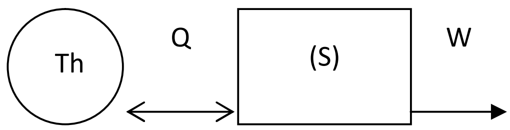
During a cycle $Q_1 + Q_2 = 0$

So $Q_1 = -Q_2 = Q$

Or, as a result, $\frac{Q_1}{T_1} + \frac{Q_2}{T_2} \leq 0$,We have $Q\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \leq 0$ which directly implies that $Q \geq 0$.

Therefore, we can derive the Clausius statement: a transformation whose sole result is to transfer heat from a cold body to a hot body is impossible.

b) The statement of Kelvin (or Kelvin's principle):



During a cycle, we have the $W + Q = 0$ According to Clausius's inequality, we necessarily have $Q \leq 0$ therefore $W \geq 0$. Such a system necessarily receives work.

This justifies Kelvin's statement: a transformation whose sole result is to convert heat taken from a single heat source into work is impossible.

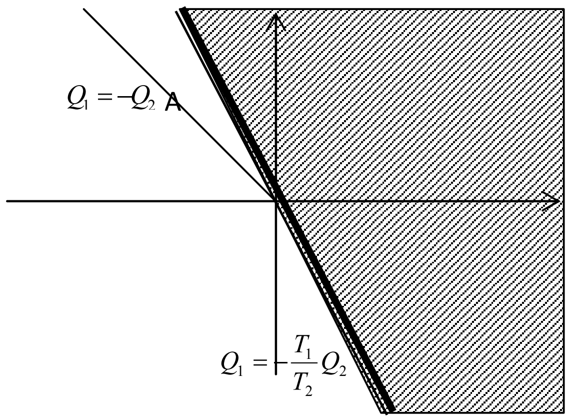
In other words, a single-temperature heat engine cycle is impossible.

II.3.3 Operating conditions of a di-thermic machine:

For a di-thermic machine, we have:

$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} \leq 0$ And we assume $T_1 > T_2$

Let's plot on a diagram $Q_1 = -\frac{T_1}{T_2} Q_2$.



Region A: Motor operation

Region D: Refrigerator or heat pump operation

→If we want a motor operation: $W < 0$, it is necessary that $Q_1 > -Q_2$. So we see that we necessarily have $Q_1 > 0$ and $Q_2 < 0$ as well as $|Q_2| < Q_1$.

So, if we want an engine to operate, regardless of its internal mechanism, it needs to take heat from a hot source and release some of it to a cold source.

→If we want $W > 0$ We need to $Q_1 + Q_2 \le 0$.

Region B is of no interest, just like region C: in the first one, we use work to transfer heat from a hot source to a cold source. In the second one, the system gives heat to both the hot and cold sources.

On the other hand, region D characterizes the refrigerator and the heat pump: we take heat from the cold source to restore it to the hot source, and we have $|Q_1| > \frac{T_1}{T_2} Q_2$

II.3.4 Efficiency and Effectiveness of Different Thermal Machines:

a)Engine:

The efficiency is defined, by definition, as follows: $\eta = \frac{|W|}{Q_1}$, Where Q_1 is theheatreceived from the hot source (for example, in a steam locomotive, water) is used to drive a turbine, producing work, and part of the heat is released into the atmosphere as waste heat (cold source).

So we have $\eta = 1 + \frac{Q_1}{Q_2}$

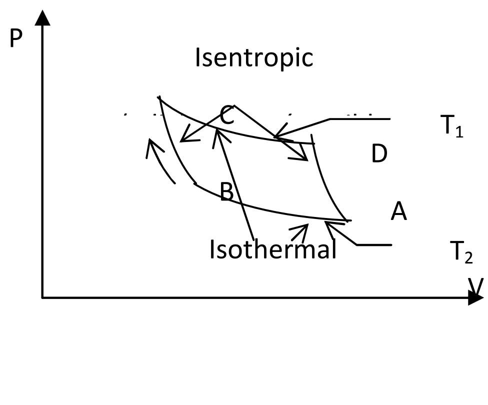
Or, we have $\frac{Q_1}{T_1} + \frac{Q_2}{T_2} \leq 0$ so $\frac{Q_2}{Q_1} \leq -\frac{T_2}{T_1}$

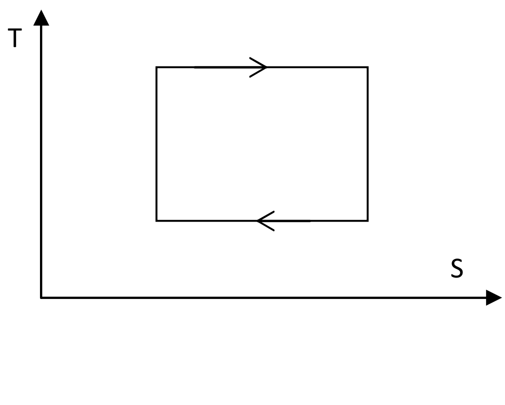
we have that $\eta \leq 1 - \frac{T_2}{T_1} \leq 1$we conclude that

We note that:

- $\eta$is maximal for a reversible cycle
- it is independent of the technical characteristics of the engine, which means that the limitation of the efficiency is intrinsic to the operation of the di-thermal engine.
- it is lessthan 1
- the upper limit can only be improved by increasing the temperature difference between the two sources (in fact, the hot source will more easily transfer heat the hotter it is, and the cold source will more easily receive heat the colder it is)

The cycle that models an engine is the Carnot cycle:





as $W_{rev} = -\oint p.dV$,We can see that due to the direction of the cycle, $W_{rev} < 0$: It is indeed a motor operation.

We have $W = RT_2 \ln\left(\frac{V_A}{V_B}\right) + \frac{R}{\gamma - 1}(T_1 - T_2) + RT_2 \ln\left(\frac{V_C}{V_D}\right) + \frac{R}{\gamma - 1}(T_2 - T_1)$

$$\text{So}\, W = RT_2 \ln\frac{V_A}{V_B} + RT_1 \ln\frac{V_C}{V_D}$$

Furthermore, we have, according to the results for the perfect gas:

$$V_A = \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}} V_D \ \text{ et } \ V_B = \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}} V_C$$

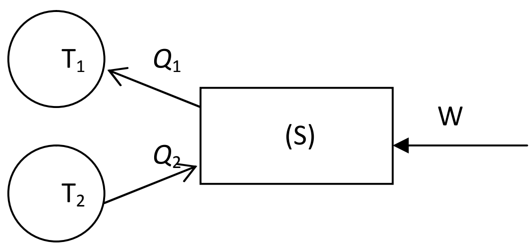
From which we derive the expression for the work provided by this reversible cycle:

$$W = R \ln\left(\frac{V_C}{V_D}\right)(T_1 - T_2) < 0$$

Furthermore, we evaluate $Q_1 = -W_{CD} = -RT_1 \ln\left(\frac{V_C}{V_D}\right)$

From this, we deduce that $\eta = \frac{-W}{Q_1} = 1 - \frac{T_2}{T_1}$

b) Refrigerators :



We always have $Q_1 + W + Q_2 = 0$

and $\frac{Q_1}{T_1} + \frac{Q_2}{T_2} \le 0$ with $Q_1 > 0$

(Heat is given to the hot source) and $Q_2 < 0$ (heat is taken from a cold source).

The efficiency is given by:

$$\varepsilon = \frac{Q_2}{W} = \frac{-1}{\frac{Q_1}{Q_2}+1}$$

$$\text{Or } \frac{Q_1}{Q_2} \le -\frac{T_1}{T_2} \text{ So } \varepsilon \le \frac{1}{\frac{T_1}{T_2}-1} = \frac{T_2}{T_1 - T_2}$$

ε (efficiency) is all the more limited as T1 is large and T2 is low. The smaller the efficiency, the more challenging it becomes to extract heat from the enclosure, and the larger the temperature difference between the hot and cold reservoirs, the more difficult it is to provide heat to the system .

c) Heat pumps:

The thermodynamic situation is the same as for the refrigerator, but here the efficiency is given by:

$\varepsilon = \frac{|Q|}{W} = -\frac{Q_1}{W}$ and according to the previous calculations $\varepsilon \le 1 + \frac{T_2}{T_1 - T_2}$

Note:

- Such a system can be used, for example, to heat a swimming pool while cooling an ice rink.
- We can see that $\varepsilon > 1$ so this type of heating is more advantageous than dissipation by Joule effect (radiator) where $\varepsilon = \frac{W}{Q} = 1$.

Chapter III: Ideal Cycles of Internal Combustion Engines

III.1 Introduction:

An internal combustion engine is an energy conversion device that converts the thermal energy produced by the combustion (fuel + oxidizer) into mechanical motive power. It is called an internal combustion engine because the combustion process occurs within the engine itself. In contrast, an external combustion engine transfers energy through a heat transfer fluid outside the engine. For example, a steam turbine operates using an external combustion process.

III.2 Different types of internal combustion engines:

There are two main types of internal combustion engines:

1. Engines that provide torque on a shaft:

- Internal Combustion Engines with Reciprocating Pistons:
  *Spark Ignition Engines (Gasoline engines)
  *Diesel Engines
- Internal Combustion Engines with Rotary Pistons
- Gas Turbines

2. Jet engines:

- Turbojets
- Ramjets
- Pulsejets
- Rocket Engines

III.2.1Thermal engines with reciprocating pistons:

Thermal engines using the thermal energy produced by the combustion of a fuel-air mixture (fuel-combustion air) to obtain mechanical energy by converting the translational motion of the piston into rotational motion of the shaft (crankshaft).

- **Definition of the 4-stroke cycle**

  A cycle is the set of phases that succeed each other in the engine. In our case, the cycle comprises four phases or strokes:

  • **Intake stroke:** air or air-fuel mixture is drawn into the cylinder.

  • **Compression stroke:** the air or mixture is compressed.

• **Power stroke (combustion-expansion):** rapid ignition of the mixture causing a sudden rise in gas pressure and their expansion

•**Exhaust stroke:** expulsion of the burned gases.

We observe that only the third stroke provides energy; it is the power stroke, while the other three strokes are resistive.

Main cycles of the internal combustion engine:

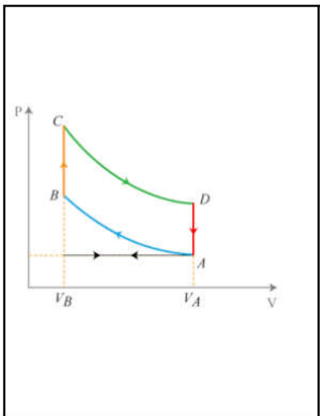
The three main cycles of the internal combustion engine can be summarized as follows:

• **Otto cycle** (constant volume heat addition cycle) used in spark-ignition engines (Fig-A).

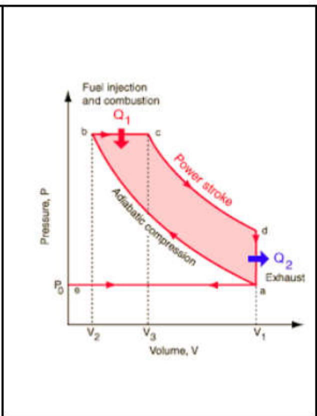
• **Diesel cycle** (constant pressure heat addition cycle) used in compression-ignition engines (Fig-B).

• **Sabathé cycle** or **mixed cycle** also known as**Seiliger cycle**. It is a combination of Otto and Diesel cycles (Fig-C).

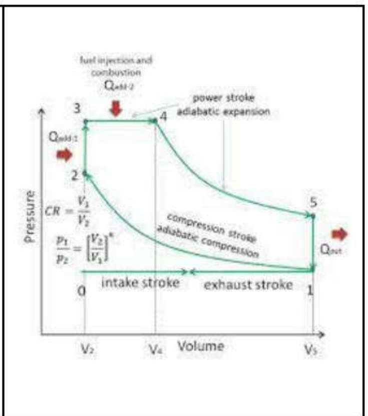
The study of these cycles can be carried out using the (P,V) diagram, and this is the type of diagram we will use.



beau de rochas cycle



diesel cycles



Sabathé cycle or mixed cycle

v_0 = v:The dead volume, also known as the volume of trapped gases in the combustion chamber.

$$V_1 = V_0 + v \quad (V_0\text{: Unit displacement or unit cylinder volume.})$$

III.2.1.1 - Thermic engines with spark ignition or controlled ignition (Gasoline engines).

The internal combustion engine is an engine primarily used for the propulsion of transportation vehicles (propeller aircraft, automobile, motorcycle, truck, boat) as well as various mobile tools (chainsaw, lawnmower) and stationary installations (generator, pump).

It includes all engines that use gasoline, alcohol, or even gas (LPG) or other fuels, and their combustion is initiated by an external energy source (spark plug).

These engines convert the stored chemical potential energy in the fuel into work (mechanical energy) through rapid combustions, hence the term "explosion." They are composed of one or multiple cylinders containing these combustions. Within each cylinder, a piston slides in an alternating linear motion. This motion is converted into rotation through a connecting rod connecting the piston to the crankshaft, an assembly of cranks on an axis.

The operating cycle can be analytically divided into four phases.
A→B : Admission of carbureted gases (air + fuel) (ma + mc).

B→C : Adiabatic compression of the mixture. Closure of the intake valve, then the piston moves upward, compressing the mixture up to 30 bars and 400 to 500 °C in the combustion chamber .

$$PV^{\gamma} = cte \Rightarrow P_1V_1^{\gamma} = P_2V_2^{\gamma} \Rightarrow (\frac{V_1}{V_2})^{\gamma} = \left(\frac{V+v}{v}\right)^{\gamma}$$

We assume $\varepsilon = \dfrac{V+v}{v}$
compression ratio

$$TV^{\gamma} = cte \Rightarrow T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1} \Rightarrow \frac{T_2}{T_1}\left(\frac{V_1}{V_2}\right)^{\gamma-1} = \varepsilon^{\gamma-1}$$

$$\text{So}\begin{cases} \dfrac{P_2}{P_1} = \varepsilon^{\gamma} \\ \dfrac{T_2}{T_1} = \varepsilon^{\gamma-1} \end{cases}$$

.***C*→D :**Combustion at constant volume (explosion)

Heat supply by the combustion of $\mathbf{m_C}$ in the presence of oxygen from $\mathbf{m_a}$

$$\mathbf{Q_1}=(m_a+m_c).C_v(T_3-T_2)=m_c.P_{Ci}$$

With :$\mathbf{m_a}$: Air mass.
$\mathbf{m_c}$: Fuel mass.
Pci:Lower Heating Value (also known as Lower Calorific Value) of the fuel.

D→E : Adiabatic expansion of gases. (power stroke) The hot gases at a pressure of 40 to 60 bars push the piston towards the bottom dead center (BDC), initiating the movement:

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \varepsilon^{\gamma-1} \Rightarrow \frac{T_2}{T_1} = \frac{T_3}{T_4} = \varepsilon^{\gamma-1}$$

$E \rightarrow B$ **:**Exhaustion of the burned gases, Upward movement of the piston towards the top dead center (TDC), expelling the expanded burnt gases into the exhaust manifold, releasing heat $\mathbf{Q_2}$.

$$\text{With : } Q_2 = (m_a + m_c)\, C_v\, (T_1 - T_4).$$

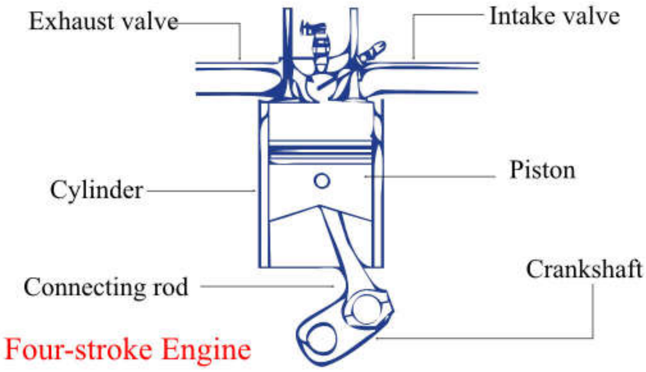


Fig.III.1.Description of 04-stroke engine

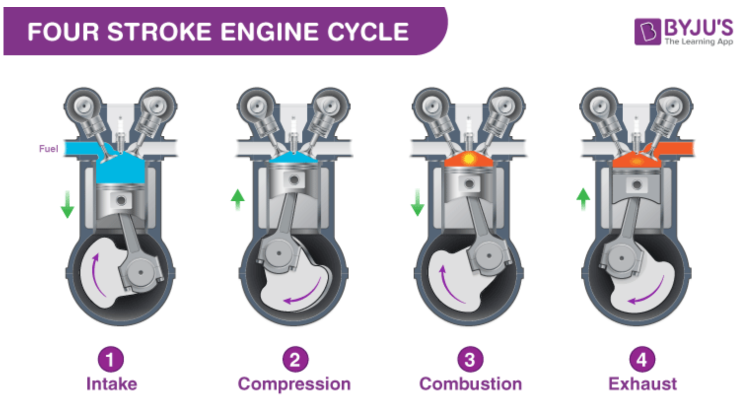


Fig.III.2.Operation of a four-stroke engine

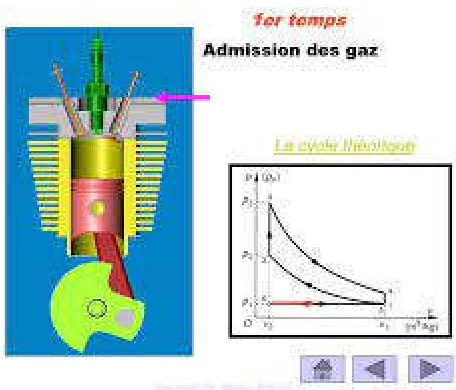


Fig.III.3. Beau de Rochas Cycle

Theoretical Efficiency of the Beau de Rochas Cycle

$$\eta_{th} = \frac{W_e}{Q_1} = -\frac{W}{Q_1} = \frac{Q_1 + Q_2}{Q_1} = 1 + \frac{Q_2}{Q_1} = 1 + \frac{(ma+mc)Cv(T_B + T_E)}{(ma+mc)Cv(T_D + T_c)}$$

$$\eta_{th} = 1 + \frac{(T_B + T_E)}{(T_D + T_c)}$$

III.2.1.2 - Diesel Engines or Compression-Ignition Engines:

In compression-ignition engines, the fuel used is diesel. It is injected under pressure into the combustion chamber containing pre-compressed and heated air, and it ignites spontaneously upon contact with the hot air. These engines are called Diesel engines.

a_ Diesel Cycle (Constant Pressure Combustion)

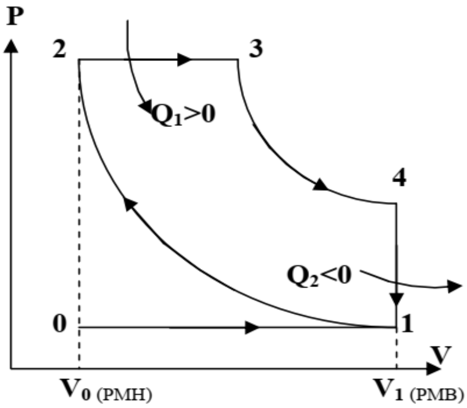


Fig.III.4. Diesel Engine Cycle

0 →1 : Admission of air.
1 →2 : Adiabatic compression of air.

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = \varepsilon^{\gamma}$$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \varepsilon^{\gamma-1}$$

2 →3 : Combustion at constant pressure, heat addition .

Q_1 = (ma + mc) Cp (T_3-T_2) = mc. Pci

0 → 4 Adiabatic expansion of gases.

$$\frac{P_3}{P_4} = \left(\frac{V_4}{V_3}\right)^{\gamma} = \varepsilon'^{\gamma}$$

$$\frac{T_3}{T_4} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \varepsilon'^{\gamma-1}$$

4→1 Echappement des gaz brûlés. La chaleur dégagée est **:**

$$\mathbf{Q_2 = (ma + mc)\ Cv\ (T_1\text{-}T_4)}$$

<u>Theoretical Efficiency of the Diesel Cycle:</u>

$$\eta_{th} = \frac{W_e}{Q_1} = -\frac{W}{Q_1} = \frac{Q_1 + Q_2}{Q_1} = 1 + \frac{Q_2}{Q_1} = 1 + \frac{(ma + mc)Cv(T_1 + T_4)}{(ma + mc)Cp(T_3 + T_2)}$$

$$\eta_{th} = 1 + \frac{1}{\gamma}\frac{(T_1 + T_4)}{(T_3 + T_2)}$$

b. Sabathé Cycle or Mixed Cycle :

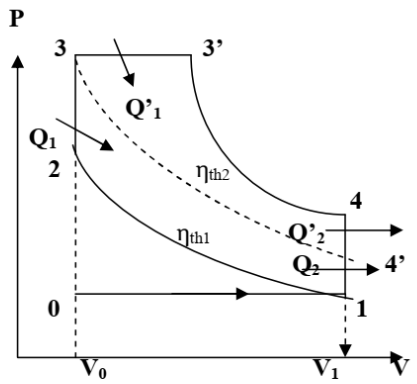


Fig.III.4 :The Sabathé Cycle or Mixed Cycle.

$$\eta_{th} = \frac{(Q_1 + Q_2) + (Q_1' + Q_2')}{(Q_1 + Q_1')}$$

$$\eta_{th} = \frac{Q_1\left(1 + \frac{Q_2}{Q_1}\right) + Q_1'\left(1 + \frac{Q_2'}{Q_1'}\right)}{(Q_1 + Q_1')}$$

$$\eta_{th} = \frac{Q_1\eta_{th1} + Q_1'\eta_{th2}}{(Q_1 + Q_1')}$$

Efficiency of the Sabathé Cycle.

η_{th1} :Theoretical Efficiency of the Beau de Rochas Cycle .

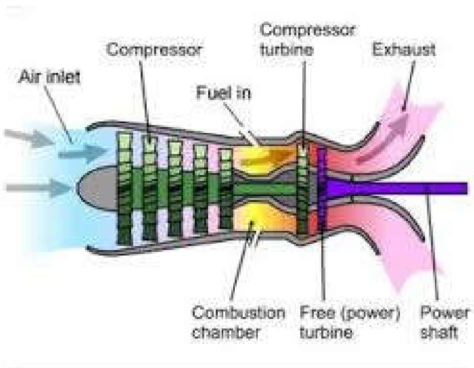
η_{th2} : Theoretical Efficiency of the Pure Diesel Cycle.

ChapterIV :Turbine à gaz et turboréacteur

VI.1. Introduction:

Reciprocating engines have drawbacks such as vibrations, energy losses in the crank mechanism, heat losses during each stroke of the piston, etc. To overcome these issues, the flow of gas will be utilized in a turbine to produce mechanical work.

A gas turbine (or combustion turbine) is a thermodynamic machine that operates as illustrated in the diagram below.



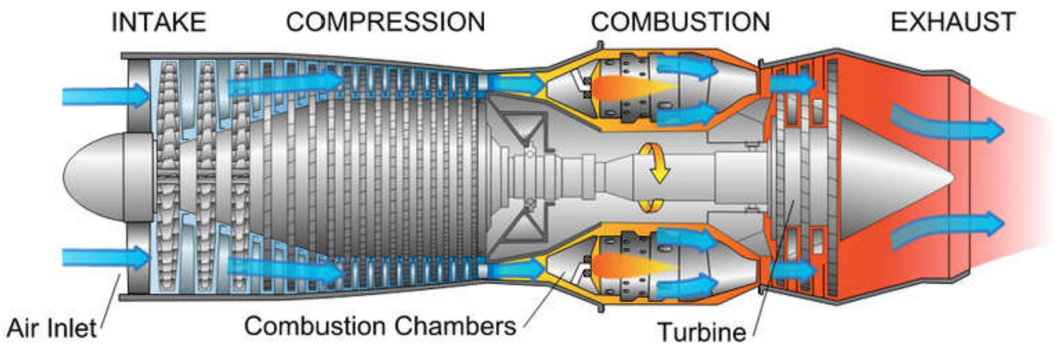
FigIV.1.*Diagram of a Gas turbine*

The air taken from the ambient atmosphere undergoes first a substantially adiabatic compression in a turbo compressor. The fuel (fuel, kerosene) is then injected by spraying, and the resulting air-fuel mixture is burned in a combustion chamber at a substantially constant pressure. The burned gases are then expanded in the fixed blades of a turbine, and their kinetic energy is transferred to the moving blades connected to the engine shaft where the compressor is mounted. A portion of the work obtained during the expansion is used to drive the compressor. The common shaft is connected to a reduction gearbox linked to the output shaft. If the turbine equips an aircraft, the output shaft rotates the propeller, and it becomes a turboprop.

If the expansion is divided, the gas is expanded in a turbine simply to rotate the compressor, and then the end of the expansion is carried out in a nozzle where the gas gains kinetic energy and exits the engine at high speed. In this case, we have a jet engine or a turbojet.

IV.2. Description of the gas turbine:

The gas turbine is an internal combustion engine, whose role is to convert the thermal energy resulting from the combustion of a hydrocarbon into mechanical energy (mechanical torque on the turbine shaft). The gas turbine takes in atmospheric air and compresses it in its own compressor, increases the energy power of the air in its combustion chamber, and converts this power into useful mechanical energy during the expansion process that occurs in the turbine section. The resulting mechanical energy is transmitted through a power coupling to a receiving machine such as <<generators, centrifugal pumps, gas compressors, etc….>>



FigIV.2: Diagram Description of the Gas Turbine

IV.3.The operating principle of a Gas turbine:

A gas turbine operates as follows:

- It extracts air from the surrounding environment.
- It compresses the air to a higher pressure.
- It increases the energy level of the compressed air by adding and burning fuel in a combustion chamber.
- It directs the high-pressure and high-temperature exhaust gases to the turbine section, where thermal energy is converted into mechanical energy to rotate the shaft. This serves to provide useful energy to the driven machine, coupled to it through a coupling, and also provides the necessary energy for air compression, which occurs in a compressor directly connected to the turbine section.
- It discharges the low-pressure and low-temperature gases resulting from the expansion process back into the atmosphere.

The transformations mentioned above occur in the gas turbine. The standard design conditions are conventionally classified as ISO conditions, with the reference values mentioned earlier.

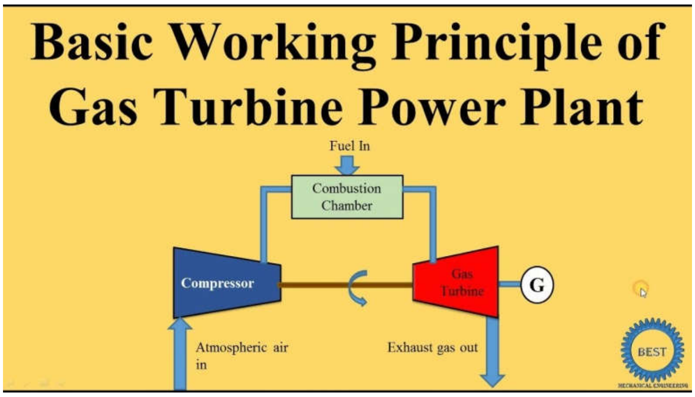


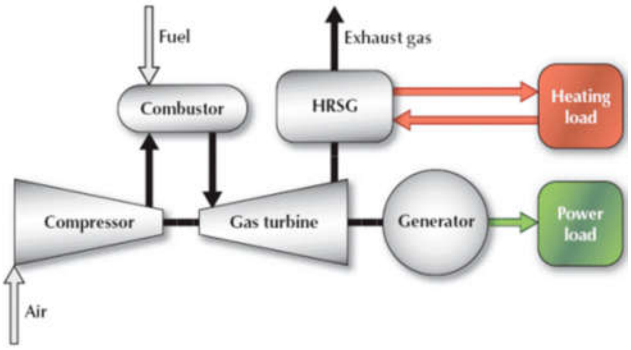
Fig.IV.3.Diagram of the basic gas turbine principle.

IV.4.Thermodynamic cycle of gas turbine:

IV.4.1The Joule-Brayton cycle:

The cycle used in gas turbines is the Joule cycle (also known as the Brayton cycle). In the case of turbines, the work is used to rotate a rotating machine (for example, an alternator to produce electricity).

This is the theoretical cycle according to which most gas turbines operate (Fig.IV.4). The cycle consists of two isentropic transformations (1-2) and (3-4) and two reversible isobaric transformations (2-3) and (4-1) (see Fig.IV.5) :



FigIV.4. Schéma simplifié d'une turbine à gaz

IV.4.2.Les diagrammes thermodynamiques sont les suivants :

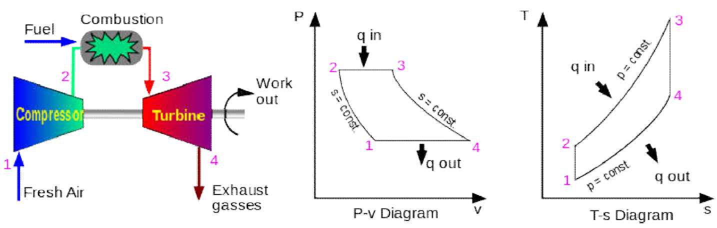


Fig.IV.5.The reversible Joule-Brayton cycle

IV.4.3.Energy Balance :

- **The transformation (1-2) is an adiabatic compression$S_1 = S_2$**

$$P_1V_1^{\gamma} = P_2V_2^{\gamma} \; / \quad T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1} \quad / \quad T_1P_1^{\frac{1-\gamma}{\gamma}} = T_2P_2^{\frac{1-\gamma}{\gamma}}$$

Internal Energy:$\Delta U = nCv(T_2 - T_1)$

Enthalpy:$\Delta H = nCp(T_2 - T_1)$

The quantity of heat: Q = 0

The work:$w = \frac{1}{\gamma-1}(P_2V_2 - P_1V_1)$

- **The transformation (2-3) is an isobaric $P_2 = P_3$**

$$\frac{T_2}{V_2} = \frac{T_3}{V_3}$$

Internal Energy:$\Delta U = nCv(T_3 - T_2)$

Enthalpy:$\Delta H = nCp(T_3 - T_2)$

The quantity of heat:Q =$nCp(T_3 - T_2)$

The work:$w = -\int_{v2}^{v3} PdV = -P(V_3 - V_2)$

- **The transformation (3-4) is an adiabatic compression$S_3 = S_4$**

$$P_3V_3^{\gamma} = P_4V_4^{\gamma} \; / \quad T_3V_3^{\gamma-1} = T_4V_4^{\gamma-1} \quad / \quad T_3P_3^{\frac{1-\gamma}{\gamma}} = T_4P_4^{\frac{1-\gamma}{\gamma}}$$

Internal Energy:$\Delta U = nCv(T_4 - T_3)$

Enthalpy:$\Delta H = nCp(T_4 - T_3)$

The quantity of heat:Q = 0

The work:$w = \frac{1}{\gamma-1}(P_4V_4 - P_3V_3)$

- **The transformation (4-1) is an isobaric$P_4 = P_1$**

$$\frac{T_4}{V_4} = \frac{T_1}{V_1}$$

Internal Energy:$\Delta U = nCv(T_1 - T_4)$

Enthalpy: $\Delta H = nCp(T_1 - T_4)$

The quantity of heat: $Q = nCp(T_1 - T_4)$

The work: $w = -\int_{v4}^{v1} Pdv = -P(V_1 - V_4)$

IV.4.4. The Theoretical Efficiency :

By the Following formula:

$$\eta = \frac{\text{énergie utile}}{\text{énergie déponse pour le fonctionment}} = \frac{-W}{Q_C}$$

The heat input is:

the amount of heat at the hot source:

the amount of heat at the cold source:

1^{st}Principle of thermodynamics :

$\Delta U = W + Q => W + Q = 0 \;=> W + \; Q_C + Q_F = 0$ (cyclic transformation)

$$W = -(Q_C + Q_F)$$

$$\frac{-W}{Q_C} = \frac{Q_C + Q_F}{Q_C} = \frac{Q_{23} + Q_{41}}{Q_{23}} = 1 + \frac{Q_{14}}{Q_{23}}\eta =$$

$$= 1 + \frac{(T_1 - T_4)}{(T_3 - T_2)} \quad = 1 + \frac{nC_p(T_1 - T_4)}{nC_p(T_3 - T_2))}$$

IV.5. Enthalpy calculation (or Joule cycle):

The most commonly used cycle is the constant pressure combustion cycle (Joule cycle).

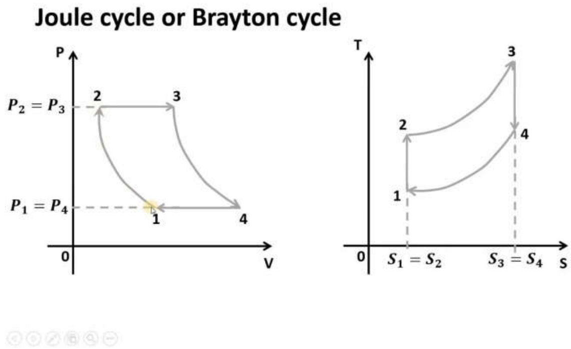


Fig.IV.6.depicts the Joule cycle.

1 →2: Isentropic compression.
2 →3: Isobaric combustion.
3 →4: Isentropic expansion.
4 →1: Isobaric cooling.

Theoretical thermal efficiency of the turbine.

$$\eta_{th} = \frac{W}{Q_1}$$

With: $W=W_T-W_C$ useful work

W_T: The work produced by the turbine per kilogram of air.

W_C: The work absorbed by the compressor to provide 1 kilogram of compressed air

$Q_1=Q_{23}$: The amount of heat expended

1^{er} principle of open systems $\Rightarrow$ W + Q = ΔH (m = 1kg)
Isentropic transformation $\Rightarrow$ Q = 0 hence:

$$|W_T| = H_3 - H_4$$
$$|W_C| = H_2 - H_1$$

$$\Rightarrow W = (H_3 - H_4) - (H_2 - H_1)$$

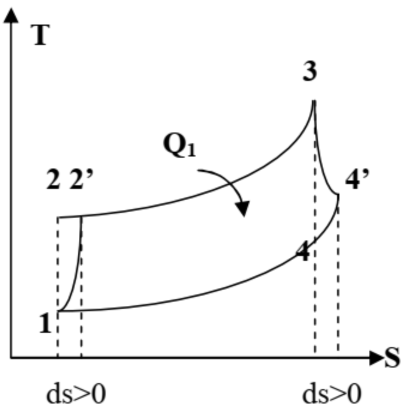
$$|Q_{23}| = H_3 - H_2 \Rightarrow \eta_{th} = \frac{(H_3 - H_4) - (H_2 - H_1)}{H_3 - H_2} = \frac{(H_3 - H_2) - (H_4 - H_1)}{H_3 - H_2}$$

$$\eta_{th} = 1 + \frac{H_4 - H_1}{H_3 - H_2}$$

In the case of an ideal Gas, we have: ΔH = Cp.ΔT hence: $\eta_{th} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$

VI.6 Real Combustion Turbine Cycle:

The real cycle differs from the theoretical cycle due to the irreversibility of real transformations. Compression and expansion are not isentropic, and the presence of internal friction forces leads to an increase in entropy



- The combustion process itself is accompanied by a slight pressure drop, and the pressure at point (3) is slightly lower than that at point.(2)
- Points 2' and 4' represent the real cycle.

Fig.IV.7: Real Combustion Turbine Cycle

The actual efficiency

$$\eta_r = \frac{W_u}{Q_{2'3}} \text{ with } W_u=W_{tr}-W_{cr}$$

In the case of the real cycle, the losses that can affect the installation are as follows.

•Losses during compression characterized by: $\eta_c = \frac{H_2 - H_1}{H_{2'} - H_1}$ adiabatic efficiency of compression.

• Losses during expansion characterized by $\eta_T = \frac{H_3 - H_4'}{H_3 - H_4}$ adiabatic turbine efficiency.

•Other losses (pressure losses, mechanical losses, losses due to unburned fuel, losses due to radiation) are not very influential.

The useful work of the real cycle is expressed as follows:

$$\bullet W_u = \eta_T - \frac{W_c}{\eta_c} \text{With } \begin{matrix} |W_T| = H_3 - H_4 \\ |W_C| = H_2 - H_1 \end{matrix}$$

$$\bullet W_u = W_{Tr} - W_{cr} = \eta_T W_T - \frac{W_c}{\eta_c} = \eta_T (H_3 - H_4) - \frac{1}{\eta_c}(H_2 - H_1)$$

IV.7. Advantages and disadvantages of the gas turbine:

Advantages:

If we compare the gas turbine to its competitors within the family of internal combustion engines, it offers significant advantages:

- Compacte size

- Excellent Power-to-Weight ratio
- Good efficiency
- Low pollutant emissions
- Quick start-up
- "Affordable" auxiliaryequipment.

Disadvantages :

- Clean and expensive fuels (the burnt gases expand directly into the turbine).
- Performance dependent on external conditions (degraded if temperature increases or pressure decreases)

- **Conclusion :**

Gas turbines play a significant role in current power systems. Their advantage of being lightweight makes them ideal for aviation applications, while in the field of high power (electricity generation), they stand out due to their adaptability to highly efficient combined cycles or cogeneration systems. On the other hand, internal combustion engines have their power limited to around 10 MW due to considerations of weight and size.

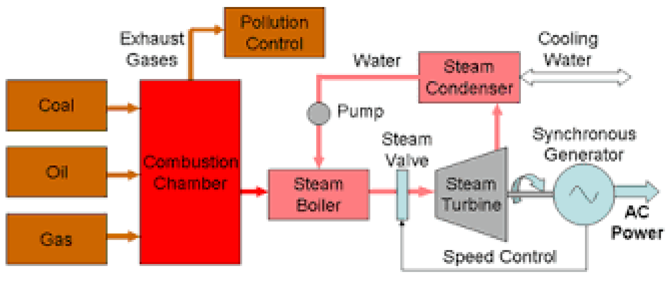
Chapter V :Steam turbine

V.1. Steam turbine:

These are machines designed to produce mechanical energy from thermal energy. The mechanical energy obtained is either used directly (propulsion - pumping) or transformed into electrical energy (thermal power plant).

V.1.1Principle of operation of a thermal power plant:

The process of producing electrical energy is based on successive conversions of different forms of energy. It can be schematically represented as follows :

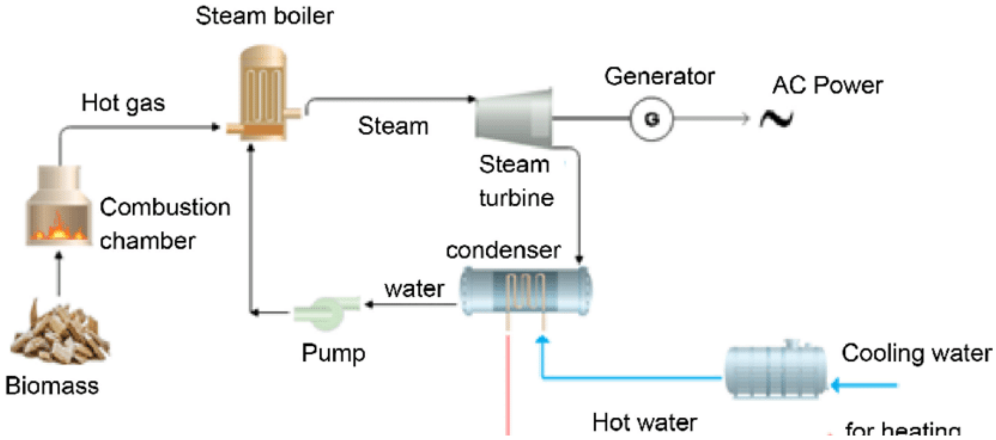


FigV.1: Electricity Generation Process

The principle of operation of the thermal cycle is illustrated in Figure 11. Pure water circulates under very high pressure in the steam generator and is transformed into steam under the heat generated by combustion, reaching a very high temperature.

The steam produced downstream of the boiler gradually expands in the turbine and is liquefied in the condenser, where the pressure decreases close to absolute vacuum.

The condensed water, recovered by pumps, is heated by steam extractions from the turbine and by the heat from the combustion gases before being reinjected into the boiler's vessel to restart the cycle. The mechanical energy generated by the steam in the turbine is then converted into electrical energy by the alternator.



FigV.2: The principle of operation of a steam turbine

V.1.2 Cycle de RANKINE:

It is the simplest theoretical cycle that allows a machine to produce mechanical work using water vapor as the fluid.

Diagram:

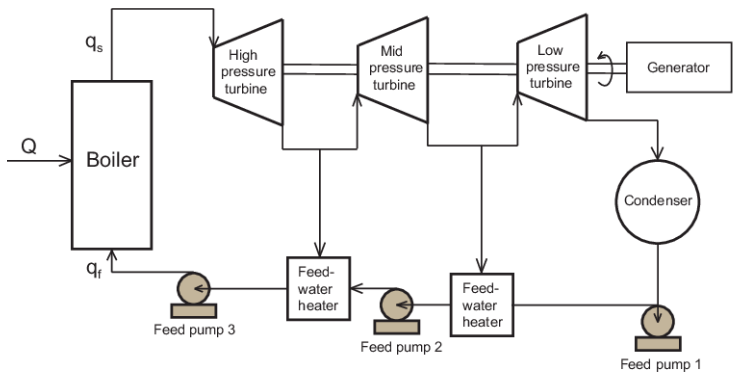


Fig.V.3.Simple Steam turbine installation

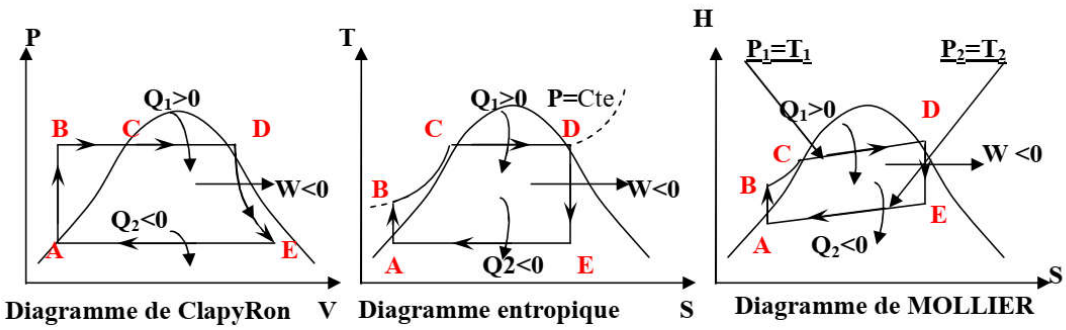


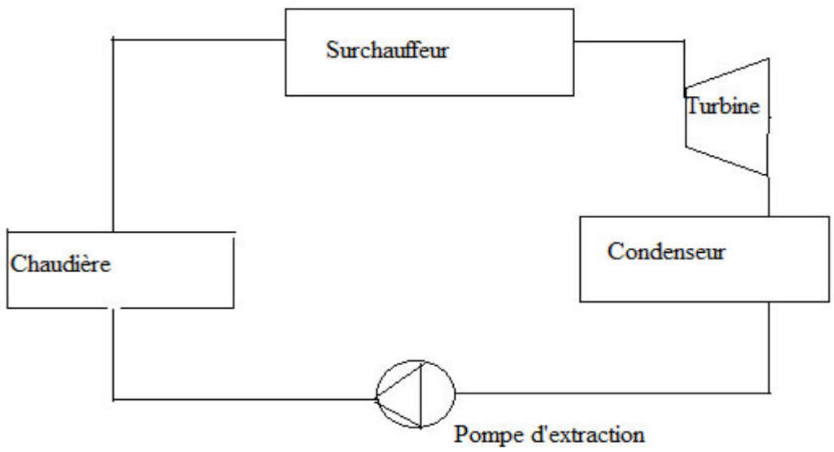
Fig.V.4. Clapet-Ron and entropic diagrams

AB: Pressure increase from PA to PB.
DE: Adiabatic expansion.
BC: Isothermal-isobaric heating.
EA : Condensation.

CD : Vaporization (Isothermal Isobaric).

V.1.3Hirn Cycle:

The Hirn cycle allows for a dry cycle, meaning that at the end of the expansion, the steam is outside the wet steam region.
To obtain superheated steam, the steam is sent downstream of the boiler to the superheater, where the combustion products raise the steam to a constant pressure ahigher temperature.



FigV.5. A heat engine operating according to the Hirn cycle.

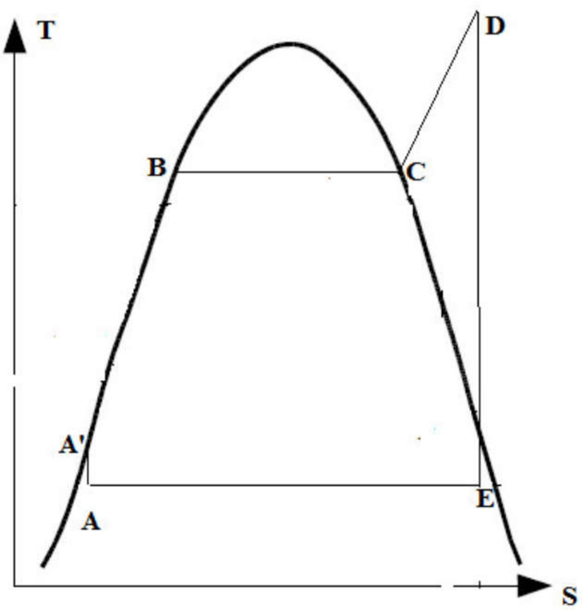


Fig.V.6 :Hirn Cycle

The efficiency is:

$$\eta = \frac{H_D - H_E}{H_D - H_A}$$

The interest of superheating:

- It increases the recoverable work per kg of fluid and therefore reduces the flow rates required for a given power output.
- It delays the appearance of liquid water during expansion. With drier steam, the turbine efficiency is increased, and losses due to moisture are reduced by superheating.
- It improves the cycle efficiency.

V.1.4. Hirn Cycle with Reheating:

Reheating moderately improves the thermodynamic cycle efficiency but increases the efficiency of the blades (turbine vanes) due to the reduction in moisture content in the last stages of the turbine.

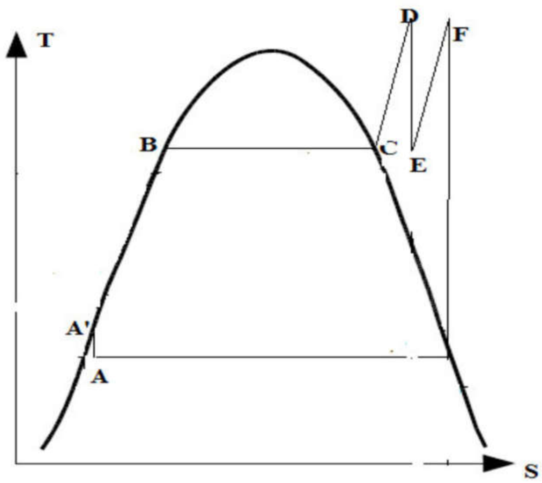


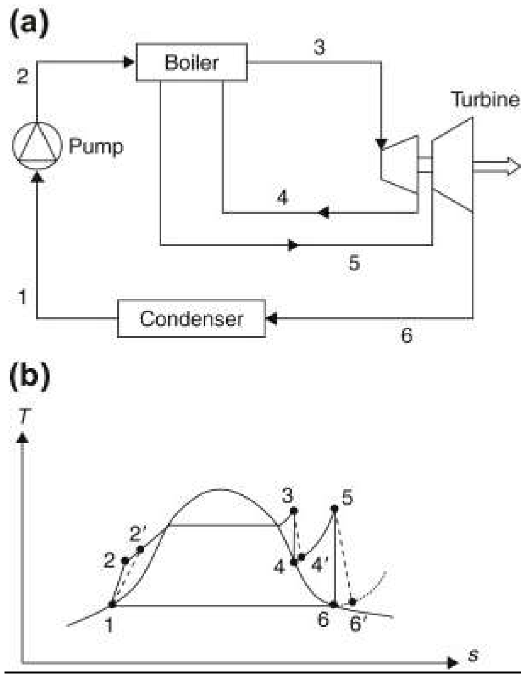
Fig.V.7. Hirn Cycle with Reheating

The efficiency is:

$$\eta_{th} = \frac{\text{Travail util fourni}}{\text{Quantité de chaleur absorbée}} = \frac{\text{Travail fourni par la turbine} - \text{travail absorbé par la pompe}}{\text{Quantité de chaleur absorbée}}$$

$$\eta_{th} = \frac{(H_D - H_E) + (H_F - H_G)}{(H_D - H_A) + (H_F - H_E)}$$

Cycle of Water Vapor.



FigV.8. Cycle of Hirn, Cycle with Reheating (x = 0.8 or 80%)

V.1.5. Cycle with Extraction :

The principle of this cycle involves extracting a portion of the total steam flow at a stage of the turbine and directing this extracted flow back into the boiler. Instead of being wasted in the condenser, a portion of the heat contained in this steam is transferred to the feedwater

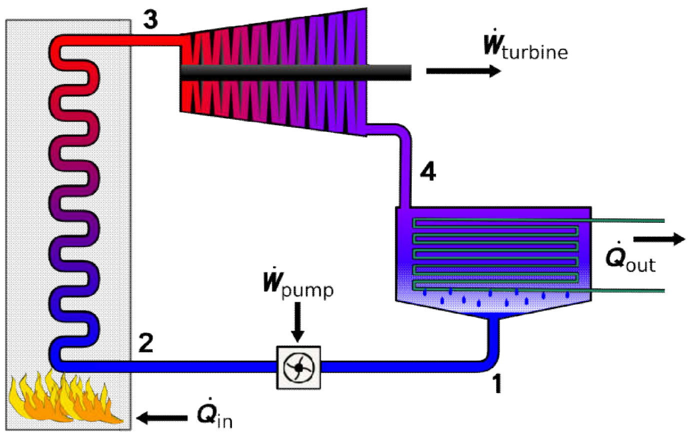


Fig V.9. Thermal machine operating on the Hirn cycle with extraction.

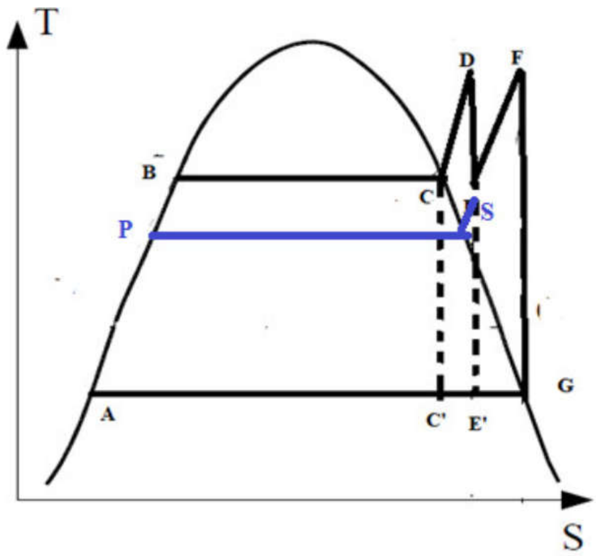


Fig.V.10. Cycle with Extraction

To calculate the efficiency of the cycle, one must determine the amount of heat converted into work during the expansion and the total amount of heat provided to the fluid.The amount of heat provided to the fluid is equal to:

$$(H_D - H_A) + q(H_D - H_S)$$

The quantity of heat transformed into work during the expansion is:

$(H_D - H_E)$ *1(Expansion of 1 kg of steam from D to E.) +(H_D-H_S) *q (Expansion of 1 kg of steam from D to S.)

Therefore, the efficiency can be expressed as follows: $\eta = \dfrac{(H_D - H_E) + q(H_D - H_S)}{(H_D - H_A) + q(H_D - H_S)}$

As the efficiency of the Hirn cycle is given by: $\eta = \dfrac{H_D - H_E}{H_D - H_A}$

We can see that the act of extracting steam during the expansion process results in adding the same amount of heat to both terms of the fraction that expresses the efficiency of the Hirn cycle. This leads to an increase in the value of this fraction. The efficiency of a cycle with extraction is always higher than the efficiency of an identical cycle without extraction.

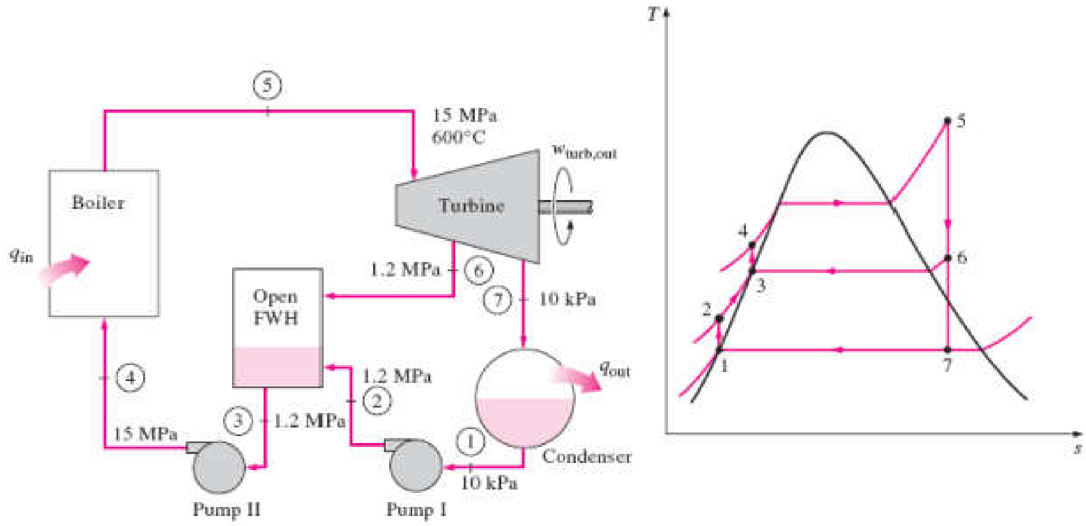


Fig .V.11. Cycle with extraction **(x#100%)**

Diagram of the steam cycle on the entropic and enthalpic axes.

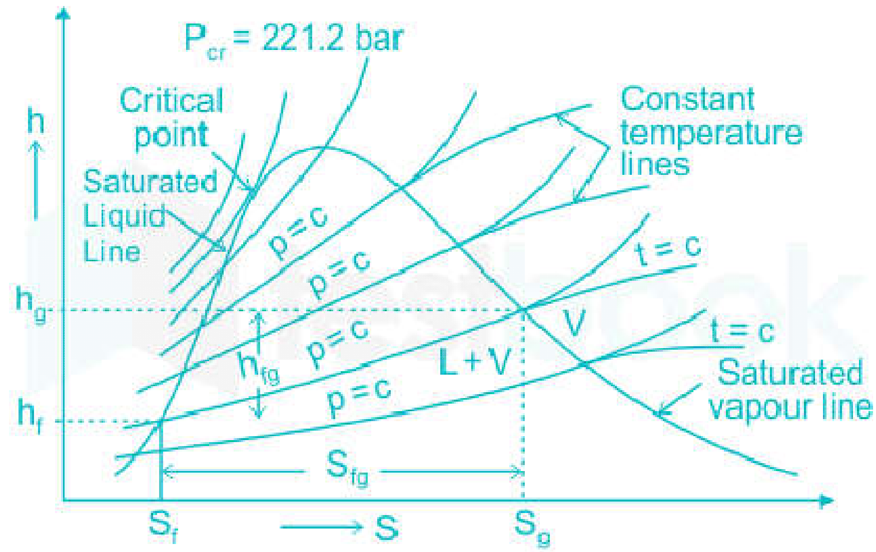
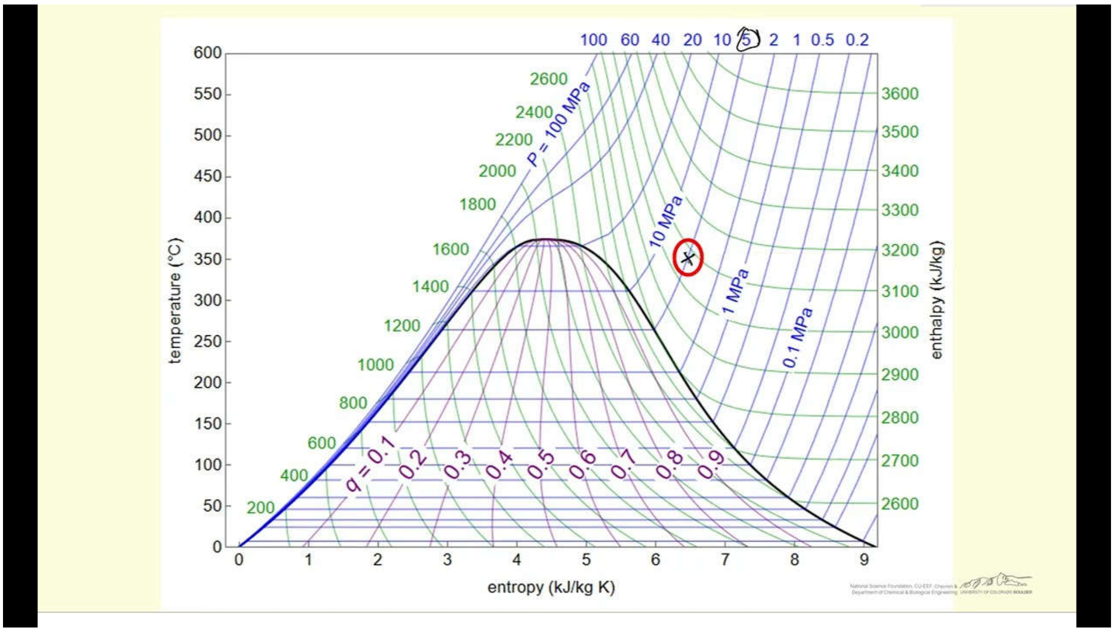


Fig.V.12: T-s diagram of water



FigV.13: h-s diagram of water

Chapter VI : Autres types de moteurs

VI.1. Stirling Engines:

VI.1.1.Introduction:

Robert Stirling invented the hot air engine in 1816, but to improve its efficiency, he equipped it with a significant modification that gave it real development: a regenerator between the two pistons that considerably improved its performance.

Relatively unknown to the general public, this engine has some advantages. It was popular during the era of steam engines, which sometimes had the serious flaw of exploding and causing casualties

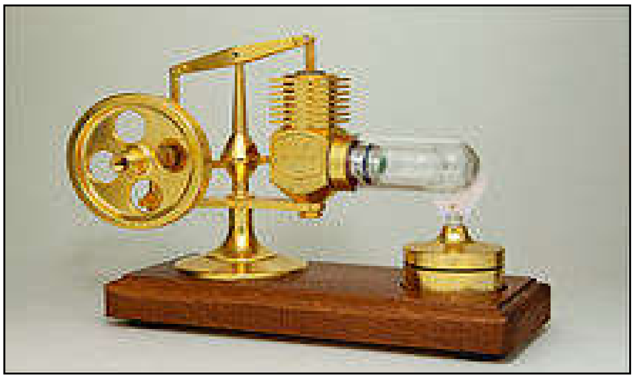


Fig.VI.1. Photograph of a Stirling engine.[5]

IV.1.2. Operating Principle :

The principle is relatively simple: the main working fluid is a gas (air, hydrogen, or helium) subjected to a cycle consisting of four phases: isochoric heating (at constant volume), isothermal expansion (at constant temperature), isochoric cooling, and isothermal compression.

The goal is to produce mechanical energy from thermal energy. At the beginning of the cycle, the gas inside the engine is placed in the hot chamber, heated by a certain energy source: its temperature and pressure increase, resulting in gas expansion. The piston of the hot chamber is in contact, and the gas expands towards the cold chamber, pushing its piston. Thermal energy is thus transformed into mechanical energy transmitted to the wheel. The wheel's movement is transmitted to the piston of the hot chamber, which pushes almost all the gas into the cold chamber. Once this is done, the gas in the cold chamber cools down, and its volume decreases, driving the cold piston in the opposite direction. Again, this movement is transmitted, via the wheel, to the piston of the hot chamber, which then moves back towards its contact. Almost all the gas volume is then drawn back to the hot chamber, and the cycle repeats. This thermodynamic cycle is known as the Stirling cycle (although it was not described by Stirling himself).

The hot source of the engine (the red piston above) is supplied by any external source: external combustion of petroleum derivatives, natural gas, coal, but also renewable energies such as solar energy, wood, or geothermal energy.

IV.1.3. Stirling Cycle :

The Stirling cycle is a thermodynamic cycle described by Stirling engines. The cycle is reversible, which means that if mechanical work is supplied to the engine, it can also act as a heat pump or refrigeration system.The theoretical Stirling cycle consists of four phases:

• Points 1 to 2, isothermal expansion: The expansion chamber is heated externally, allowing the gas to undergo an isothermal expansion.

• Points 2 to 3, constant volume cooling (isochoric process): The gas passes through the regenerator, cooling down and transferring its heat to be used in the next cycle.

• Points 3 to 4, isothermal compression: The compression chamber is cooled, causing the gas to undergo an isothermal compression.

• Points 4 to 1, constant volume heating: The gas flows through the regenerator and absorbs heat.

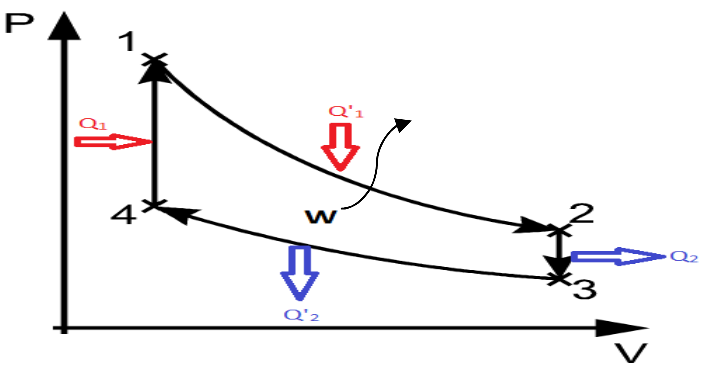


Fig.IV.2.Le diagramme du cycle Stirling Pf(V)

IV.1.3.1. Operation

1 - 2: Heat Q1 received from the hot reservoir at temperature T1 causes an isothermal expansion of the gas, pushing the working piston downwards.

2 - 3: The displacer piston forces the gas to move into the lower part of the cylinder, while transferring heat to the copper wool. During this isochoric cooling process, the temperature of the gas decreases from T1 to T2.

3 - 4: The working piston compresses the gas at temperature T2 while in thermal contact with the cold heat reservoir. The gas releases excess heat Q2 to the cold reservoir, as it is an isothermal compression.

4 - 1: Under the effect of the displacer piston, the gas passes into the upper part of the cylinder, warming up to temperature T1 as it crosses the copper wool. This process is an isochoric heating

Energy Balance :

1-2-Type of transformation: Isothermal expansion $T_1=T_2$

$$P_1V_1=P_2V_2$$

- **Internal Energy :** $\Delta U = nc_v\ \Delta T = nc_v(T_2-T_1)$
- **Enthalpy :** $\Delta H= nc_p\ \Delta T = nc_p(T_2-T_1)$
- **Work:** $W = -n\ RT_1\ln(\frac{V_2}{V_1})$
- **Quantity of Heat:** $Q = -W = n\ RT\ \ln\frac{V_2}{V_1}$

2-3-Type of transformation: Isochoric $V_2=V_3$

$$\frac{T_2}{P_2}=\frac{T_2}{P_3}$$

- **Internal Energy :** $\Delta U = nc_v\ \Delta T = nc_v(T_3-T_2)$
- **Enthalpy :** $\Delta H = nc_p\Delta T = nc_p(T_3-T_2)$
- **Work :** $W = 0$
- **Quantity of Heat :** $Q = \Delta U = nc_v\ \Delta T = nc_v(T_3-T_2)$

3-4-Type de transformation : compression isotherme $T_3=T_4$

$$P_3V_3=P_4V_4$$

- **Internal Energy :** $\Delta U = nc_v\ \Delta T = nc_v(T_4-T_3)$
- **Enthalpy :** $\Delta H= nc_p\ \Delta T = nc_p(T_4-T_3)$
- **Work:** $W = -n\ RT_3\ln(\frac{V_4}{V_3})$
- **Quantity of Heat:** $Q = -W = n\ RT\ \ln\frac{V_4}{V_3}$

4-1-Type de transformation :isochore $V_4=V_1$

$$\frac{T_4}{P_4}=\frac{T_1}{P_1}$$

- **Internal Energy :** $\Delta U = nc_v\ \Delta T = nc_v(T_1-T_4)$
- **Enthalpy :** $\Delta H = nc_p\ \Delta T = nc_p(T_1-T_4)$
- **Work :** $W = 0$
- **Quantity of Heat :** $Q = \Delta U = nc_v\ \Delta T = nc_v(T_1-T_4)$

Thermal Efficiency (Rendement thermique):

$$\eta = \frac{\textbf{Useful energy}}{\textbf{Energy expended for operation}}$$

$$\eta = \frac{-W}{Q_c} = \frac{Q_c+Q_f}{Q_c} = 1 + \frac{Q_f}{Q_c}$$

- **The amount of heat at the hot source :Qc**

$$Q_c = Q_1 + Q_1'$$

$$Q_1 = Q_{41} = nc_v\ (T_1 - T_4)$$
$$Q_1' = Q_{12} = n\ RT_1 \ln\frac{V_2}{V_1}$$
$$\mathbf{Q_c} = nc_v\ (T_1 - T_4) + n\ RT_1 \ln\frac{V_2}{V_1}$$

- **<u>The amount of heat at the cold source:Q_f</u>**

$$Q_f = Q_2 + Q_2'$$
$$Q_2 = Q_{23} = nc_v\ (T_3 - T_2)$$
$$Q_2' = Q_{34} = n\ RT_3 \ln\frac{V_4}{V_3}$$
$$\mathbf{Q_f} = nc_v(T_3 - T_2) + nRT_1 \ln\frac{V_4}{V_3}$$

$$\boldsymbol{\eta} = 1 + \frac{nC_v(T_3 - T_2) + n\ RT_3 \ln\frac{V_4}{V_3}}{nC_v(T_1 - T_4) + n\ RT_1 \ln\frac{V_2}{V_1}}$$

$$\boxed{\boldsymbol{\eta} = 1 + \frac{\frac{1}{\gamma-1}(T_3 - T_2) + T_3 \ln\left(\frac{V_4}{V_3}\right)}{\frac{1}{\gamma-1}(T_1 - T_4) + T_1 \ln\left(\frac{V_2}{V_1}\right)}}$$

IV.2.The compressed air engine:

The choice of the compressed air engine for automobiles is based on the desire to have a non-polluting, easily storable, and cost-effective energy source.

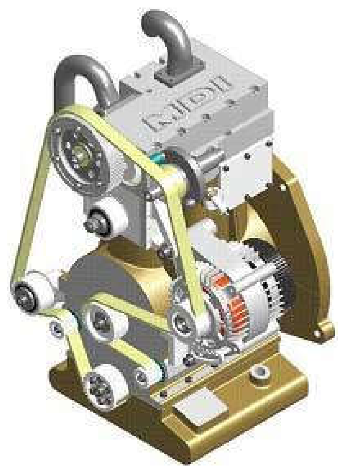


Fig.IV.3. The compressed air engine.**[4]**

The ambient air is compressed into the vehicle's reservoirs. The air from the high-pressure reservoir passes through a regulator. It is then used in an expansion system with work composed of an active chamber and an expansion cylinder.

IV.2.1. The different phases:

The intake phase: It involves drawing the outside air into the first cylinder, known as the intake and admission cylinder. The air enters as the piston descends.

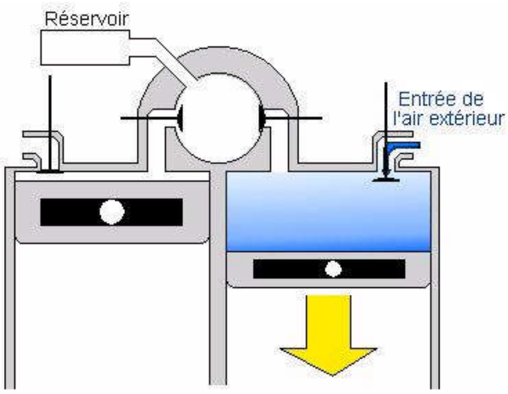


Fig.IV.4. The intake phase

The compression phase: Here, the outside air is compressed by the piston of the intake cylinder into the expansion chamber. It is compressed to 21 bars and reaches a temperature of 400°C. This small piston undergoes expansion, meaning it changes direction and returns to the top of the cylinder where it then expels the air into the expansion chamber.

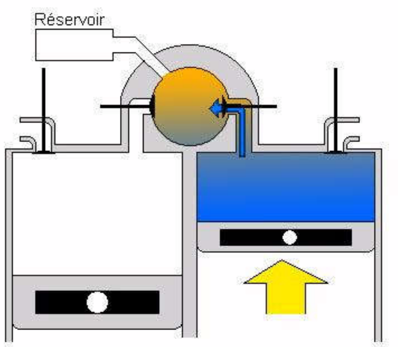


Fig.IV.5. The phase of compression

The expansion phase: Here, the outside air is mixed with compressed air between 40 and 50 bars at 25°C. The collision of these two fluids creates an increase in pressure, leading to overheating of the mixture.

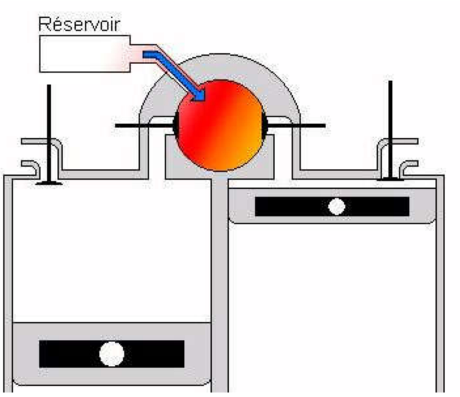


Fig.IV.6. The expansion phase

The descent phase: Finally, this mixture is released into the second cylinder called the expansion and exhaust cylinder. The overheating of the air causes an increase in volume that pushes the piston downward

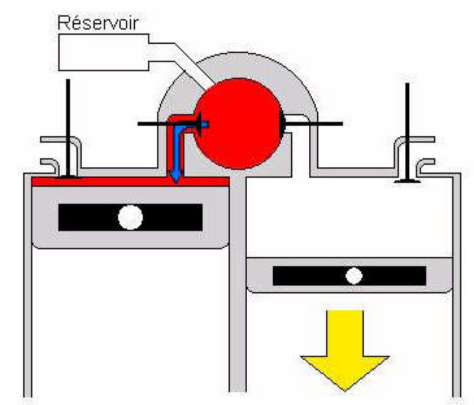


Fig.IV.7. The descent phase

The second piston then undergoes its expansion. At the end of the expansion, it expels the air back outside, which is the exhaust phase. The cycle repeats continuously. In their movements, the two pistons drive two connecting rods and a crankshaft to enable rotational motion.

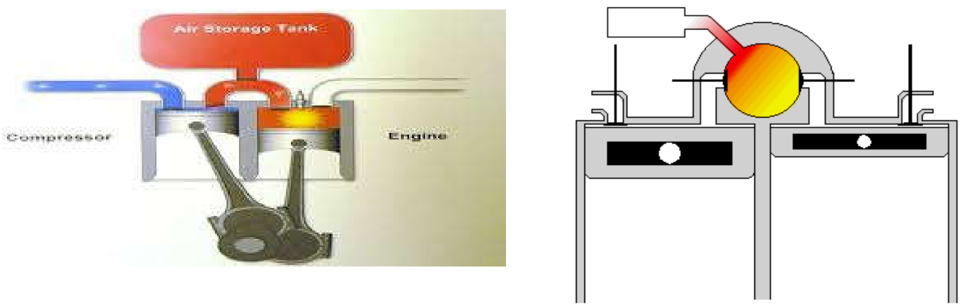


Fig.IV.8. The exhaust phase.

Single-energy compressed air engines are completely clean from the tank to the wheel.

$$P = \frac{F}{S}$$

P :Pressure (bar)

F :Force (daN)

S :Surface (cm2)

IV.2.2. Advantages of a compressed air vehicle:

Compressed air, when applied to a vehicle, offers numerous advantages compared to other vehicles with internal combustion engines or electric motors.

- The cost of compressing air for vehicle propulsion is lower than the energy cost of operating an internal combustion engine.
- Air is abundant, economical, transportable, storable, and, most importantly, non-polluting.
- Compressed air technology reduces vehicle production costs by 20% as there is no need to build a cooling system, fuel tank, spark plugs, or a muffler.
- Air itself is not inflammable.
- The mechanical design of the compressed air engine is simple and robust.
- It is not affected by the corrosion issues experienced by hot batteries.
- Its manufacturing and maintenance costs are lower compared to other vehicles.
- Compressed air tanks can be eliminated or recycled in a less polluting manner than batteries.
- The reservoir can be refilled more frequently and, in less time, compared to recharging batteries

IV.3.Ericsson Engine:

IV.3.1.The operating principles of the Ericsson engine:

In its simplest description, the Ericsson engine consists of a first cylinder where air is compressed and a second motor cylinder where the air is expanded through heating.

This page offers an exploration of the operating principle of this engine. This is done progressively by studying the following stages:

- The four elementary phases.
- The Pressure-Volume diagram.

First observation: the gas used, air, is renewed during the different phases of operation. It is an "open" engine.

Second observation: the heat energy is supplied externally to the cylinder. The Ericsson engine can thus be classified as a **"hot air engine"** or an **"external combustion engine".**

IV.3.2. The four Elementaryphases :

The thermodynamic cycle of the Ericsson engine is very simple in principle: it involves two movements during which 4 phases occur. The gas used undergoes the Followingtransformations :

IV.3.2.1. First movement: intake of fresh air and discharge of hot air

As shown below, air enters the upper cylinder, which is put under vacuum by the downward movement of the piston. The left valve is open while the right valve is closed.

The pressure inside the upper cylinder is equal to atmospheric pressure.

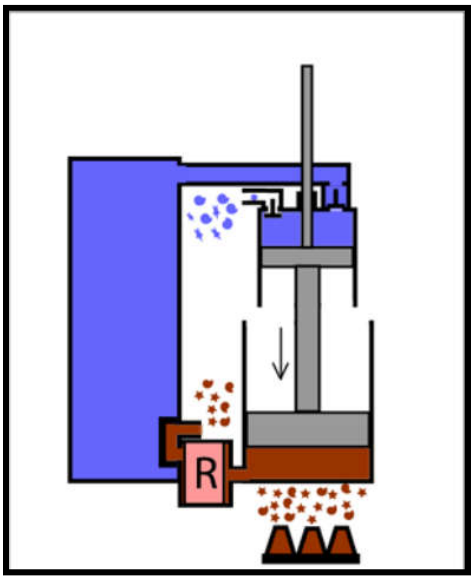


Fig.IV.9. First phase: Air intake

The first phase :

during the same downward movement of the piston, the hot air in the lower cylinder is discharged into the atmosphere as the slide connects the lower piston with the outside.

During this phase, the air is at atmospheric pressure, and its temperature gradually becomes that of the external air.

IV.3.2.2. Second movement: Compression of fresh air, filling of the lower cylinder, and expansion of the hot air.

Second phase: During the entire upward movement of the piston, the fresh gas is pressurized at a constant temperature. The left valve remains closed, and the right valve opens as soon as the gas pressure equals that of the air reservoir

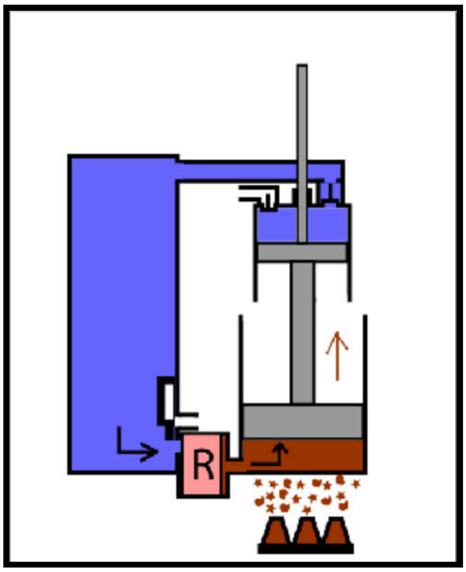


Fig.IV.10. Second phase: Compression of fresh air.

Third phase: During the first part of the piston's upward movement, fresh air is sent to the lower cylinder. This air remains at the pressure of the air reservoir but takes on the temperature of the hot source.

To achieve this, the slide valve had to be in the upper position, allowing the lower cylinder of the engine to be connected to the air reservoir.

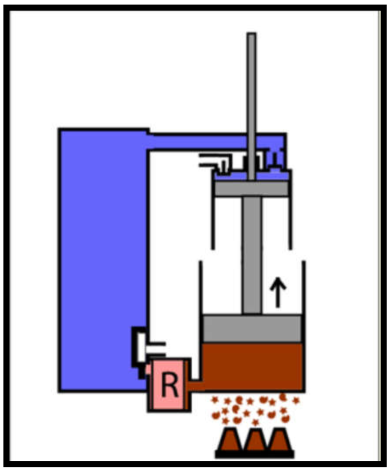


Fig.IV.11. Third phase

When the filling phase is completed, the slide valve descends slightly to block the passage of air between the reservoir and the lower piston.

Fourth phase: the piston completes its upward stroke, and the air in the lower cylinder expands at constant temperature, which is the same as the temperature of the hot source.

In the upper cylinder, the fresh air continues to be compressed at constant temperature.

The sequence of these different phases is shown below

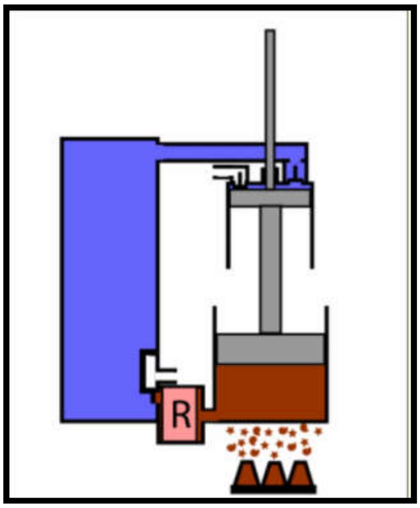


Fig.IV.12. Fourth phase

IV.3.3 The Pressure-Volume Diagram:

We can plot a Pressure-Volume diagram representing the thermodynamic cycle.

This diagram is shown below along with the entropy diagram

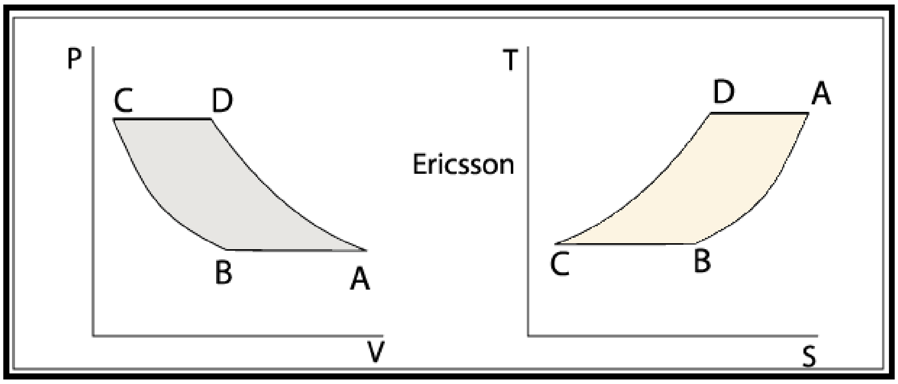


Fig.IV.13. The Ericsson Engine Diagram

The different phases, described in the previous chapter, are represented on this diagram:

- First phase AB: evacuation of hot air to the atmosphere.
- Second phase BC: compression of fresh air at constant temperature.
- Third phase CD: isobaric heating of air.
- Fourth phase DA: expansion at constant temperature.

The work done during one cycle is proportional to the gray area of the PV diagram.

(See explanations on the thermodynamic principles of the general website on hot air engines.)

On the theory page of this website, we will calculate this work and the efficiency of the engine.

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Résumé

Ce manuscrit de cours, destiné aux étudiants de premier master énergétique, présente une étude approfondie des machines thermiques. Il explore les principes fondamentaux de ces systèmes thermodynamiques complexes, en examinant leurs cycles, leurs composants clés et leurs applications variées. Les machines thermiques jouent un rôle fondamental dans notre quête continue d'efficacité énergétique et de confort thermique. Elles nous permettent de maintenir des températures optimales, que ce soit pour conserver nos aliments, maintenir des conditions de travail confortables ou encore participer à la transition vers des sources d'énergie renouvelables.

Ce manuscrit est conçu pour fournir aux étudiants une base solide dans la compréhension de ces technologies essentielles. Il aborde les aspects théoriques et pratiques des machines thermiques , ainsi que les considérations techniques, environnementales et les innovations récentes qui redéfinissent le paysage de ces technologies.

Mots-clés : Machines thermiques ; rendement ; Thermodynamique ; Efficacité

Abstract

This course manuscript, intended for first energy master's students, presents an in-depth study of thermal machines. It explores the fundamental principles of these complex thermodynamic systems, examining their cycles, key components and varied applications. Thermal machines play a fundamental role in our ongoing quest for energy efficiency and thermal comfort. They allow us to maintain optimal temperatures, whether to preserve our food, maintain comfortable working conditions or even participate in the transition to .renewable energy sources

This manuscript is designed to provide students with a solid foundation in understanding these essential technologies. It addresses the theoretical and practical aspects of thermal machines, as well as technical and environmental considerations and recent .innovations that are redefining the landscape of these technologies

Keywords: Thermal machines; yield ; Thermodynamics; Efficiency