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Basics of Systems and Machines for Energy Conversion

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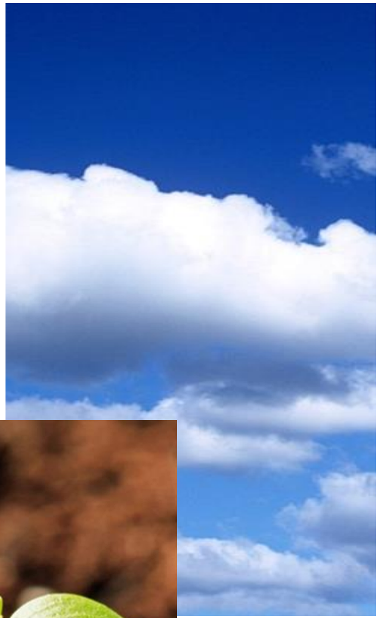
Master Degree in Innovative Technologies in Energy Efficient Buildings for Russian & Armenian Universities and Stakeholders



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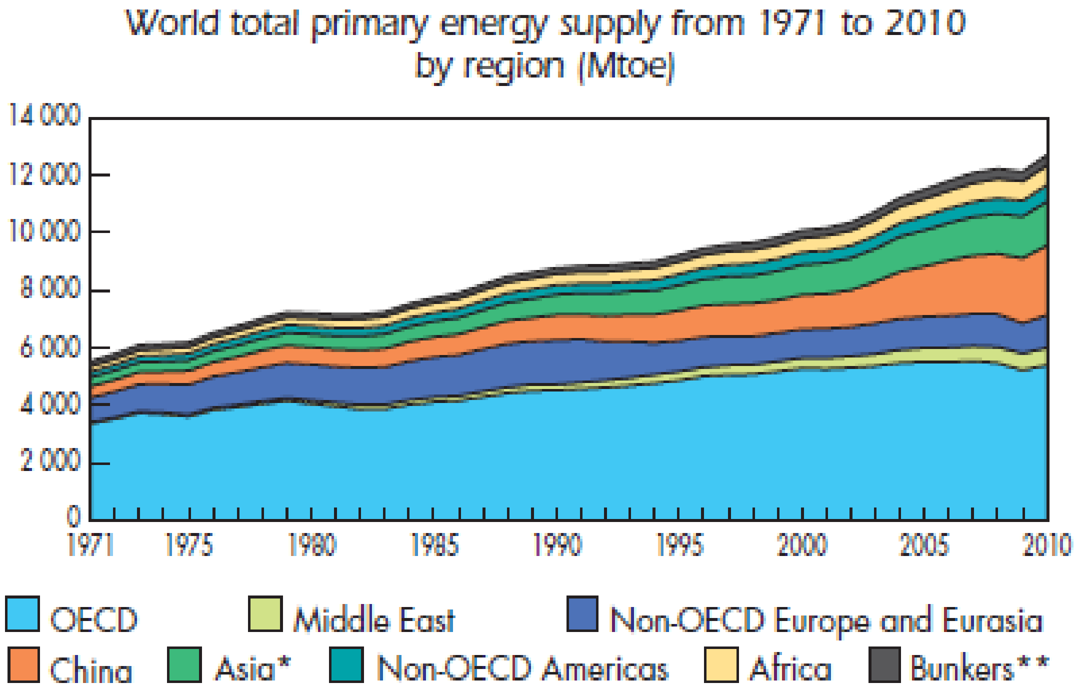
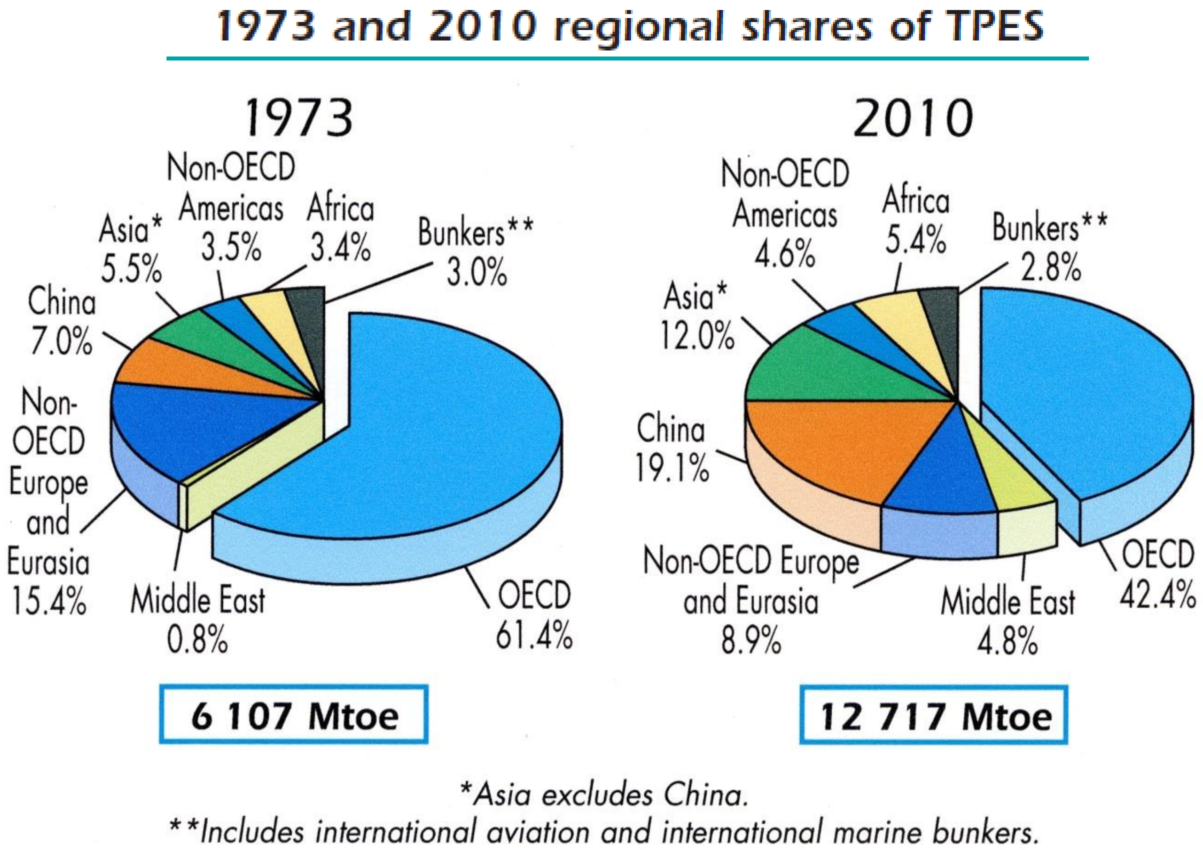
Energy consumption and emissions statistics

World primary energy consumption



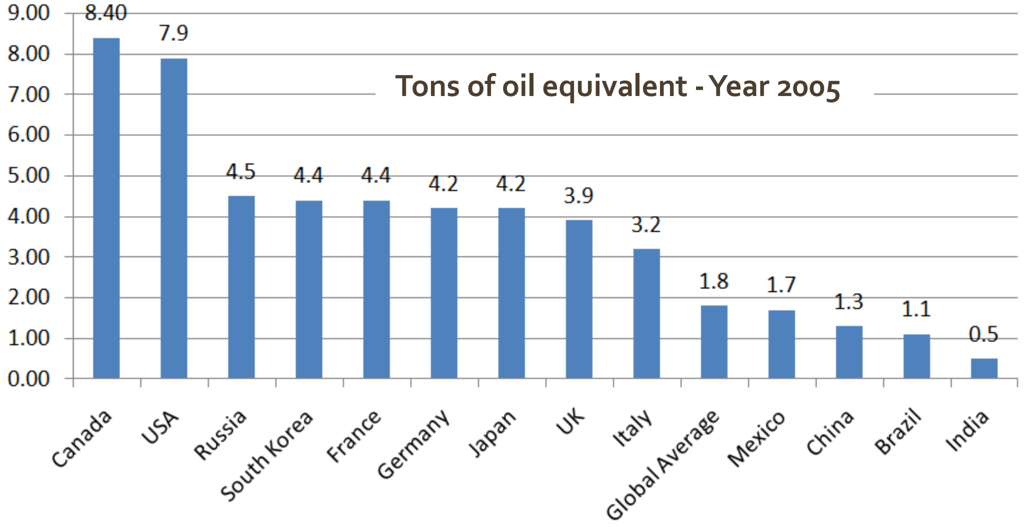
(Source: International Energy Agency, *"2012 Key World Energy Statistics"*)



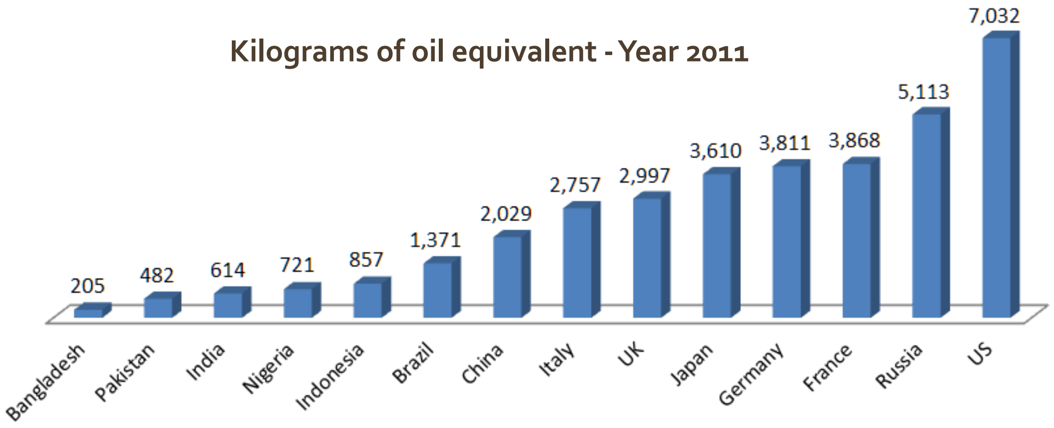
Notes:

- 1 toe (tonne of oil equivalent) = 10^7 kcal = 4,186 10^7 kJ = 11,628 10^3 kWh
- OECD (Organisation for Economic Co-operation and Development) – 34 countries (USA, Canada, Mexico, EU, Japan, Australia, etc)

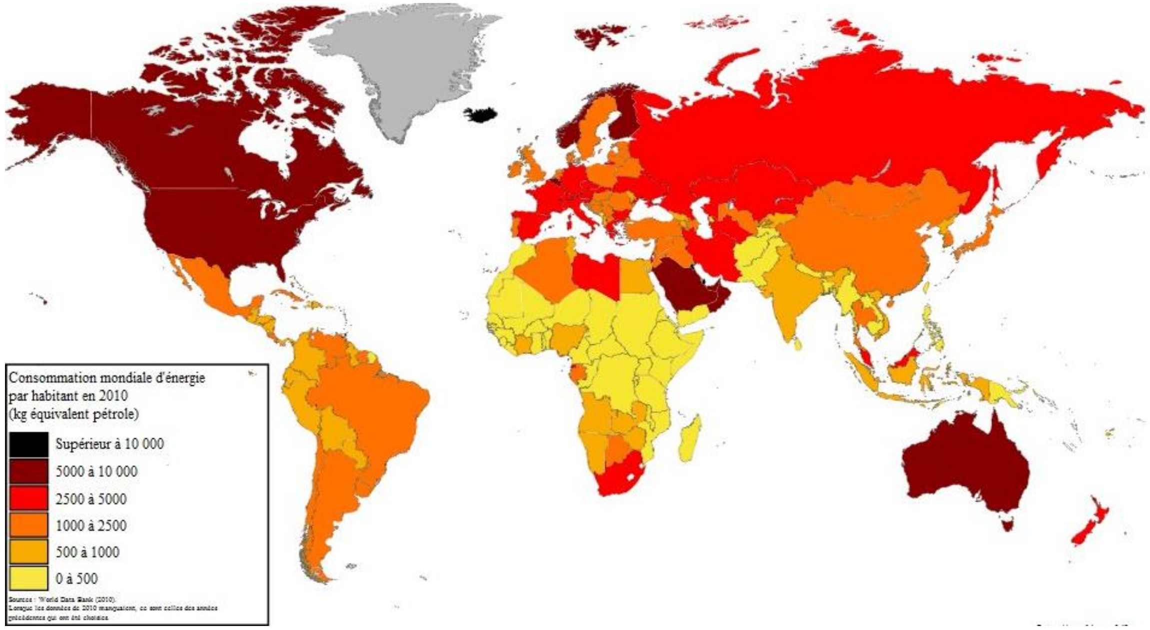
Energy consumption per person



(Source: Energy Balances of OECD and Non-OECD Countries 2004-2005)

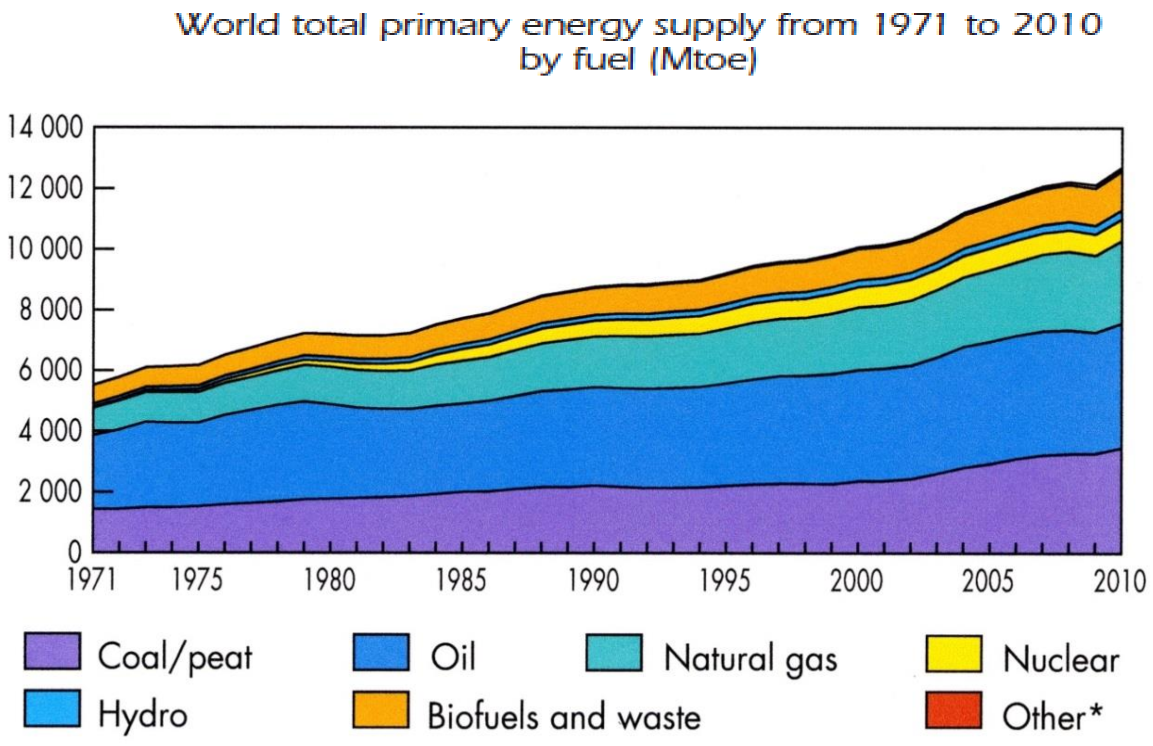


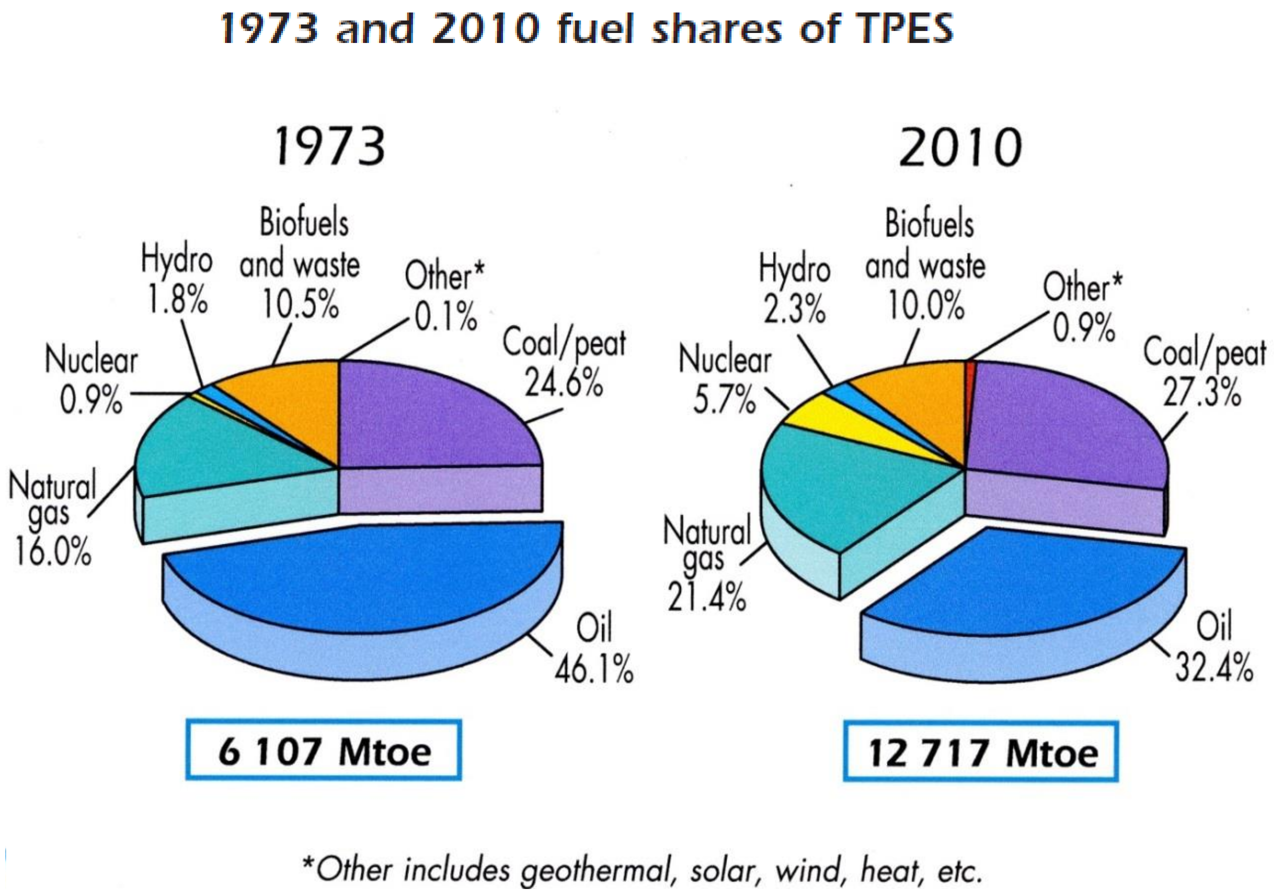
(Source: The World Bank)



(Source: World Data Bank, 2010)

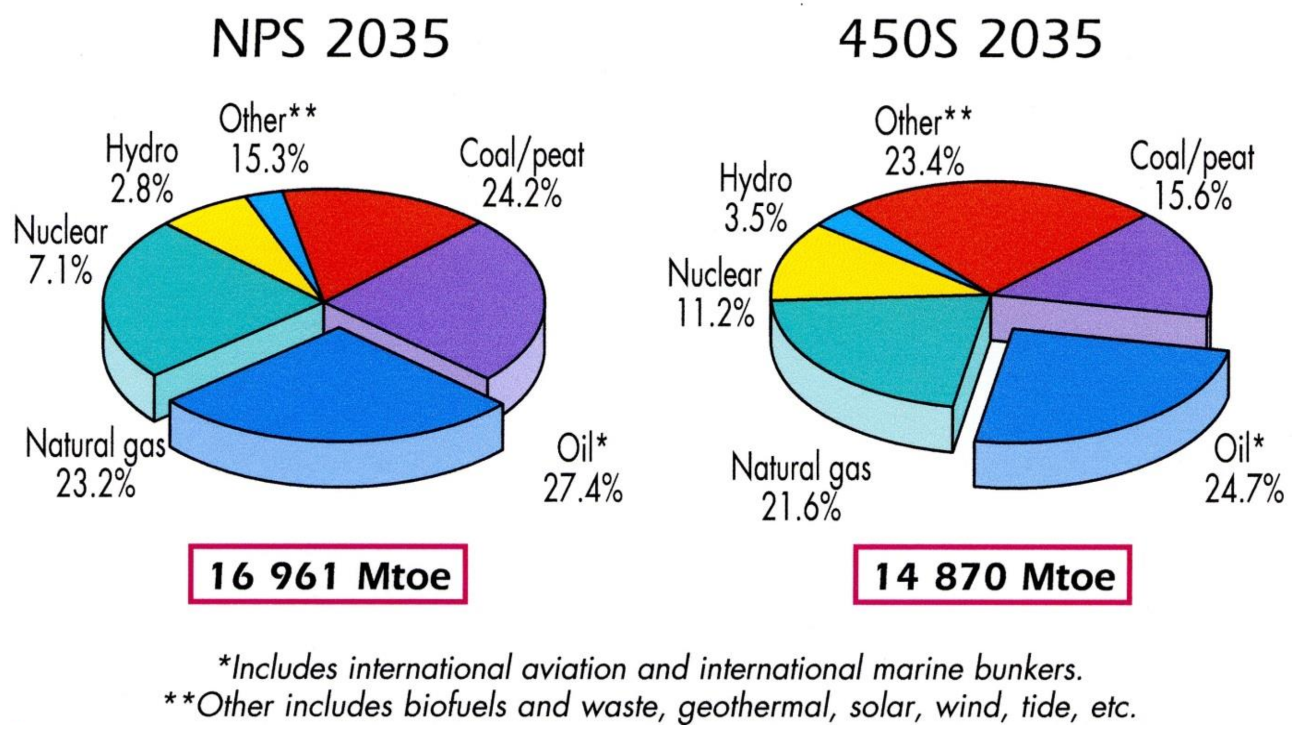
Primary energy consumption by fuel





(Source: International Energy Agency, *"2012 Key World Energy Statistics"*)

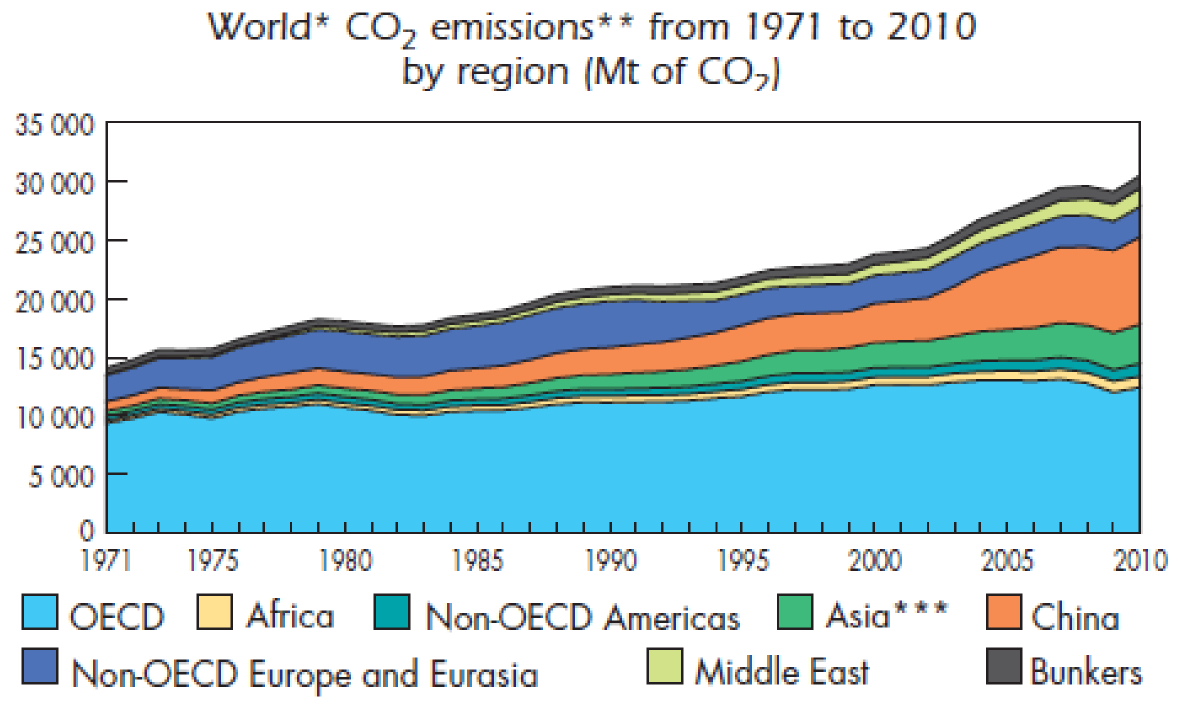
Primary energy consumption scenarios in 2035

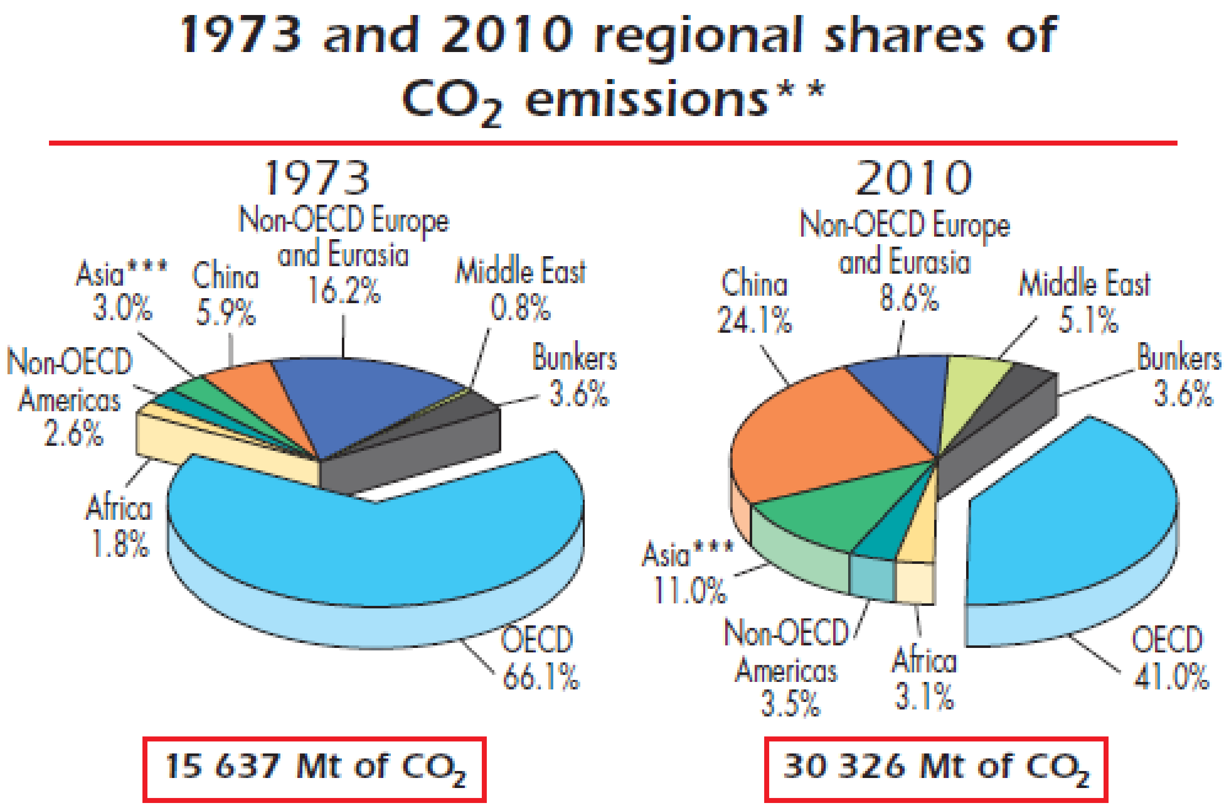


(Source: International Energy Agency, "*2012 Key World Energy Statistics*")

- NPS: New Policies Scenario (based on announced policy commitments and plans).
- 450S: 450 Scenario (based on a plausible post-2012 climate-policy framework to stabilize the concentration of global greenhouse gases at 450 ppm CO_2-equivalent.

World CO_2 emissions





*World includes international aviation and international marine bunkers, which are shown together as Bunkers. **Calculated using the IEA's energy balances and the Revised 1996 IPCC Guidelines. CO_2 emissions are from fuel combustion only. ***Asia excludes China.

Pollutant emissions, breakdown by inventory (EU-27, 2005)

	CO [%]	NO_x [%]	SO_x [%]	NMVOC [%]	CH_4 [%]	PM10 [%]
Energy Production (1)	2,2	22,5	**65,0**	1,2	0,4	11,0
Combustion (others) (2)	28,4	7,0	8,7	10,9	2,0	**24,0**
Combustion (industry) (3)	11,8	14,2	15,6	1,7	0,3	9,6
Industrial Processes (4)	8,6	2,3	6,5	16,6	17,8	17,8
Road Transport (7)	**38,0**	**39,5**	0,6	19,3	0,6	14,4
Other Transports (8)	5,8	12,6	3,5	4,4	0,1	6,6
Others (5, 6, 9, 10)	5,2	1,9	0,1	**45,9**(1)	**78,8**(2)	16,6

Notes:
(1) 40,1% for sector 6, 1,1% for sector 9 e 4,8% for sector 10
(2) 31,1% for sector 9, 47,7% for sector 10

The COoRdinatio INformation AIR (CORINAIR) classification is the following:

1. Combustion in Energy and Transformation Industry
2. Non-industrial Combustion Plants
3. Combustion in Manufacturing Industry
4. Production Processes
5. Extraction and Distribution of Fossil Fuels and Geothermal Energy
6. Solvents and Other Products Use
7. Road Transport
8. Other Mobile Sources and Machinery
9. Waste Treatment and Disposal
10. Agriculture

Source:
Elaboration from http://dataservice.eea.europa.eu/dataservice.
Original data distributed using the IPCC (Intergovernmental Panel on Climate Change) classification adopted by the European Environment Agency

Fundamentals of energy conversion systems

Energy conversion processes

- Energy demand is mainly referred to the following types (exploitable energy):
  - Thermal energy
  - Mechanical energy
  - Electrical energy
- These energy types are often not available in nature in the requested form, place, time and amount.
- It is therefore necessary to transform energy from primary sources in types of energy that can be easily exploited by men and industries.
- An energy conversion system (or “energy system”) is an organized ensemble of different components connected each other that allows to transform a primary energy in an exploitable energy through the action of a working fluid (liquid, gas or vapor). These energy systems are often referred as “power plants”.
- If all the transformation processes occur in a single component the energy system is called “prime mover”. A typical example of prime mover is the internal combustion engine, widely used as propulsion system in mobile applications.

Energy conversion flowchart

Natural energy availability

- Solar radiation
- Gravitational energy
- Matter transformation

→ **Natural conversion processes**

- Biological processes
- Atmospheric movements
- Nuclear reactions
- Water evaporation and condensation

Primary energy sources

- Radiant energy
- Fossil fuels
- Geothermal energy
- Nuclear energy
- Wind energy
- Hydraulic energy
- Tidal energy
- Sea waves energy
- Sea thermal gradients

→ **Power plants**

Exploitable energy

- Thermal
- Mechanical
- Electrical

Thermal power plants

- According to the primary energy used, power plants can be divided into thermal, hydraulic, wind, etc. plants.
- Today thermal power plants are the most important and widely used energy systems. In these plants the available primary energy (often represented by chemical energy of fossil fuels) is usually converted into thermal energy through a combustion process.
- Thermal power plants in which the thermal energy is generated by a combustion process can be divided into **internal and external combustion systems**.
- In internal combustion energy systems the combustion process of a fuel mixed with an oxidizer occurs in a combustion chamber, which is an integral part of the working fluid flow circuit and the thermal energy is directly generated within the system. Gasoline and diesel vehicle engines, open cycle gas turbines (for power generation and aircraft propulsion) and rocket motors are types of internal combustion plants.
- In external combustion energy systems the combustion process occurs outside the working fluid flow cycle and the thermal energy is transferred to the working fluid through the engine wall or a heat exchanger. Typical examples of external combustion energy systems are steam power plants, closed cycle gas turbines and steam piston engines.

Fluid machines

- As above reported, energy conversion systems usually include different components: fluid machines, heat exchangers, steam generator or combustion chamber, etc.
- Fluid machines are the most important components of power plants. In these devices energy transfer occurs between a working fluid (liquid, gas or vapor) and their moving parts. Fluid machines can be classified according to three different aspects:
  - Direction of energy transfer:
    - Motor (or power generating) machines convert the working fluid energy (thermodynamic, kinetic, gravitational energy) in a mechanical energy output
    - Operating (or power absorbing) machines convert a mechanical energy input into an increase of the working fluid energy (fluid position, pressure and/or kinetic energy)
  - Behaviour of the working fluid:
    - Uncompressible fluid (usually water → hydraulic machines)
    - Compressible fluid (gas, vapor). Since thermal phenomena (i.e., temperature variations, heat transfer, etc..) are involved in the expansion or compression of a compressible fluid, these fluid machines are usually referred as thermal
  - Operating way of the fluid machine:
    - Volumetric or positive displacement machines, in which the work exchange is associated to a change of volume and/or a displacement of the working fluid (cyclic operation, limited flow rate)
    - Turbomachines or steady flow fluid machines, in which the work exchange is associated to dynamic actions associated to changes of working fluid angular momentum (continuous flow operation, high flow rates)

Power generation systems

- The main energy conversion systems today used to make available large amounts of exploitable energy are:
  - Reciprocating internal combustion engines, widely used in mobile applications (road vehicles, ships, rail propulsion) and in small power production plants
  - Steam power plants (fed with fossil or nuclear fuel), mainly used in large size electricity production plants
  - Hydraulic plants, primarily used to generate electricity
  - Gas turbine power plants, used for electricity generation, aircraft propulsion and industrial applications
- Internal combustion engines, steam and gas turbine power plants today fulfill over 80% of exploitable energy demand. These thermal power plants are generally fed with fossil fuels (coal, oil derivative fuels and natural gas) and present the following operational issues:
  - Limited overall efficiency (mainly due to the conversion of thermal into mechanical energy)
  - High combustion temperatures (impacting on material specifications)
  - Need of cooling fluids
  - Discharge of combustion products (polluting emissions and related environmental impact)

Energy system cycles (1/3)

- As above mentioned, in a thermal power plant the conversion of fuel chemical energy into exploitable energy involves different steps.
- A first phase is related to the conversion of chemical fuel potential energy into heat (associated to the combustion process). The produced heat is then converted into mechanical work (which can be directly used or further transformed in another energy type, typically electricity).
- The processes occurring in energy systems are usually described referring to thermodynamic cycles.
- A cycle is a series of processes that begins and ends at the same state and that can be repeated indefinitely.
- Since in internal combustion energy systems the working fluid changes its chemical composition due to the combustion process, it is necessary to replace the fluid at the beginning of each new cycle.

Energy system cycles (2/3)

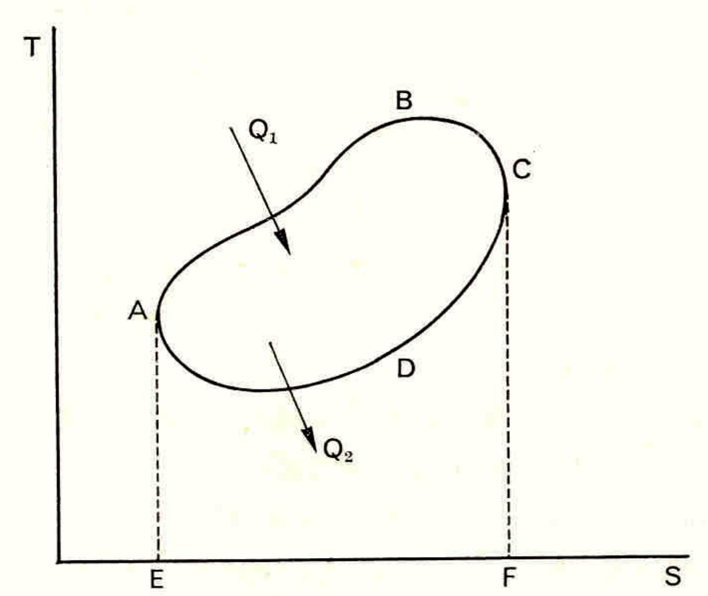
- According to the first law of thermodynamics (energy conservation), in an energy system operating on a cycle the work produced is given by:

$$W = Q_1 - Q_2$$

  where
  - Q_1 is the heat entering the system
  - Q_2 is the heat rejected (leaving the system)
- In fact, due to the second law of thermodynamics, heat entering the system cannot be completely converted into work but a portion of it has to be rejected as low-grade heat after the work has been done.
- Different approaches can be used for the calculation of thermodynamic cycles associated to energy systems operation, depending on the assumptions for working fluid and processes occurring in the system components.
- The working fluid can be considered ideal, technically real (no viscosity) or real.
- The processes in the system components can be ideal (reversible transformations) or real (irreversible transformations).

Energy system cycles (3/3)

- In thermal power plants using a gas as working fluid, three different approximation levels of real system behavior can be considered, characterized by an increasing calculation complexity
  - **Ideal cycle**: idealized perfect gas and reversible processes
  - **Fuel-air cycle**: accurate working fluid model (no viscosity) and reversible processes
  - **Real cycle**: accurate working fluid model (including viscosity) and not reversible processes
- In any case, if the cycle is made up of reversible processes, its area on pressure-volume and temperature-entropy thermodynamic diagrams represents the work exchanged by the system.



The following conventions are generally adopted:

- The work done by the system is positive and the work done on the system is negative
- The work is positive if the reversible cycle is described clockwise
- The heat entering the system is positive and the heat rejected by the system is negative

Power plant overall efficiency

- As above mentioned, energy demand is mainly referred to thermal, mechanical and electrical energy.
- In order to get the required energy type, several conversions are often necessary. Each energy conversion (or transportation) implies an energy loss, which can be expressed through an efficiency. As an example, the conversion of thermal into mechanical energy is characterized by low efficiency levels (typically 0.3÷0,5) due to the Second Law of Thermodynamics.
- In any case, the power plant overall efficiency (η_o) can be defined as the ratio between the net work produced (W) and the energy supplied to the energy conversion system.
- In the case of a thermal power plant fed with a fossil fuel, the overall efficiency is given by:

$$\eta_0 = \frac{W}{m_f H}$$

where

- m_f = mass of burnt fuel
- H = fuel heating value (amount of heat released during the combustion of fuel mass unit)

Correlation between efficiency and pollution

- When concerning the power plant environmental impact, a higher efficiency solution is always the best choice. In fact, referring to thermal power plant efficiency, it is:

$$\eta_0 = \frac{W}{m_f H} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

- By raising the plant efficiency it is possible to achieve:
  - a reduction of heat leaving the system (Q_2) → lower thermal pollution
  - a reduction of burnt fuel mass (m_f) for the same work level, thus decreasing the pollutant production associated to the combustion process → lower chemical pollution

Processes in energy system components

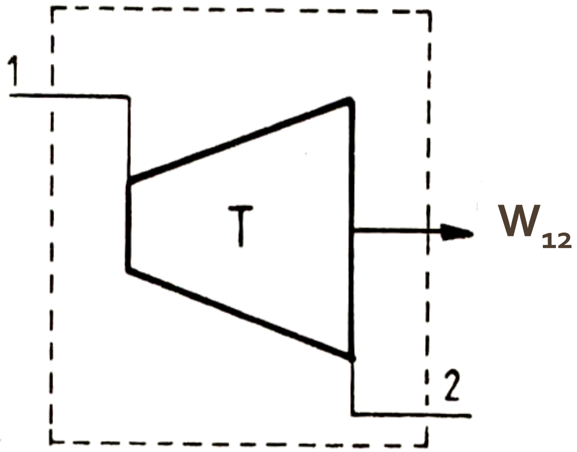
- Most energy system components can be considered as open systems, since energy (work and heat) and mass flow exchanges are allowed across their boundaries.
- In the case of an open system fitted with a one-inlet-one-exit control volume, the first law of thermodynamics (energy conservation equation) for unit mass can be written as:

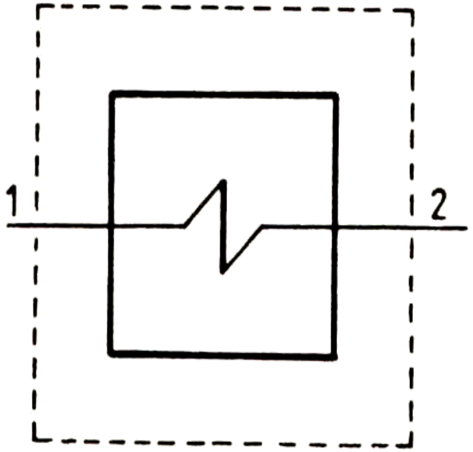
$$W_{12} = Q_{12} + (h_1 - h_2) + (c_1^2/2 - c_2^2/2) + g\,(z_1 - z_2)$$

where subscripts 1 and 2 indicate the inlet and exit stations of the system

and

- W = work exchanged per unit mass
- Q = heat exchanged per unit mass
- h = specific enthalpy
- c = velocity of the mass
- g = gravity acceleration (equal to 9.80665 m/s^2)
- z = elevation





Work exchange in fluid machines

- Fluid machines are primary components of power plants. Although there exist some heat transfer between fluid machines and their surroundings, in most cases it is possible to neglect it and assume that fluid machines operate under adiabatic condition ($Q_{12} = 0$).
- As a consequence, the expression of work exchanged by a fluid machine (open system) becomes:

$$W_{12} = (h_1 - h_2) + (c_1^2/2 - c_2^2/2) + g\,(z_1 - z_2)$$

- In many applications the change of kinetic and potential energy between fluid machine inlet and exit stations is negligible compared with the enthalpy change of the process. Therefore, it is possible to write:

$$W_{12} \cong h_1 - h_2$$

- The fluid machine power is given by:

$$P_{12} = W_{12} \cdot M$$

where

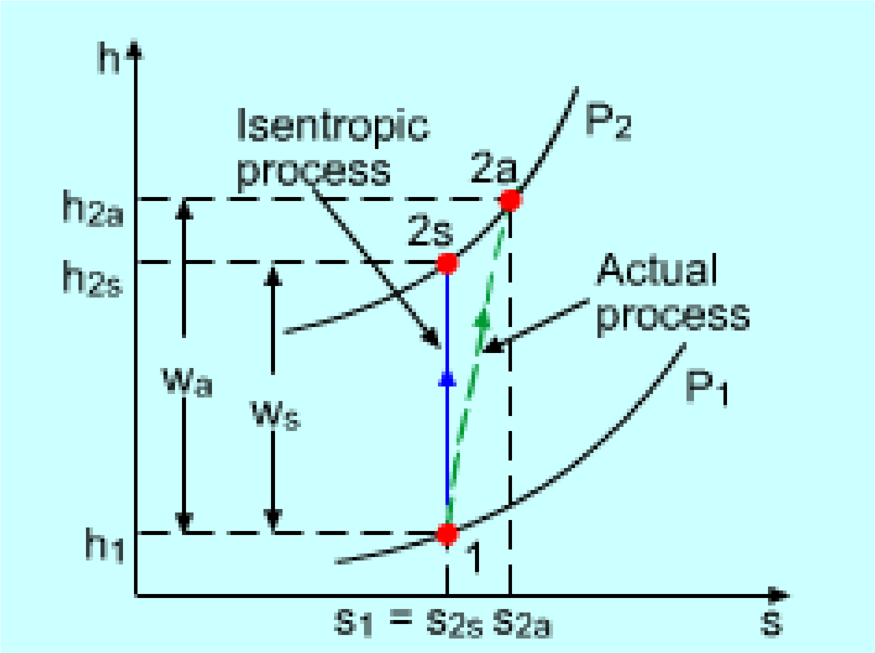
- M = mass flow rate

Isentropic efficiency of compressors and pumps

- Since the process in fluid machines is generally assumed as adiabatic, the isentropic (or adiabatic) efficiency is a parameter to measure the degree of degradation of energy in these devices. It involves a comparison between the actual performance and the performance that would be achieved under idealized circumstances for the same inlet and exit states. In the case of adiabatic devices, an isentropic process is normally chosen as reference idealized process.

- Compressors and pumps are operating (or power absorbing) fluid machines. Therefore, for a steady flow process, the isentropic efficiency of a compressor or pump is defined as the ratio of the work input to an isentropic process, to the work input to the actual process between the same inlet and exit pressures.
- If the inlet and exit stations are respectively denoted by subscripts 1 and 2, the compressor isentropic (or adiabatic) efficiency is given by:

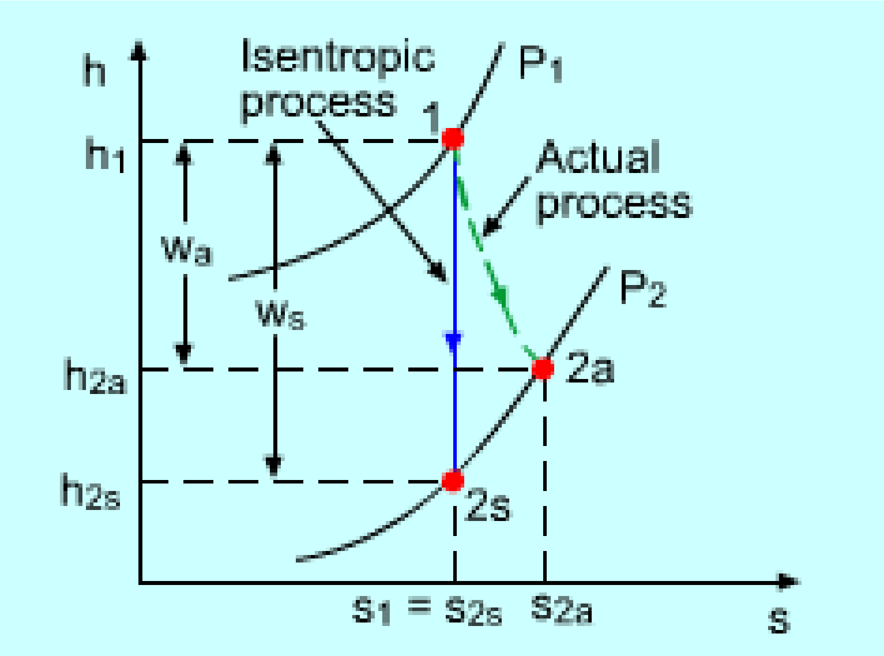
$$\eta_c = \frac{W_s}{W_a} = \frac{h_1 - h_{2s}}{h_1 - h_{2a}}$$



Turbine isentropic efficiency

- Turbines are motor (or power generating) machines that convert the working fluid energy into mechanical work.
- Assuming a steady flow adiabatic process, the turbine isentropic efficiency is defined as the ratio of the actual work output of the turbine to the work output of the turbine assuming an isentropic process between the same inlet and exit pressures.
- If the inlet and exit stations are respectively denoted by subscripts 1 and 2, the turbine isentropic (or adiabatic) efficiency is given by:

$$\eta_t = \frac{W_a}{W_s} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$



Combustion processes and pollutants formation

Combustion

- At present, combustion is the simplest and most convenient way to make available large amounts of thermal energy starting from fuel chemical energy.
- Combustion is a high-temperature exothermic chemical reaction between a fuel and an oxidant, usually atmospheric oxygen, that produces oxidized, often gaseous products. Combustion is often hot enough that light in the form of a flame is produced.
- In the case of fossil fuels the efficiency combustion is very high, approaching unity (i.e., the fuel chemical energy is almost completely converted to heat).
- For the combustion process to take place, fuel, oxygen, and an ignition heat source are required to start a chemical chain reaction.
- The combustion processes are mainly classified as premixed or diffusion (non-premixed) flames. These flames may be both laminar or turbulent types.
- In a premixed flame the fuel and the oxidant are molecularly mixed before the combustion process takes place.
- In a diffusion flame the fuel and air are initially not mixed. The fuel and oxidizer are kept on either side of the reaction zone and moved to the reaction zone.

Air-fuel ratio

- The air-fuel ratio (α) is a fundamental parameter to characterize any combustion process. It is the mass ratio of air to fuel present in a combustion process:

$$\alpha = \frac{m_a}{m_f} = \frac{M_a}{M_f}$$

where

- m = mass per unit cycle
- M = mass per unit time (mass flow rate)
- a = air
- f = fuel

- If exactly enough air is provided to completely burn all of the fuel, the mass ratio between air and fuel is known as the stoichiometric air-fuel ratio (α_{st}), that is typical of each fuel.
- If air content is less than the stoichiometric ratio ($\alpha < \alpha_{st}$), the air-fuel mixture is said to be (fuel) rich.
- If air content is higher than the stoichiometric ratio ($\alpha > \alpha_{st}$), the air-fuel mixture is said to be (fuel) lean.

Polluting emissions

- The combustion processes give rise to primary and secondary pollution phenomena.
- Primary pollutants are directly discharged in the atmosphere at the exhaust of thermal energy plants. The main primary pollutants are:
  - Carbon monoxide (CO)
  - Unburnt hydrocarbons (HC)
  - Nitrogen oxides (NO_X)
  - Sulfur oxides (SO_X)
  - Particulate
  - Carbon dioxide (CO_2) (greenhouse gas)
- Secondary pollutants are produced in the atmosphere by the interaction between the various primary pollutants and normal constituents of the atmosphere, with or without photochemical activation. The main secondary pollution phenomena are:
  - acid rain
  - photochemical smog

Energy conversion power plants

Internal Combustion Engines

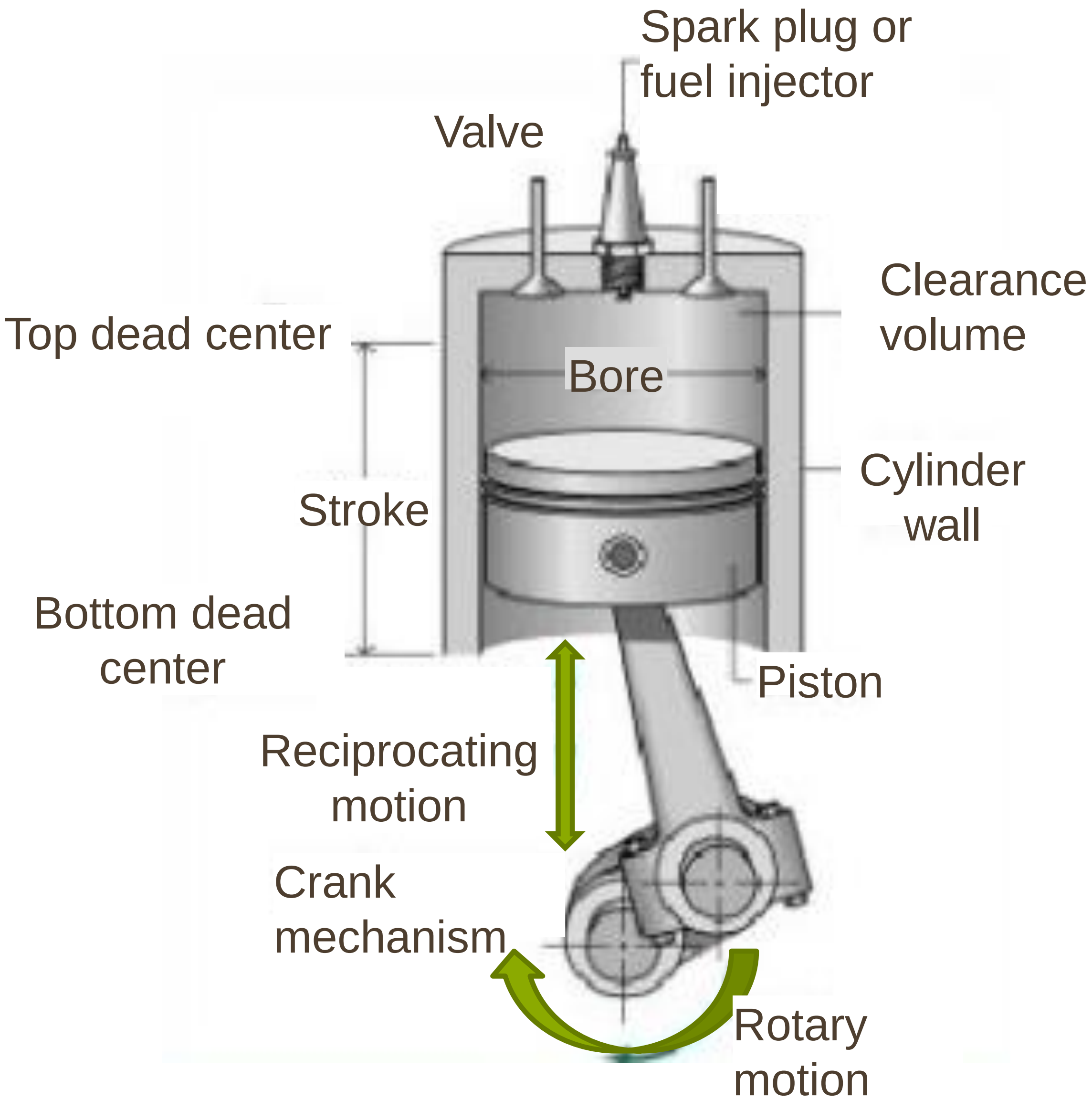
Introduction

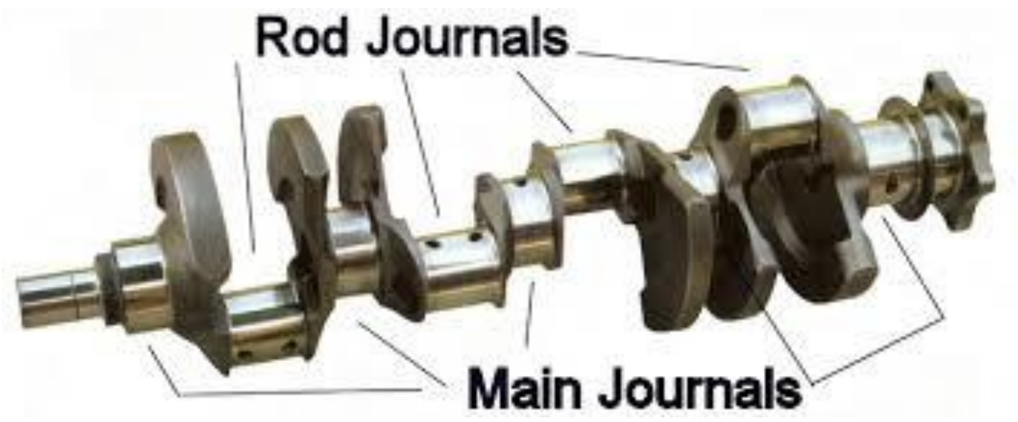
- The Internal Combustion Engine (ICE) was conceived and first developed in the late 1800s. Since that time the ICE has been continuously developed with the introduction of new technologies in order to fulfil the demand of new applications and meet energy and environmental constrains.
- The last decades have seen an explosive growth in engine research and development as a consequence of the issues related to air pollution, fuel economy and market competitiveness.
- The Internal Combustion Engines can deliver power in the range from 0.01 kW to 20 MW and now play a dominant role in several areas. The major ICE applications are in the vehicular (motorcycles, cars and trucks), railroad, marine, home use and stationary areas.
- The main reasons of the widespread ICE application are:
  - high flexibility
  - high overall efficiency
  - high power-weight ratio

ICE classifications

- ICEs belong to the category of internal combustion energy systems, since the fuel chemical energy is released by burning the fuel mixed with an oxidizer inside the engine.
- Since all the transformation processes associated to ICE operation occur in a single component, the internal combustion engine is a typical example of “prime mover”.
- Reciprocating engines are more used than rotary ones (Wankel).
- There are many different ICE classification criteria. The most important are related to:
  - Working cycle:
    - **two-stroke** engine, in which a power cycle is completed in one crankshaft revolution, corresponding to two strokes (up and down movements) of the piston
    - **four-stroke** engine, in which a power cycle is completed in two crankshaft revolutions, corresponding to four strokes of the piston
  - Method of ignition:
    - **spark ignition (SI)** engine, in which a spark is needed to ignite the fuel-air mixture (premixed combustion process)
    - **compression ignition (CI) or diesel** engine, in which the fuel auto-ignites when injected in the combustion chamber due to the air thermodynamic energy (pressure and temperature) (diffusion combustion process)

Engine components



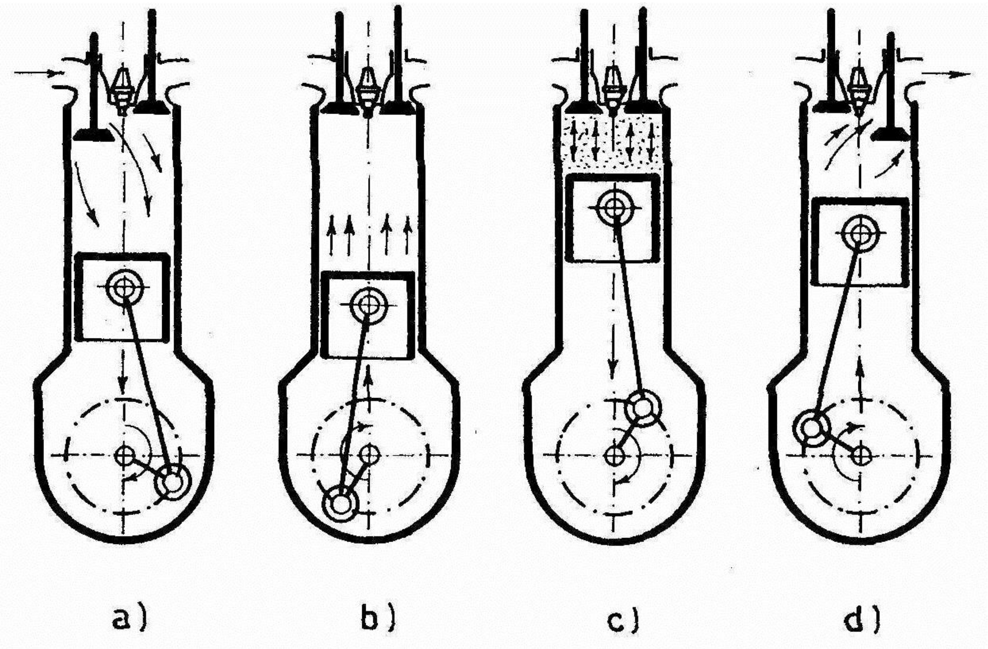


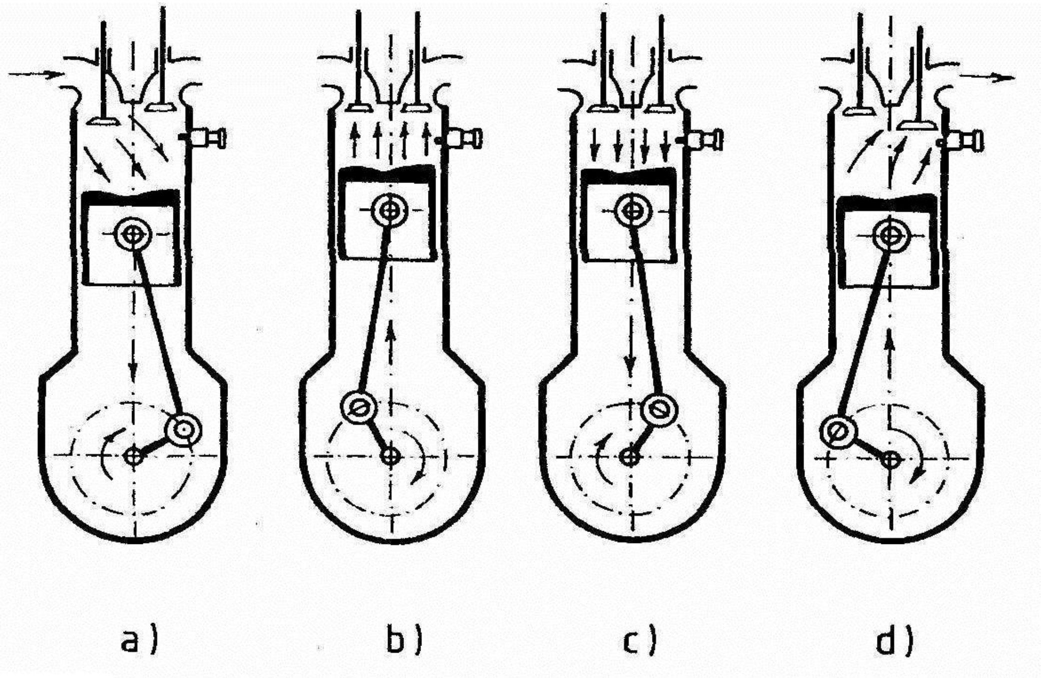
Engine parameters

- Geometric parameters:
  - b = bore
  - s = stroke
  - r = crank radius = s/2
  - θ = crank angle (equal to zero at tdc)
  - $V_c = V_2 =$ clearance volume (piston at tdc)
  - V_1 = maximum cylinder volume (piston at bdc)
  - $\rho = V_1/V_2$ = compression ratio
  - $V_d = V_1 - V_2$ = displacement volume
  - z = number of engine cylinders
  - $V_t = V_d \cdot z$ = total displacement volume
- Kinematic parameters:
  - n = crankshaft (engine) rotational speed [rpm]
  - ω = engine frequency [rad/s] = $2 \pi n / 60$
  - u_p [m/s] = $2 s n / 60 = s n / 30$ = mean piston speed (related to engine inertial stresses)

Modern SI engine for automotive application

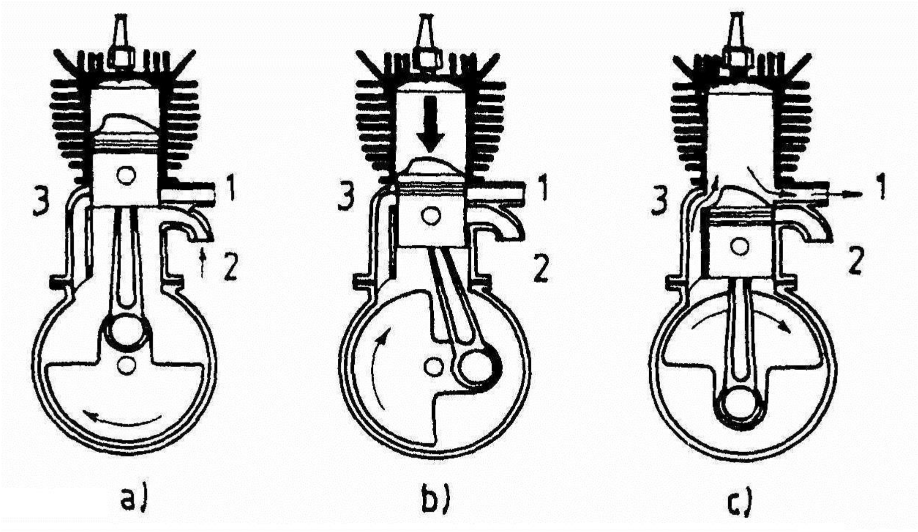
Four-stroke engine theoretical operation

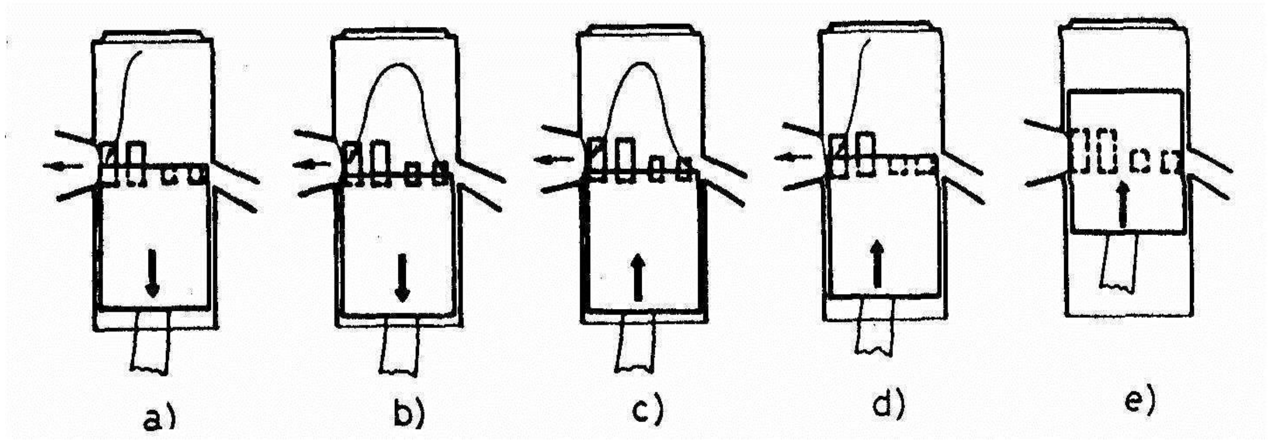




Four-stroke spark ignition engine cycle:
a) Intake
b) Compression
c) Ignition, combustion and expansion
d) Exhaust

Four-stroke compression ignition engine cycle:
a) Intake
b) Compression
c) Injection, combustion and expansion
d) Exhaust



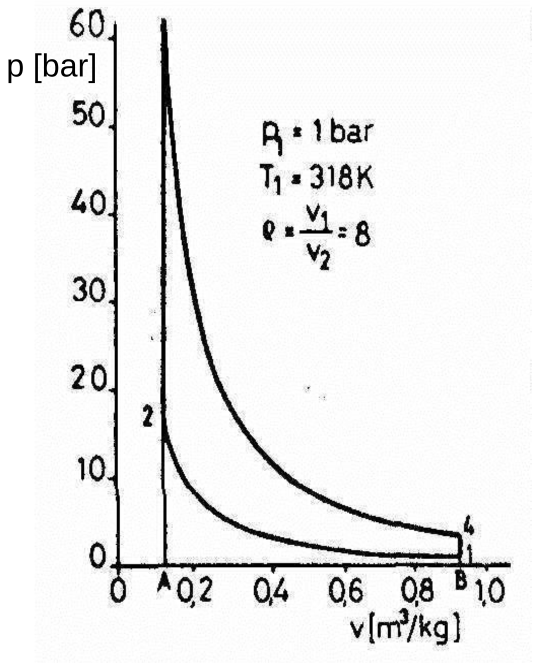


Two-stroke crankcase-scavenged engine cycle:
a) Crankcase intake and cylinder compression
b) Combustion and expansion
c) Exhaust and scavenging process

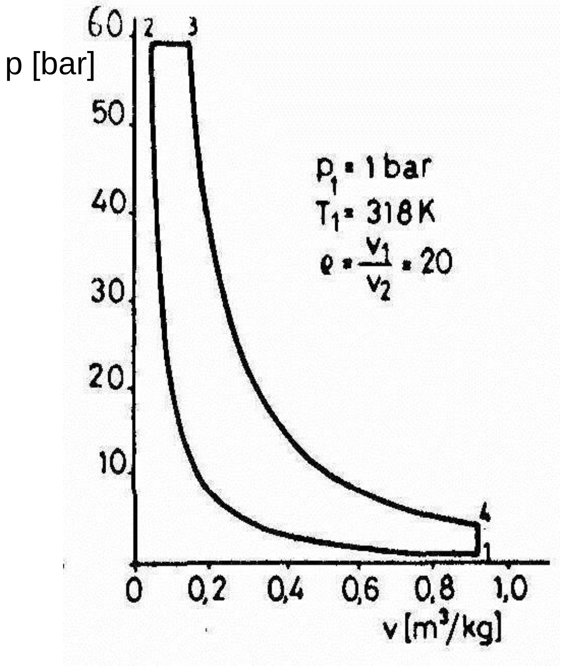
1 Exhaust port
2 Inlet port
3 Scavenging (transfer) port

Detail of two-stroke engine scavenging process:
a) Spontaneous exhaust (blowdown)
b) and c) Scavenging
d) Forced exhaust
e) Compression

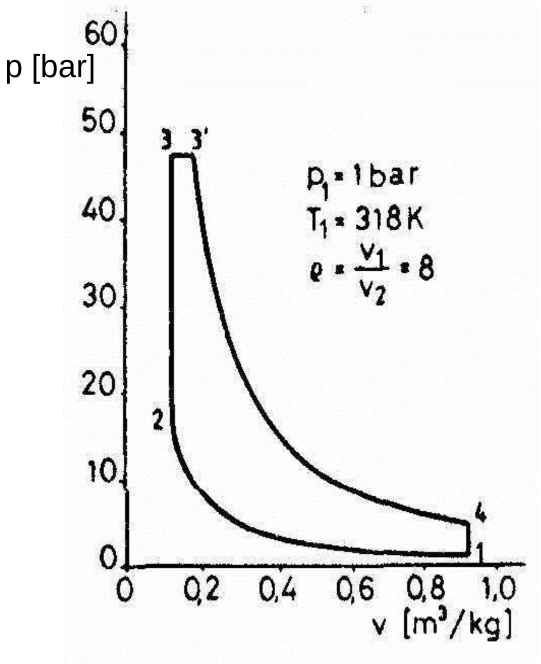
Engine thermodynamic cycles



Beau de Rochas (Otto)



Diesel



Limited-pressure combustion

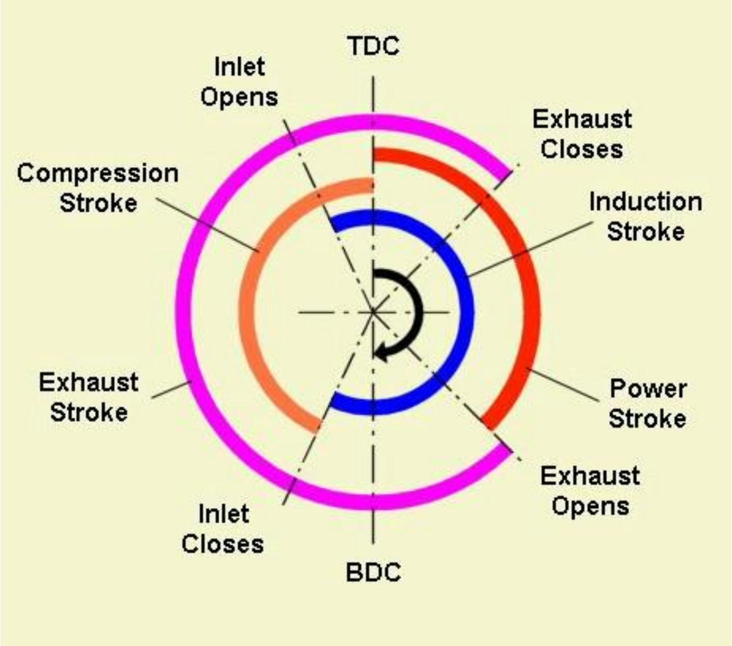
1→2 isentropic compression
2→3 constant-volume heat addition (Q_1)
3→4 isentropic expansion
4→1 constant-volume heat rejection (Q_2)

1→2 isentropic compression
2→3 constant-pressure heat addition (Q_1)
3→4 isentropic expansion
4→1 constant-volume heat rejection (Q_2)

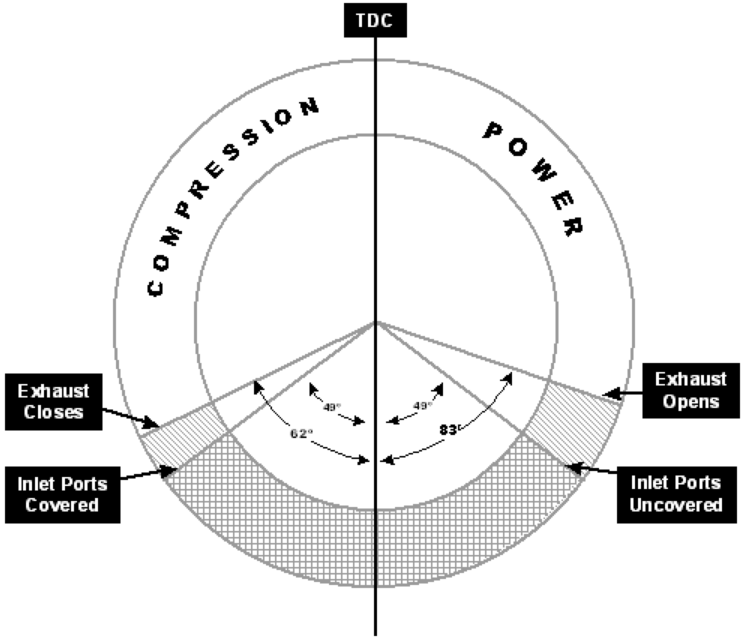
1→2 isentropic compression
2→3 constant-volume heat addition (Q_1')
3→3′ constant-pressure heat addition (Q_1'')
3′→4 isentropic expansion
4→1 constant-volume heat rejection (Q_2)

Real engine operation
Valve timing diagrams

- A valve timing diagram is a polar representation of the complete cycle of events in terms of engine valves (or ports) opening and closing crank angles.
- In the case of a four-stroke engine the complete cycle is shown as a 720° spiral, which represents two complete crankshaft revolutions. In the case of a two-stroke engine the complete cycle is shown as a circumference.



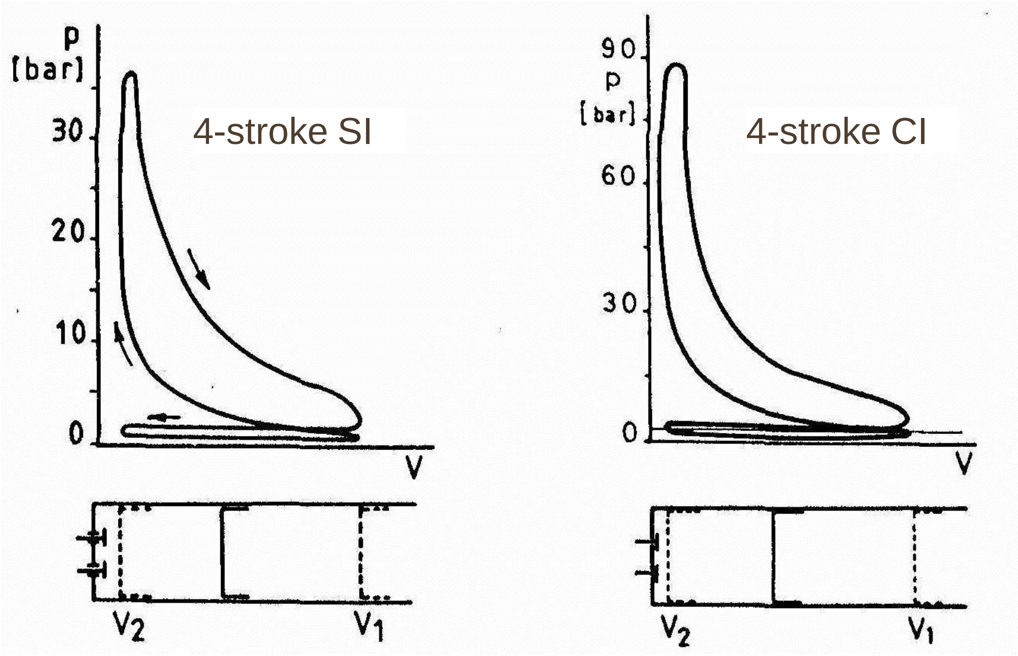
Four-stroke engine

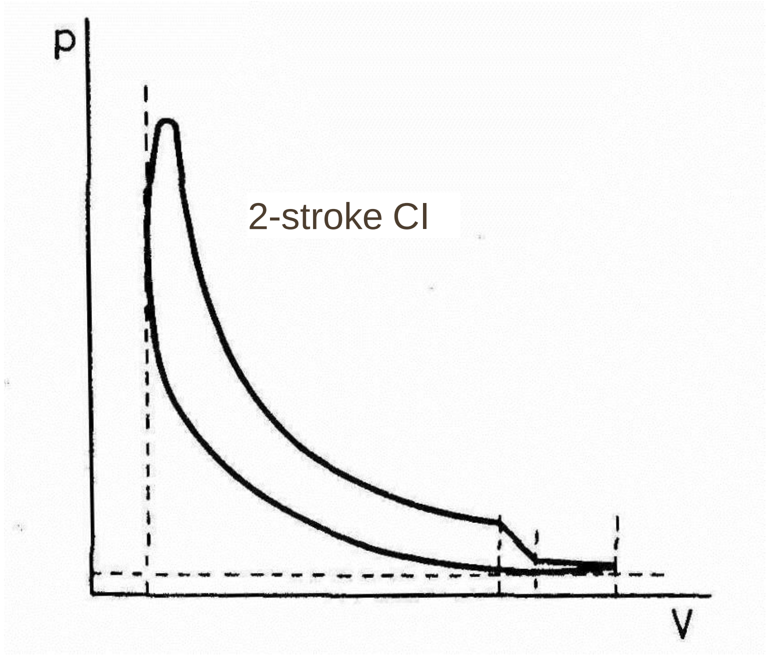


Two-stroke engine

Real engine operation
Indicator diagrams

- An indicator diagram is the representation throughout the engine cycle of a parameter measured inside the cylinder versus the crank angle (open diagram) or the instantaneous cylinder volume (closed diagram).
- Usually the cylinder pressure and corresponding cylinder volume throughout the engine cycle are plotted on a p-V diagram.
- Pressure indicator diagrams of four-stroke engines differ from the two-stroke ones due to the pumping work associated to the inlet and exhaust strokes.





Indicated work and power

- The engine indicated work per cycle W_i (per cylinder) represents the work exchanged between piston and gas inside the cylinder. It is given by the sum of the areas enclosed on the indicator diagram by the working and the pumping cycle.
- The indicated mean effective pressure (imep) is defined as the mean value of pressure in the indicator diagram and represents the indicated work per unit displacement volume. It is:

$$W_i = imep \cdot V_d$$

- The indicated power can be easily calculated from the indicated work:

$$P_i = \frac{W_i\, n}{60\, \varepsilon} = \frac{imep \cdot V_d \cdot n}{60\, \varepsilon}$$

where:

ε = number of crank revolutions for each engine cycle (2 for four-stroke engines, 1 for two-stroke engines)

- In the case of a multi-cylinder engine of total displacement volume V_t, the indicated power is:

$$P_i = \frac{imep \cdot V_t \cdot n}{60\, \varepsilon}$$

Engine brake power (1st formulation)

- A portion of the indicated power is used to overcome the friction of the bearings, pistons and other mechanical components of the engine, and to drive the engine accessories. All of these power requirements are grouped together and called friction power (P_f).
- Thus, the brake power is given by:

$$P_b = P_i - P_f$$

- The ratio of the brake power delivered by the engine to the indicated power is called mechanical efficiency:

$$\eta_m = \frac{P_b}{P_i} = 1 - \frac{P_f}{P_i}$$

- The engine brake power can be expressed as:

$$P_b = P_i \cdot \eta_m = \frac{imep \cdot \eta_m \cdot V_t \cdot n}{60\ \varepsilon} = \frac{bmep \cdot V_t \cdot n}{60\ \varepsilon}$$

where:

bmep = imep $\cdot\ \eta_m$ = brake mean effective pressure

Brake mean effective pressure

- The brake mean effective pressure is an important engine operating parameter since it represents the engine torque per unit displacement volume.
- The maximum brake mean effective pressure is essentially constant over a wide range of sizes for the same engine type and provides an assessment of the effectiveness with which the engine designer has used the engine's displacement volume.

Engine type	*Application*	*Brake mean effective pressure (bmep) [bar]*
2-stroke naturally aspirated SI	Small 2 wheel vehicles (motorcycles and mopeds)	6÷7
4-stroke naturally aspirated SI and diesel	Road vehicles	8÷10
4-stroke high-sped turbocharged diesel	Road vehicles	12÷16
2-stroke low-sped turbocharged diesel	Ships	12÷16
4-stroke medium-sped turbocharged diesel	Ships	up to 30

Engine brake power (2^{nd} formulation)

- The engine brake power can be also derived following a different approach, starting from the definition of engine brake (overall) efficiency:

$$\eta_0 = \frac{W_b}{m_f \, H}$$

- By introducing the air-fuel ratio, it is possible to write:

$$W_b = \frac{m_a}{\alpha} \, H \, \eta_o$$

and

$$P_b = W_b \frac{n}{60 \, \varepsilon} = \frac{m_a}{\alpha} \, H \; \eta_0 \; \frac{n}{60 \, \varepsilon}$$

- Another important engine performance parameter is the volumetric efficiency η_v. It is defined as the mass of fresh charge (m_c) induced into the cylinder during the intake process divided by the mass that would occupy the displaced volume at the density ρ_i in the intake manifold:

$$\eta_v = \frac{m_c}{\rho_i \, V_d} \cong \frac{m_a}{\rho_i \, V_d}$$

- Therefore, in the case of a multi-cylinder engine, the brake power can be expressed by:

$$P_b = \rho_i \, \eta_v \; V_t \, \frac{H}{\alpha} \, \eta_0 \, \frac{n}{60 \, \varepsilon}$$

Engine brake power control

- The two formulations of brake power highlight the parameters mainly affecting engine output:

$$P_b = \text{bmep}\ V_t\ \frac{n}{60\ \varepsilon}$$

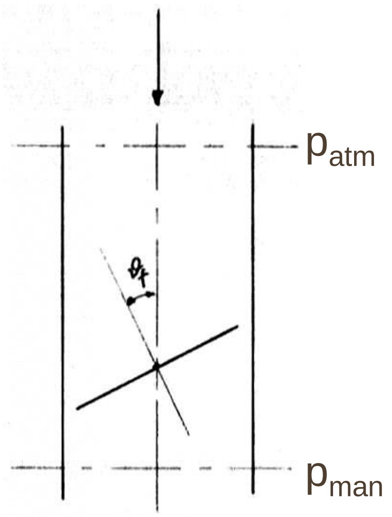
$$P_b = \frac{m_a}{\alpha}\ H\ \eta_0\ \frac{n}{60\ \varepsilon} = \rho_i\ \eta_v\ V_t\ \frac{H}{\alpha}\ \eta_0\ \frac{n}{60\ \varepsilon}$$

- Internal combustion engines often operate at part load, i.e., with a power output lower than the nominal one. This situation is typical of road vehicle engines.
- The operating parameters controlled to allow engine part load operation are:
  - the air-fuel ratio (α) for diesel engines (diffusion flame combustion process), thus carrying out engine power regulation by mixture quality control (with α ranging from 20 to 80-100)
  - the air mass (m_a) for spark ignition engines (premixed flow combustion process) working with $\alpha \cong$ const (close to the stoichiometric value), thus carrying out engine power regulation by mixture quantity control, with a proportional change of air and fuel mass

SI engine load control systems

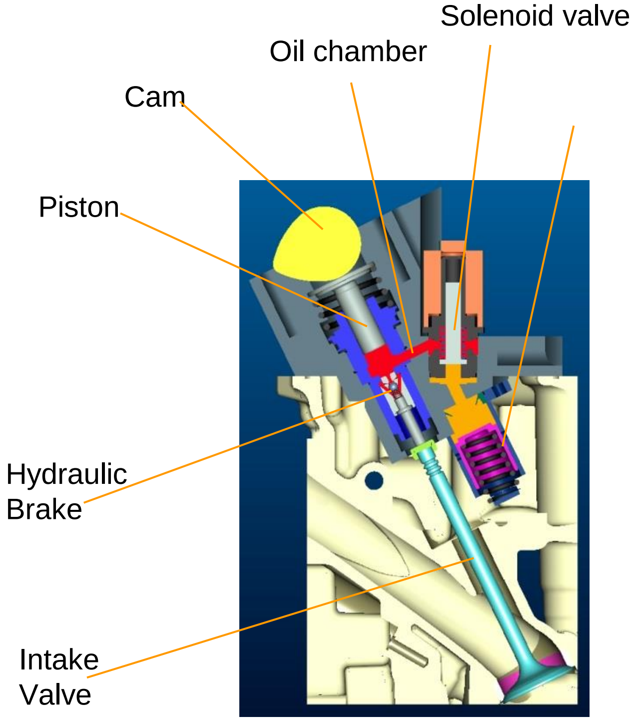
- The air mass in SI engines can be controlled through:
    - a throttle valve laminating the engine intake flow ($\rightarrow$ reduction of ρ_i)
    - advanced intake valves control systems (VVA Variable Valve Actuation)

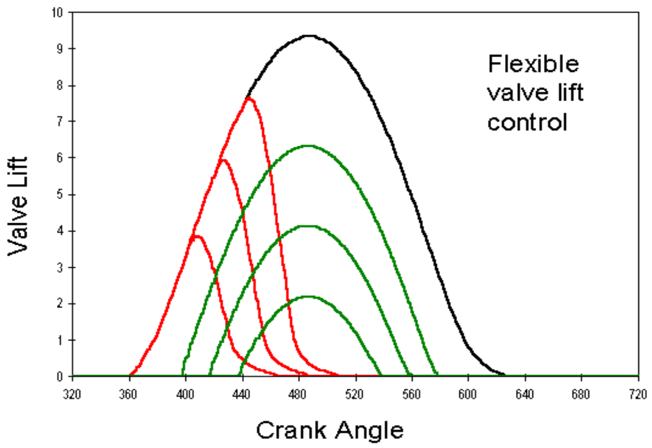
Throttle valve



$p_{man} < p_{atm}$

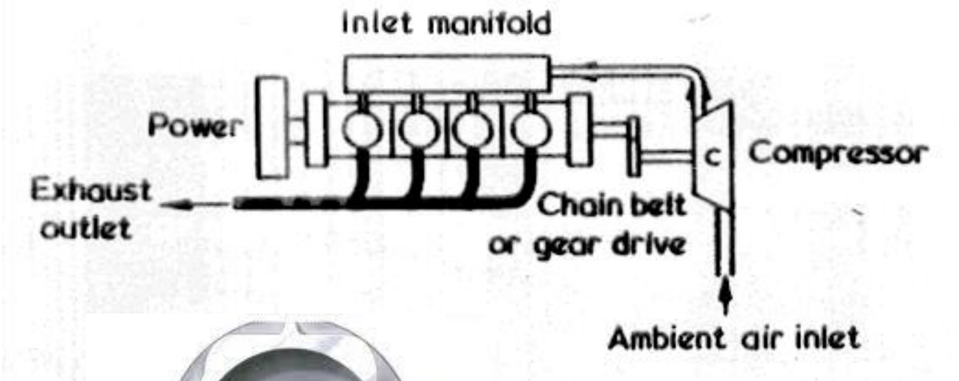
Fully flexible VVA system

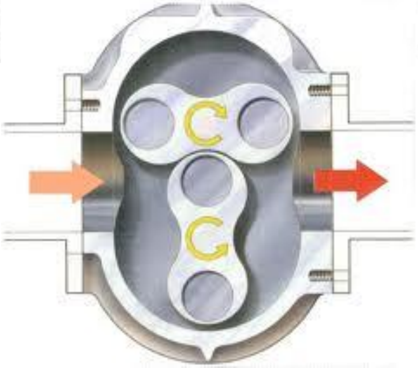


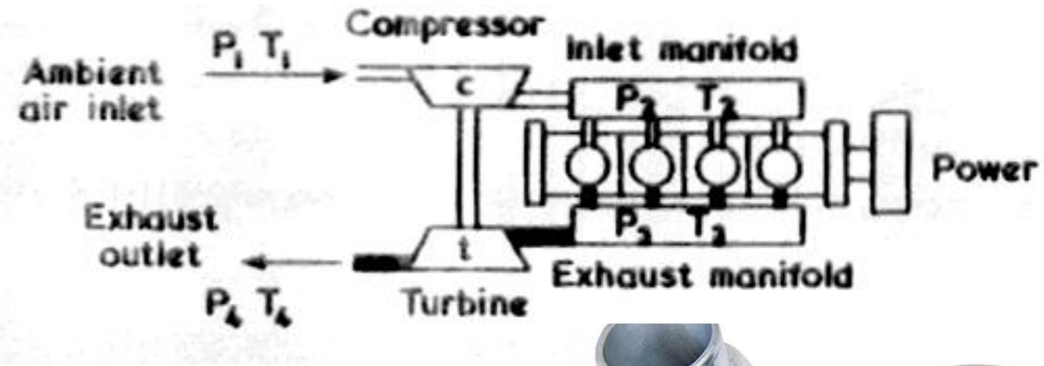


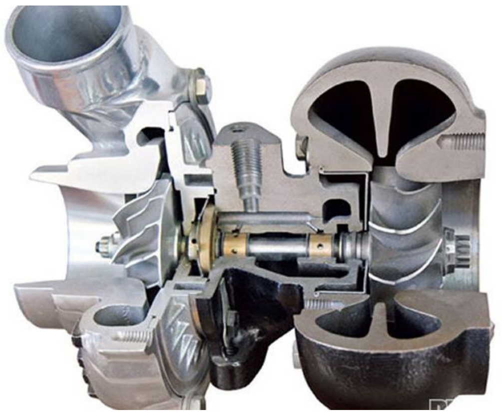
Charge boosting

- Charge boosting allows to increase the inlet charge density (ρ_i) through an upstream compressor, thus resulting in higher engine brake power per unit displacement volume (specific power).
- Two main arrangements are today used:
  - **Supercharging**, with the compressor (generally a positive displacement one) mechanically driven by the engine
  - **Turbocharging**, in which the boosting compressor is driven by an exhaust gas turbine. The compressor and turbine (generally both of radial flow type) form a self-contained unit (turbocharger)







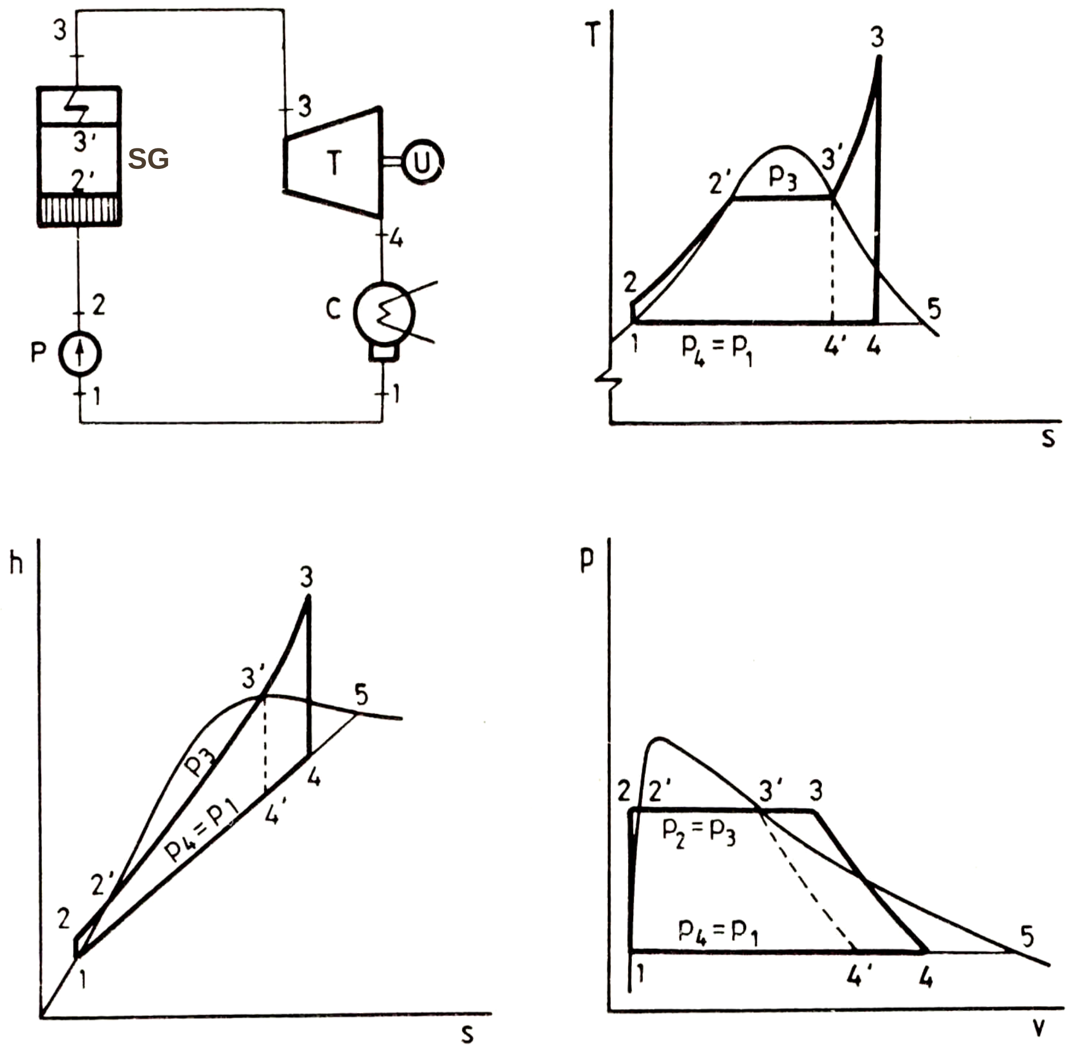


Energy conversion power plants

Steam Power Plants

The Rankine cycle

- The Rankine cycle is the reference cycle for steam power plants. It is a vapour-and-liquid cycle involving a phase change.
- In the figure a schematic of the plant circuit is reported together with the representation of the ideal Rankine cycle on the T-S, h-S and p-v diagrams with respect to the saturated liquid and vapour lines of the working fluid (generally water).
- Cycle 1-2-2'-3'-4'-1 is a saturated Rankine cycle, meaning that saturated vapour enters the turbine.
- Cycle 1-2-2'-3-4-1 is a superheat cycle (often called Hirn cycle), meaning that superheated vapour enters the turbine.



Rankine cycle efficiency

- The reversible Rankine cycle includes the following processes:
  - 1-2: isentropic compression of saturated liquid (pump)
  - 2-3 (or 2-3′): constant pressure heat addition (steam generator)
  - 3-4 (or 3′-4′): isentropic expansion (turbine)
  - 4-1 (or 4′-1): constant temperature (and pressure) heat rejection (condenser)
- The cycle efficiency can be expressed as:

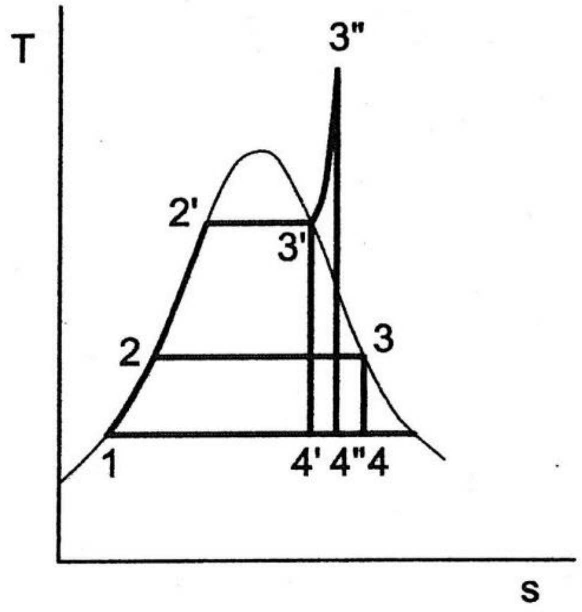
$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} = \frac{(h_3 - h_2) - (h_4 - h_1)}{h_3 - h_2}$$

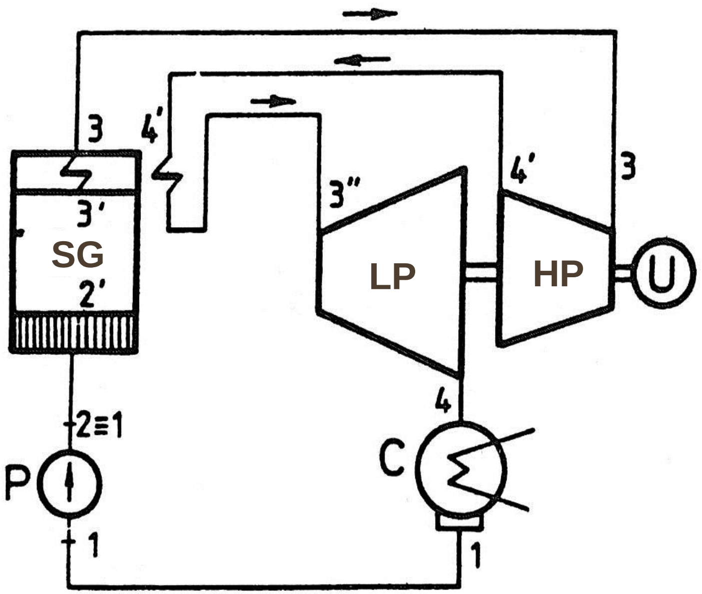
- Since the enthalpy change associated to the liquid isentropic compression ($h_2 - h_1$) is relatively small, it is possible to assume $h_2 \cong h_1$. Therefore, the reversible Rankine cycle efficiency is generally written as:

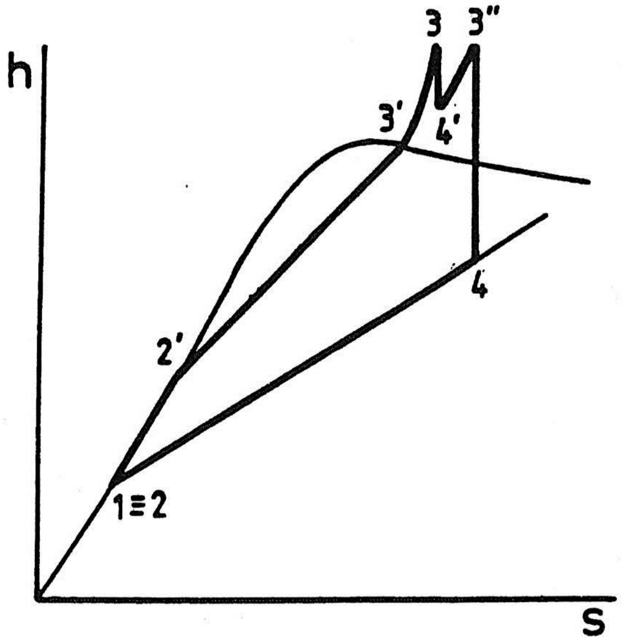
$$\eta = \frac{h_3 - h_4}{h_3 - h_1}$$

Superheat and reheat

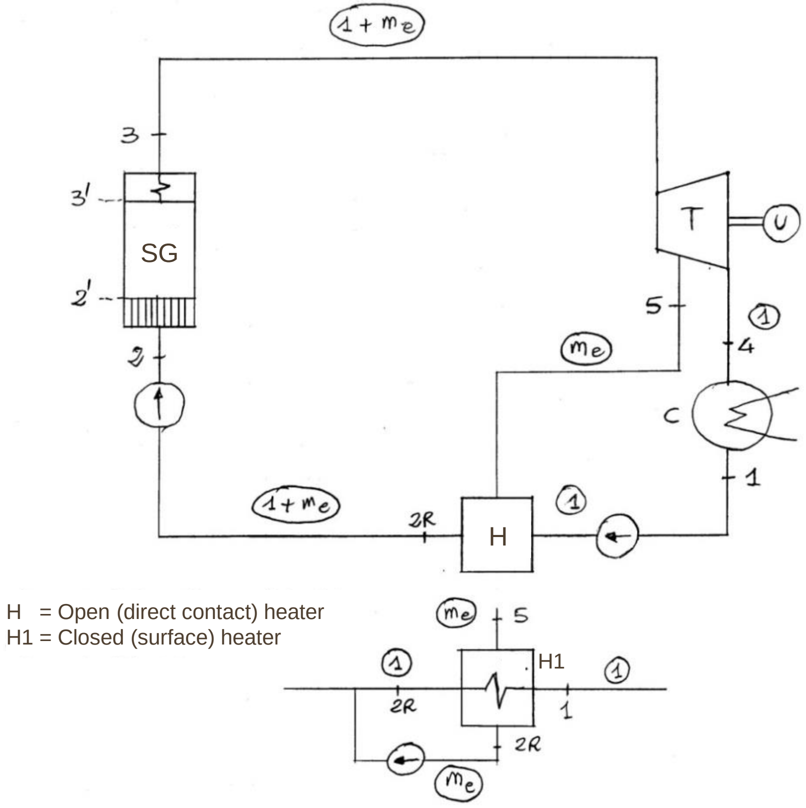
- The Rankine cycle efficiency can be improved by:
  - lowering the condensation pressure → reduction of the heat rejection temperature
  - increasing the vaporization pressure → increase of the relative heat addition temperature
  - superheating steam → increase of the relative heat addition temperature
  - reheating steam after a partial expansion → increase of the mean effective heat addition temperature
- Superheat and reheat have the additional benefit of drier vapour and lower moisture content at the turbine exit → higher turbine efficiency

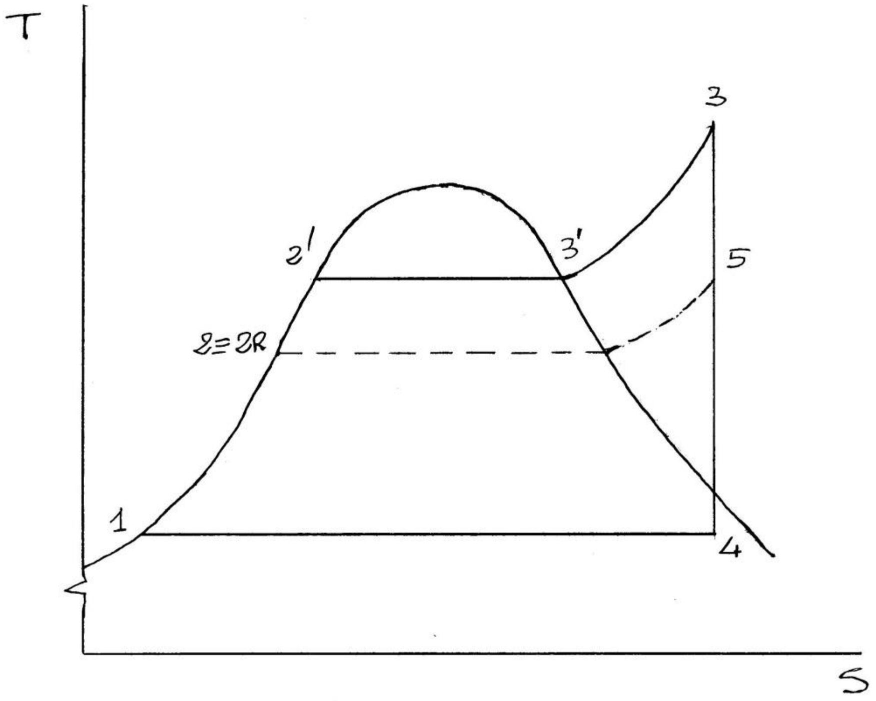






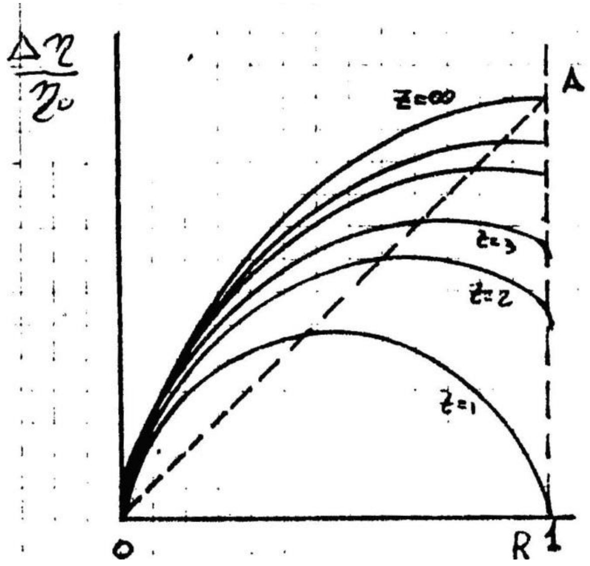
- The regeneration process involves an internal heat exchange between the expanding fluid in the turbine and the compressed liquid before heat addition, resulting in an efficiency increase.
- In a regenerative Rankine cycle some of the steam is bled, after it has undergone partial expansion in the turbine, and used to heat the liquid before the steam generator.





Effect of regeneration on cycle efficiency

- Heating of the liquid takes place in heat exchangers called feed-water heaters. Two types of heaters can be employed: open (or contact) heaters and closed (or surface) heaters.
- It is possible to demonstrate that regeneration allows to increase the cycle efficiency due to the internal heat exchange.
- The efficiency increase ($\Delta\eta/\eta_o$) is dependent on the number of bleedings and heaters (z) and the regeneration degree R (ratio between the heat added to the liquid through regeneration and the total liquid heating energy).



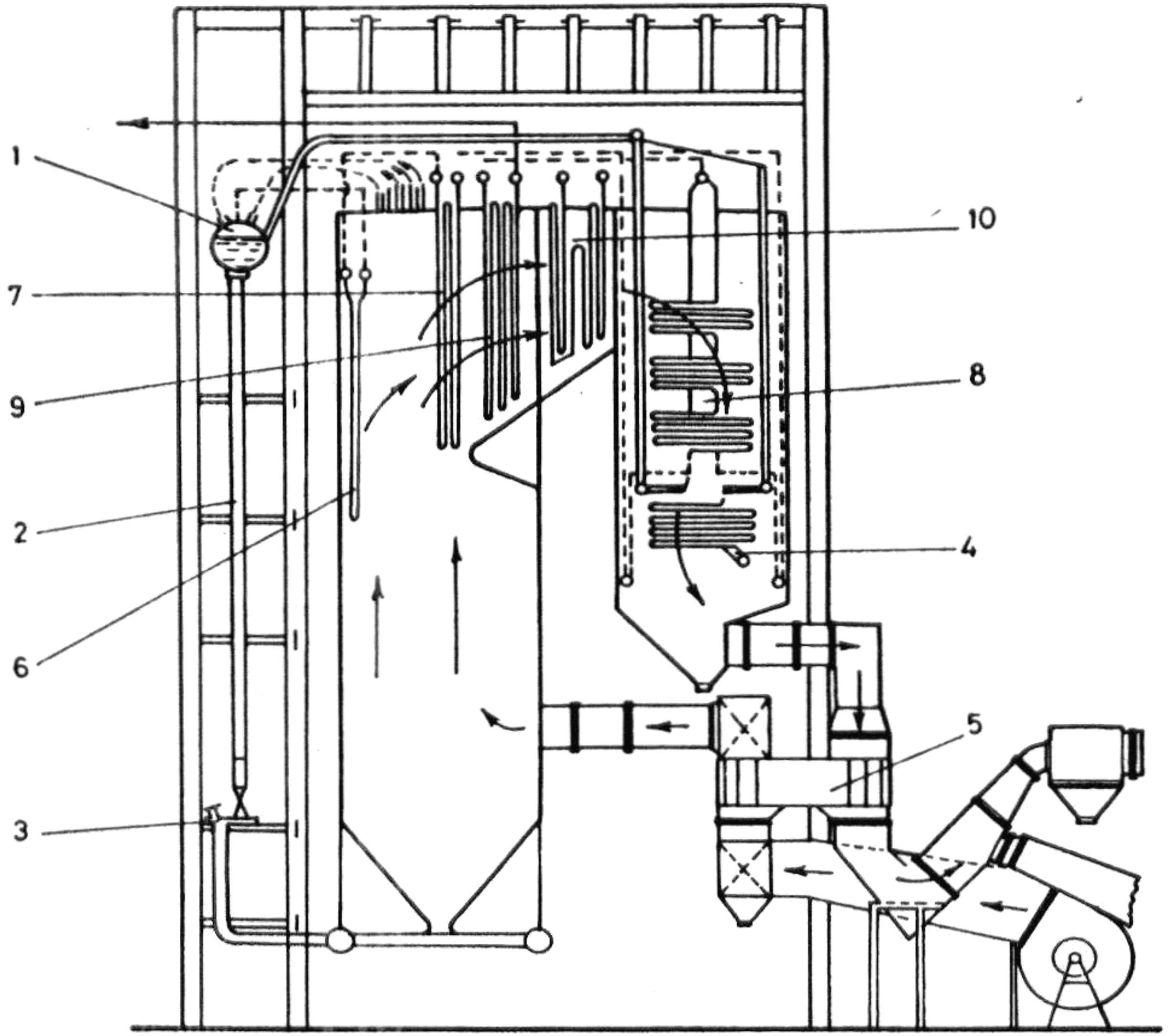
Steam generator

Steam generators classification:

- water-tube boilers
- fire-tube boilers

Schematic of a water-tube boiler:

1. Steam drum (cylindrical body)
2. Insulated down comer pipe
3. Circulating pump
4. Economizer
5. Rotary air pre-heater
6. First superheater
7. Second superheater
8. Third convection superheater
9. Fourth superheater
10. Reheater

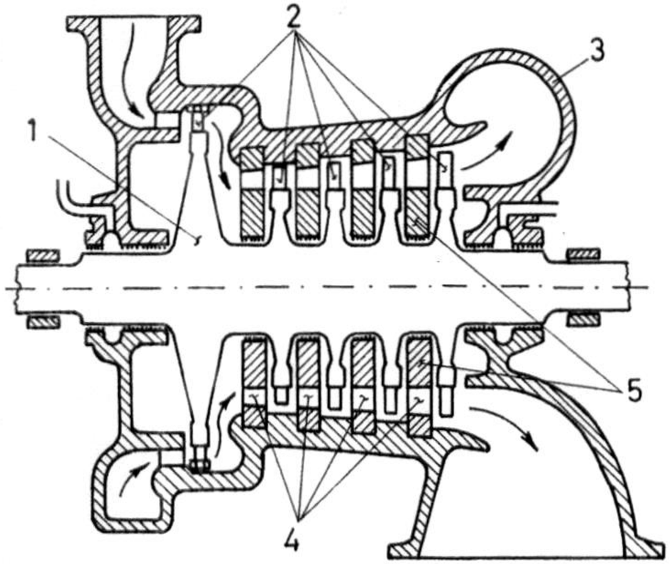


Steam turbines

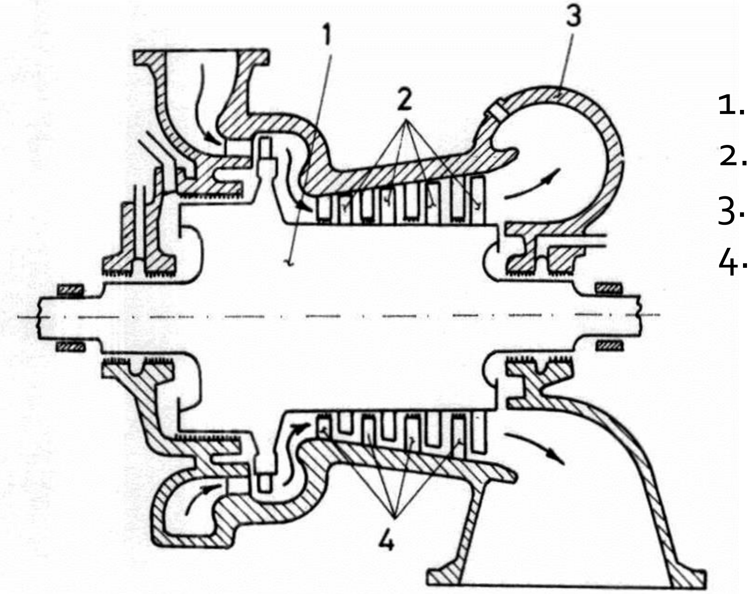
- Axial flow turbines with multiple stages are generally used in steam power plants. Each stage is composed of a row of fixed blades (called stator or nozzles or distributor) followed by a row of moving blades (rotor).
- There are two types of turbine stage:
  - **impulse stage**, in which the static pressure at the rotor inlet is the same as that at the rotor exit
  - **reaction stage**, where a change of static pressure occurs during the flow through the rotor

multiple stage impulse turbine

1. Rotor shaft and discs
2. Rotor blades
3. Upper half casing
4. Stator blades (nozzles)
5. Diaphragms

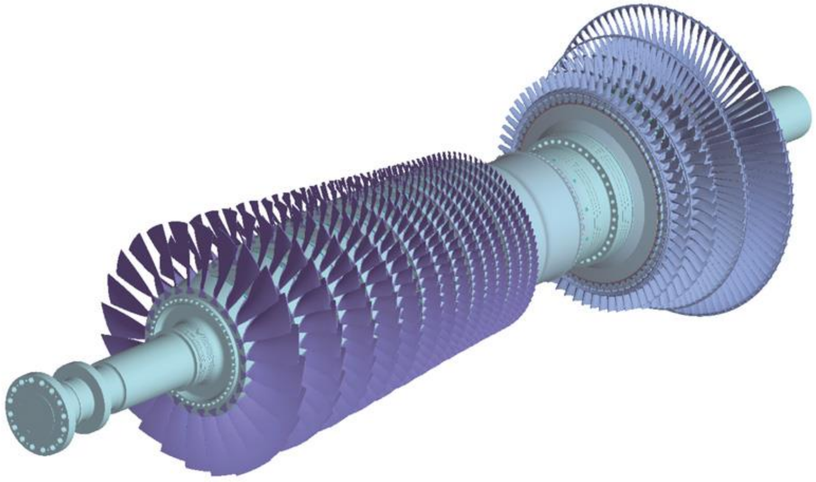


multiple stage reaction turbine



1. Drum-type rotor
2. Rotor blades
3. Upper half casing
4. Stator blades (nozzles)

Axial steam turbines for power generation plants

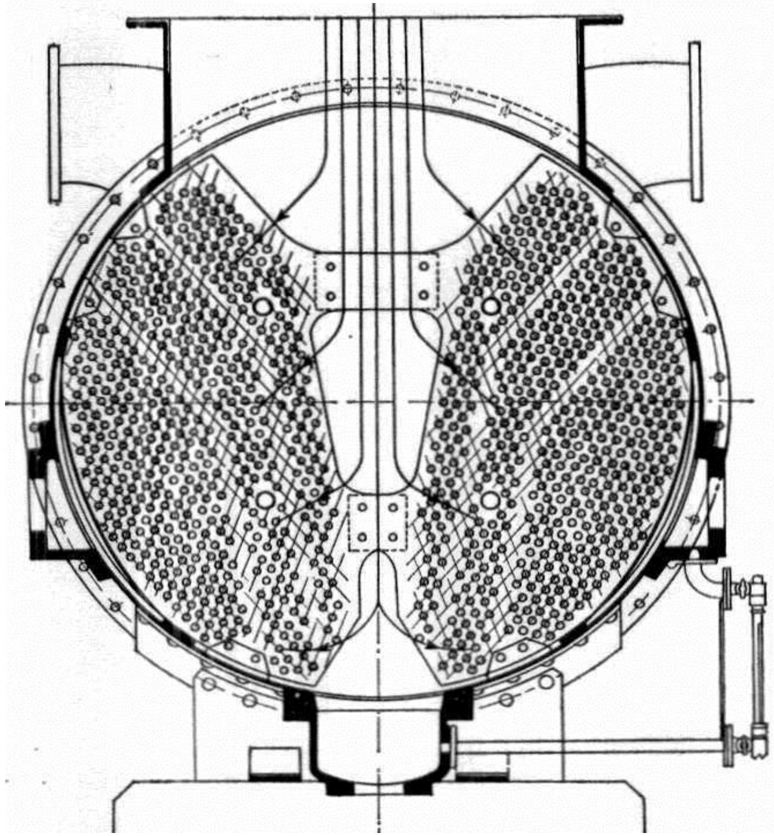


Condenser

- The primary purpose of the condenser is to condense the exhaust steam from the turbine and then recover the high-quality feed water for reuse in the cycle.
- If the circulating cooling water temperature is low enough, as is usually the case, it creates a low back pressure (vacuum) downstream the turbine.
- This pressure is equal to the saturation pressure that corresponds to the condensing steam temperature, which in turn is a function of the cooling water temperature.
- A lower condensation pressure increases the enthalpy drop and hence the work of the turbine.

Water cooled surface condenser

turbine exhaust



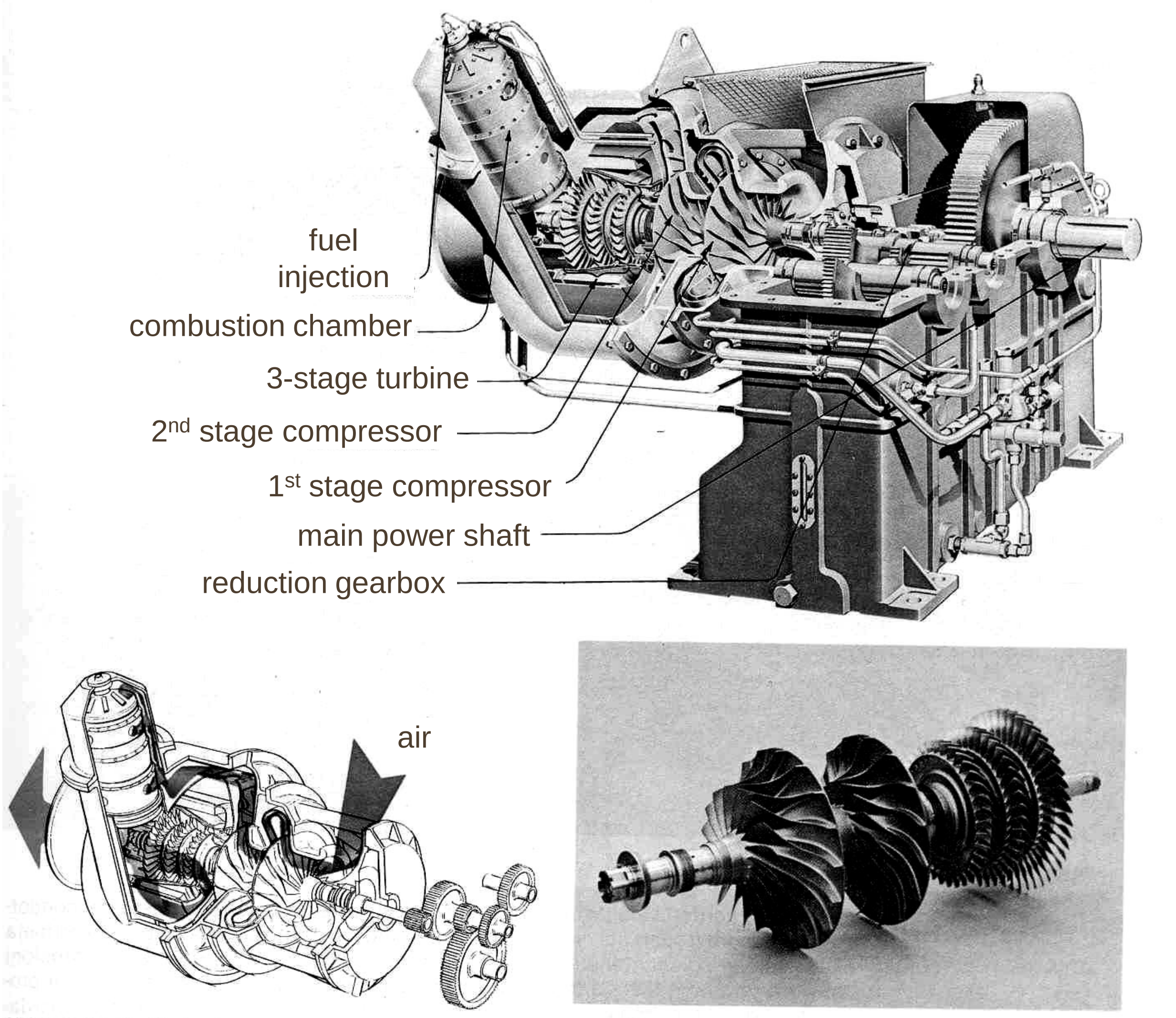
condensate exit

Energy conversion power plants

Gas Turbines

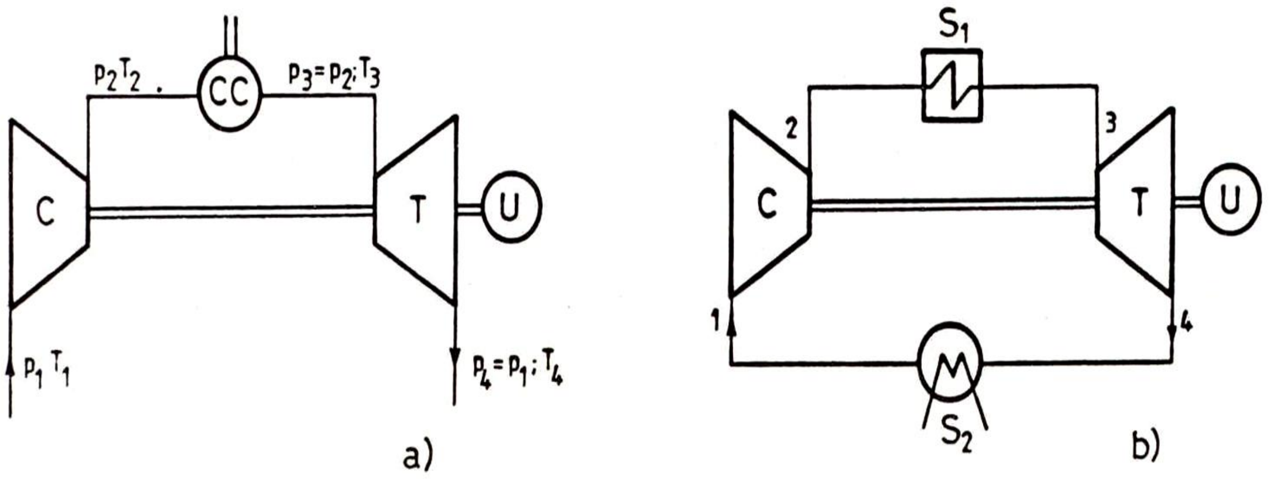
Introduction

- Gas turbines are power generating plants using a gas as working fluid. They are able to convert fuel chemical energy into mechanical work.
- Today gas turbines are widely used for powering aircrafts but also in industrial plants for driving pumps, compressors, etc. and for producing electric power.
- There is also growing interest in using gas turbines in combined-cycle configurations in conjunction with steam power plants.
- The main advantages of gas turbine plants are simplicity, compactness, lightness and low investment costs. However, the overall efficiency is lower if compared to other energy plants.
- In the figure the main components of a gas turbine plant for industrial application are shown.



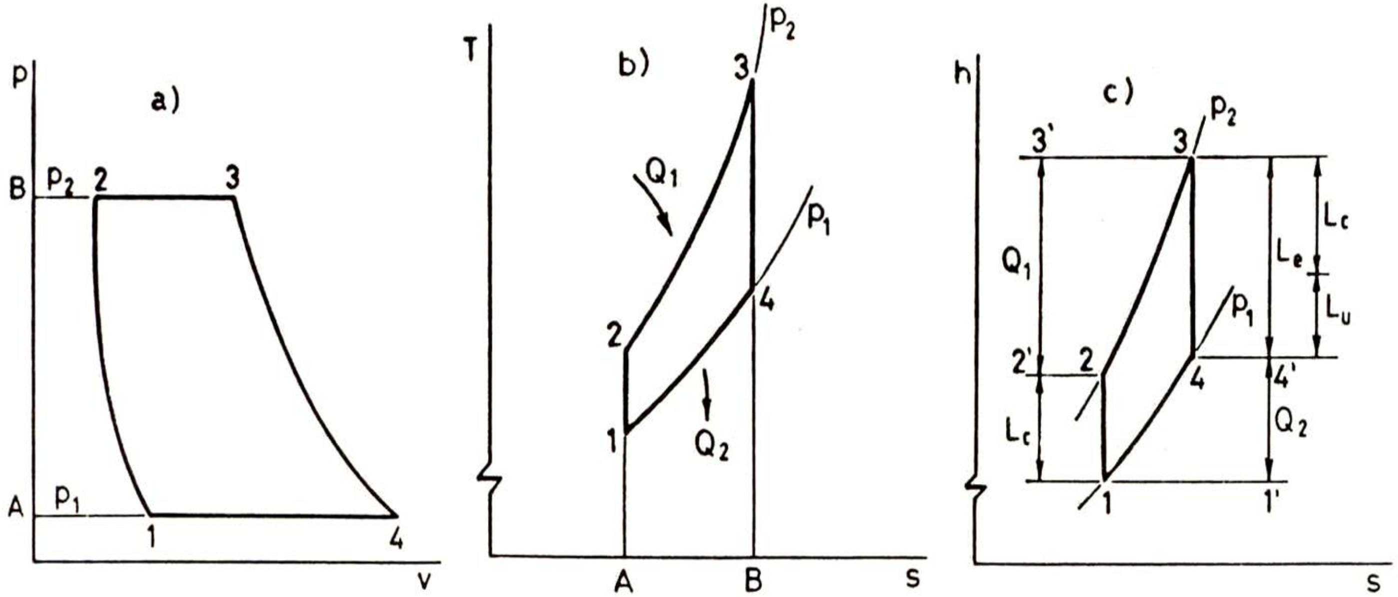
Open and closed cycle gas turbines

- In a gas turbine open cycle layout (a), air at atmospheric pressure (state 1) is drawn into a compressor (C), compressed to state 2 and forced through a combustion chamber (CC), where fuel is burned, providing thermal energy at constant pressure. The high temperature combustion gases at state 3 expand through a turbine to state 4 and are finally released to atmosphere.
- In a closed cycle layout (b) the compressed gas receives heat in a heat exchanger (S1) and, after the expansion through the turbine, is cooled in another heat exchanger (S2). The working gas is therefore re-used, can be pressurised and may be different from air.
- In any case, the expansion in the turbine provides enough mechanical output to drive the compressor and the coupled user (U).

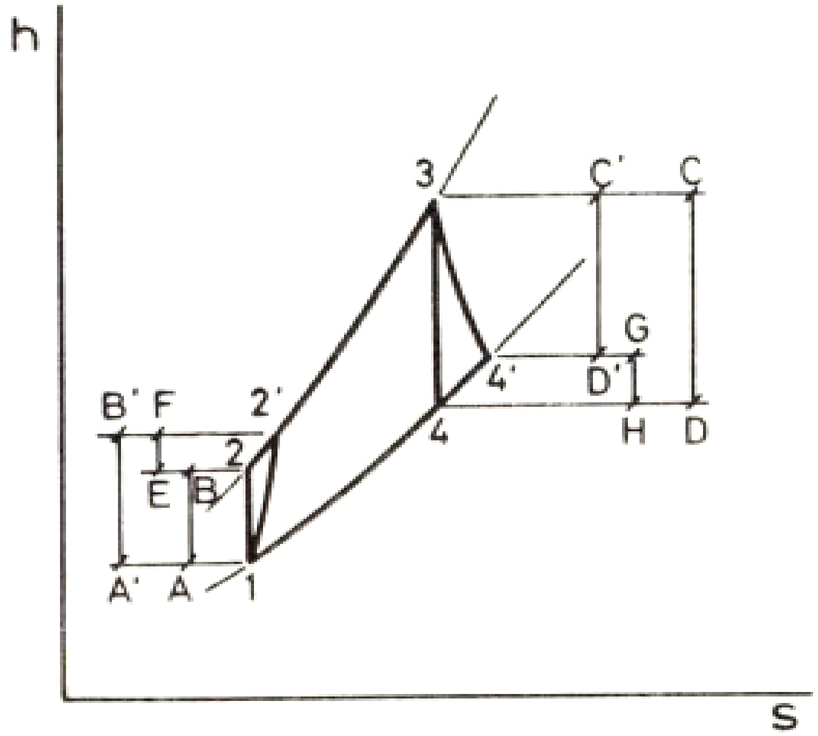


The ideal Joule-Brayton cycle

- The ideal cycle for gas turbine plants is the Joule (or Brayton) cycle. It is composed of:
  - 1→2 isentropic compression
  - 2→3 constant-pressure heat addition (Q1)
  - 3→4 isentropic expansion
  - 4→1 constant-pressure heat rejection (Q2)
- Cooling occurs from point 4 to point 1, either in a heat exchanger (closed cycle) or in the open atmosphere (open cycle).



- The actual gas turbine Joule-Brayton cycle is characterized by several losses:
  - fluid-dynamic losses in the compressor and turbine
  - thermal losses
  - pressure losses
  - losses due to cooling air flow
  - mechanical losses
- The lost energy in the compressor and turbine is converted into heat, involving an entropy increase in the actual compression and expansion processes.
- Since the process in fluid machines is generally assumed as adiabatic, the isentropic (or adiabatic) efficiency of compressor and turbine (η_c and η_t) is used to measure the degree of degradation of energy in these devices.

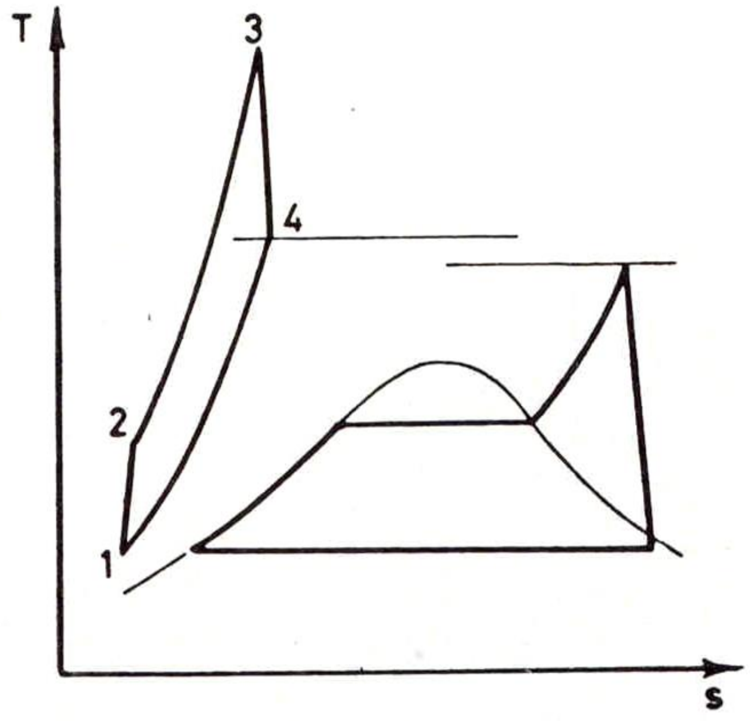


$$\eta_c = \frac{W_{cs}}{W_{ca}} = \frac{h_1 - h_2}{h_1 - h_{2'}}$$

$$\eta_t = \frac{W_{ta}}{W_{ts}} = \frac{h_3 - h_{4'}}{h_3 - h_4}$$

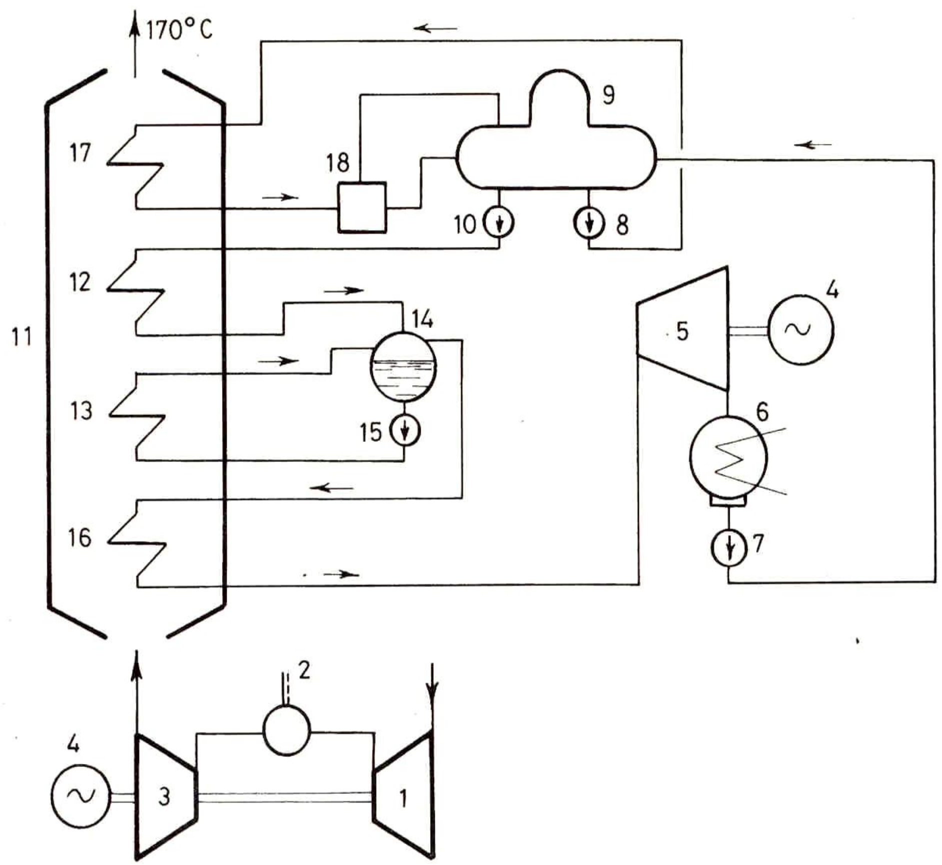
Combined cycle plants

- To overcome the limits of both steam and gas turbine plants, they can be combined in a single power generating plant, maximizing the synergies between the two technologies.
- In particular, a good way to overcome the main thermodynamic limit of the Joule-Brayton cycle, that rejects heat at high temperature (resulting in low efficiency levels), is to bottom the gas cycle by a steam cycle, that recovers the heat exhausted by the gas turbine.
- Beside both high efficiency and high power outputs, combined cycles are characterized by flexibility, quick part-load starting and high efficiency over a wide range of loads.
- In last decades several combined cycle plants have been installed worldwide, with overall efficiency levels always higher than 50%.
- New generation combined plants with advanced turbomachines and optimized steam cycles often achieve overall efficiencies up to 60%.



Combined cycle plant with heat-recovery boiler

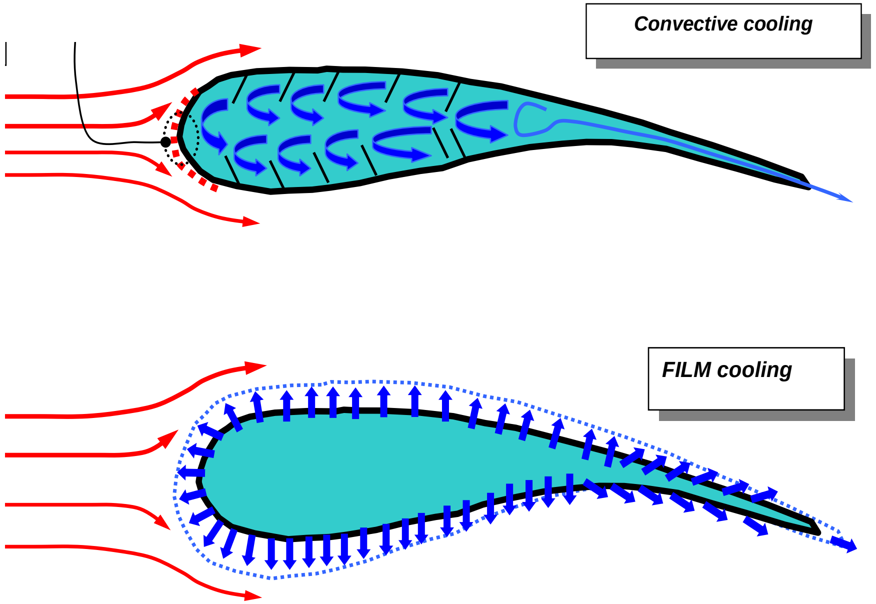
- In the most common combined cycle plant scheme, a simple gas turbine cycle is used with the turbine exhaust gas going to a heat-recovery boiler to generate superheated steam. The steam is used in a standard steam cycle. Both gas and steam turbines drive electric generators.

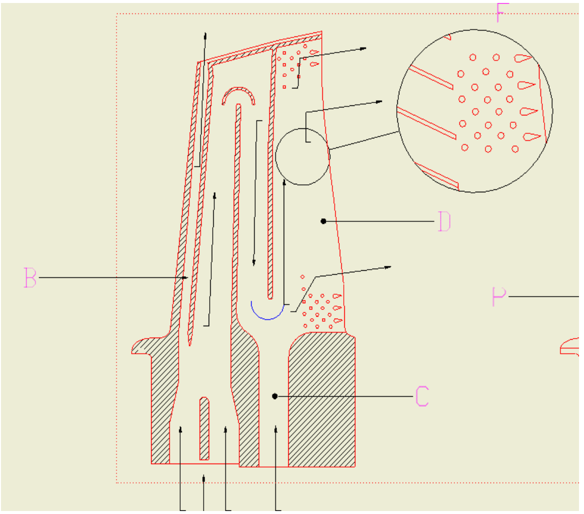


1. Compressor; 2. Combustion chamber; 3. Gas turbine; 4. Electric generator; 5. Steam turbine; 6. Condenser; 7, 8, 10, 15. Pumps; 9. Gas separator; 11. Heat-recovery boiler; 12. Economizer; 13. Heating pipes; 14. Cylindrical body; 16. Superheater; 17. Low pressure economizer; 18. Separator.

Gas turbine design for high temperature

- Since both the useful work and the overall efficiency of gas turbine cycle increase with T_3, it is evident that turbine inlet temperature should be higher and higher. As a consequence the problem of the material strength at high temperature has to be faced.
- The components that suffer most for a combination of high temperatures (continuous in time), high pressures and chemical attack are those of the turbine first stages.
- To overcome this problem heat resistant materials (cobalt-based alloys with high chromium content) and precision casting are used, firstly adopted in aircraft applications.
- Even if new materials are also being developed (ceramic materials are able to stand up to 2300 K but have bad mechanical properties), during the past decades the greatest progress to increase turbine inlet temperature was achieved by blade cooling.
- Turbine blade cooling is often performed using air brought from the compressor as coolant fluid. Convection and film air cooling can be used, often together.
- In convection cooling air is forced to flow inside the blade in channels suitably designed and then discharged into the main gas flow.
- In film cooling air flows through holes from the inside of the blade to the outside boundary layer to form a protective insulating film between the blade and the hot gases.


Convective cooling
FILM cooling

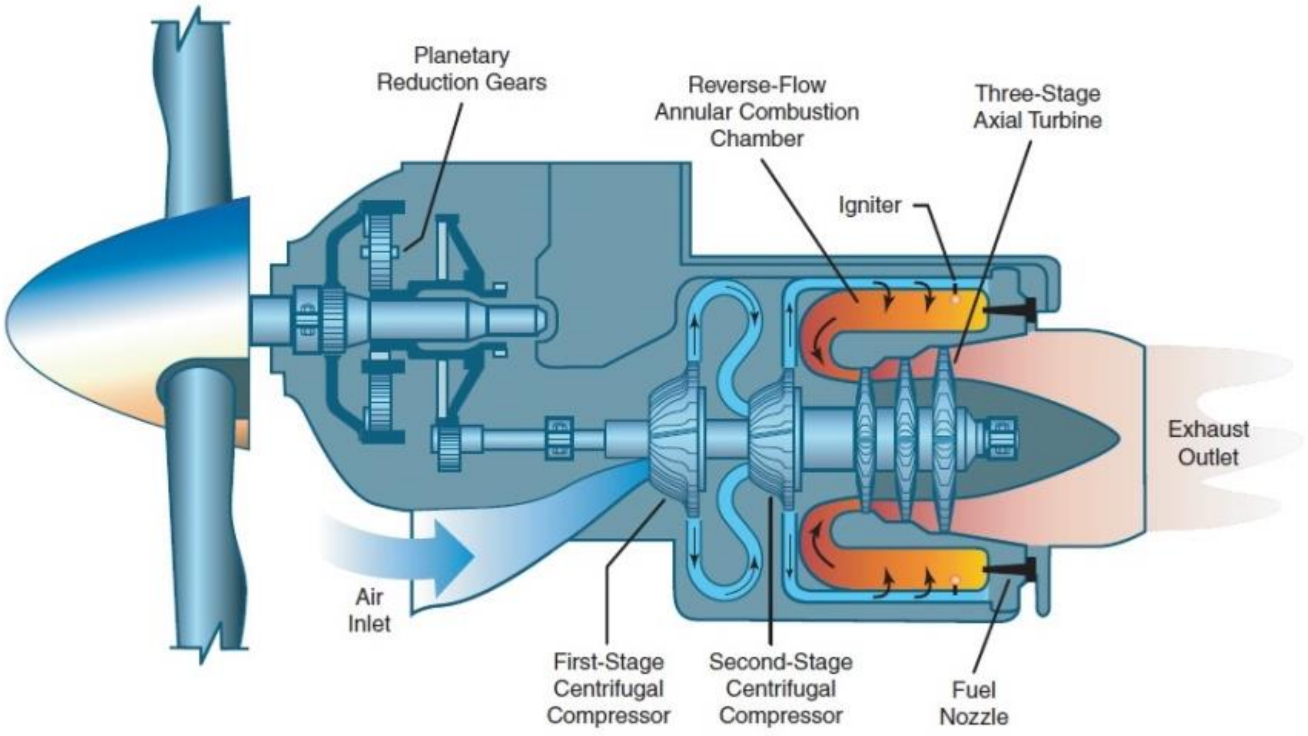

B
C
D

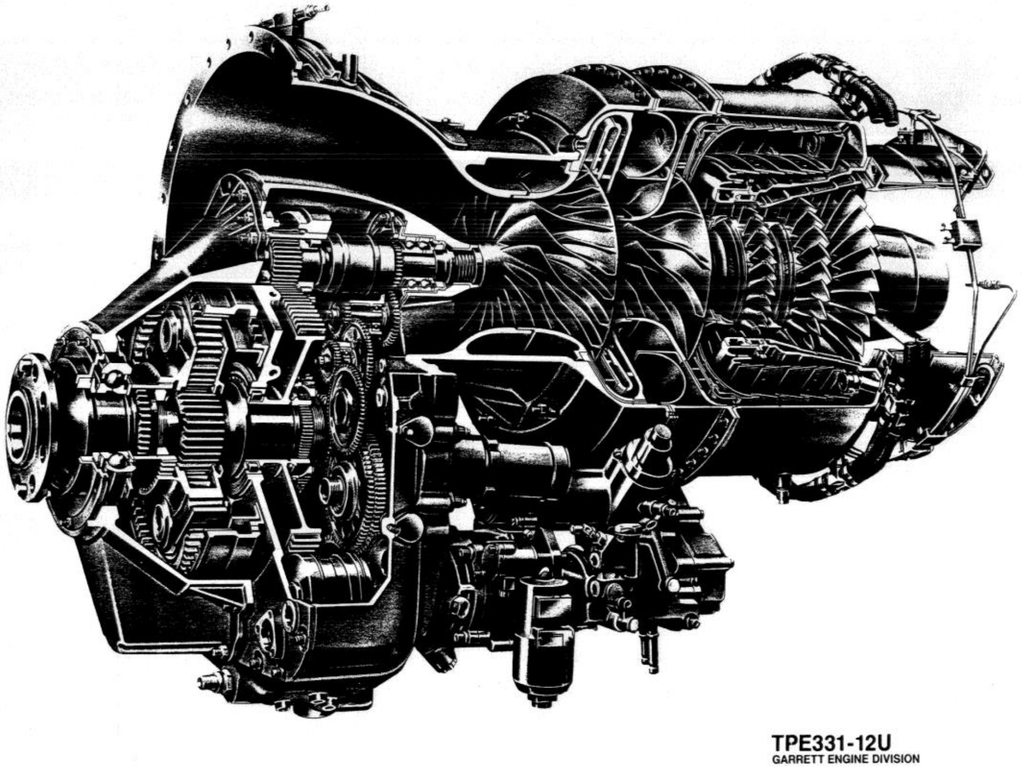
Gas turbine applications

- Gas turbines are today widely used in different applications. The power size ranges from 30 kW to over 400 MW. It is possible to distinguish between:
  - **Aircraft propulsion gas turbines**, with low weight, small frontal section to reduce drag and good efficiency, to decrease fuel consumption and therefore the fuel weight carried by the aircraft. Hence they are designed for high β and T_3 levels, with complex cooling systems and advanced materials and fluid-dynamic solutions.
  - **Heavy duty (or industrial) gas turbines**, designed just for industrial use and often used to produce electric energy. In this case low plant costs are more important than reduced weight and bulks, hence complex design and costly materials are avoided. In some applications for electricity generation, aero-derived gas turbines are used, derived with minor changes from aircraft units. They are more expensive but have high efficiency and reduced operating costs.
  - **Micro-cogeneration gas turbines**, for distributed generation of energy. They are small generation units that can provide at the same time electric and thermal energy that can be used directly for civil heating or cooling or for industrial processes.

Aircraft turboprop engines

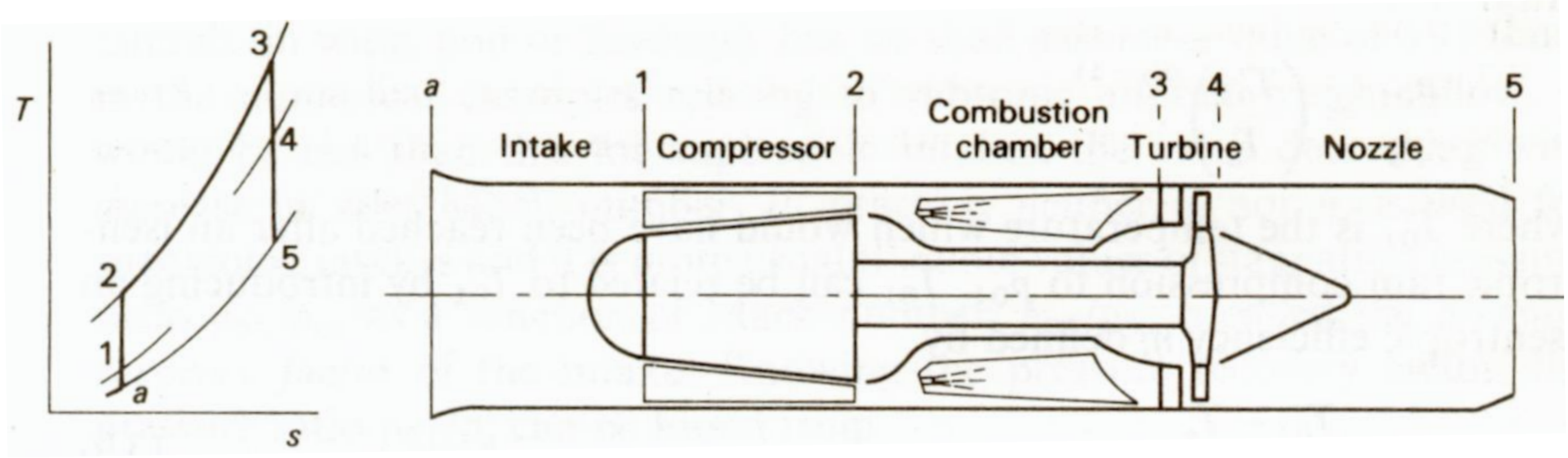
- A turboprop engine is a gas turbine unit that drives an aircraft propeller. The propeller is generally coupled to the turbine through a reduction gear. Turboprop engines are mostly used on small subsonic civil aircrafts with flight speeds usually ranging between 400 and 600 km/h.





Aircraft turbojet engines (1/2)

- In aircraft turbojet engines the turbine just drives the compressor, without any net work output.
- Air at first is compressed in the diffuser, where it is decelerated and its relative kinetic energy (due to the aircraft velocity V) is converted into pressure rise (a-1).
- Air is then further compressed in the compressor (1-2) and heated in the combustion chamber (2-3).
- Gases resulting from combustion first expand through the turbine (3-4) and then through the jet nozzle, where they are accelerated and forced out at high velocity (V_g).

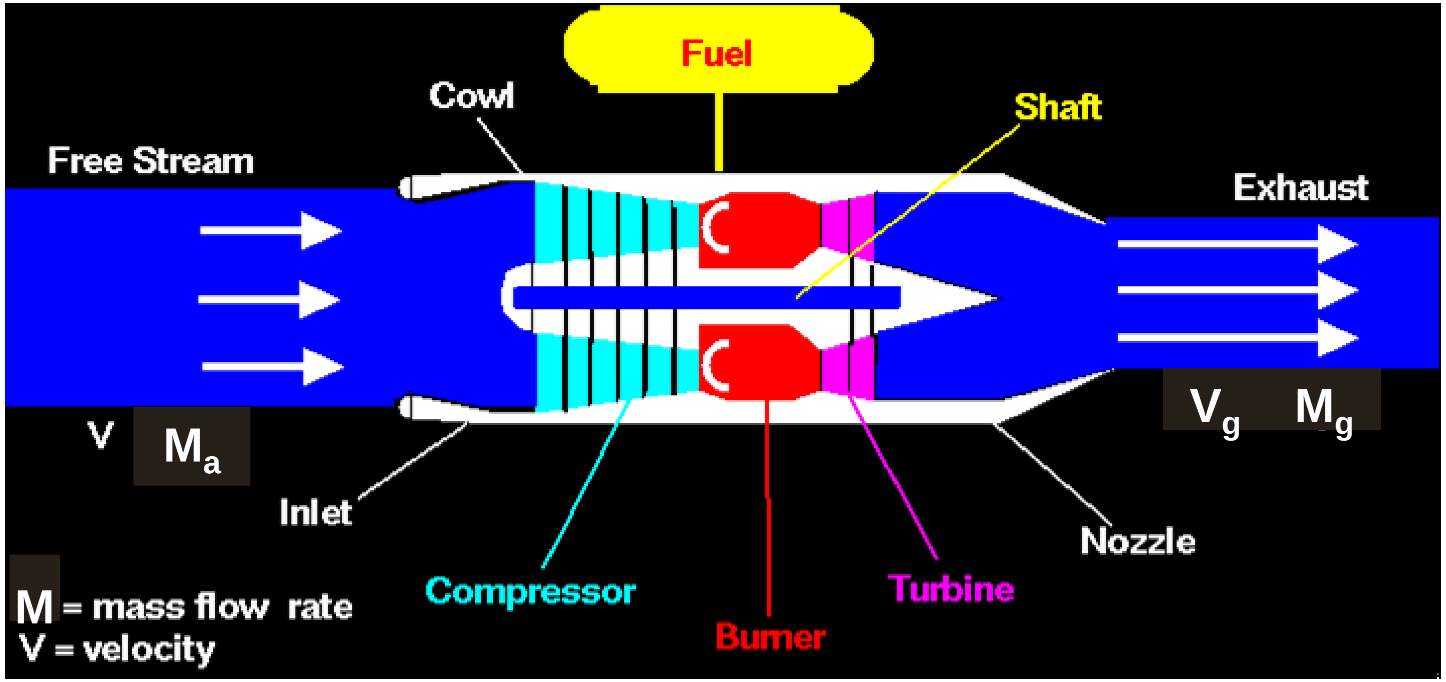


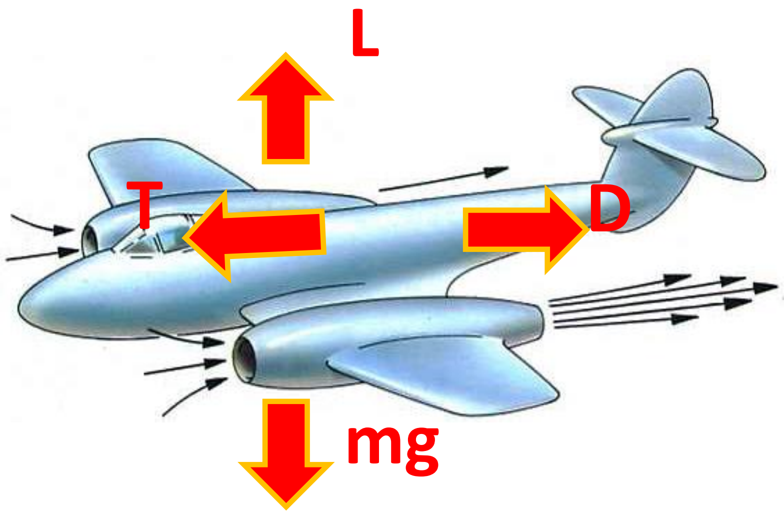
Aircraft turbojet engines (2/2)

- Due to the momentum conservation in an isolated system, a thrust T is generated, given by:

$$T = M_g V_g - M_a V \cong M_g (V_g - V)$$

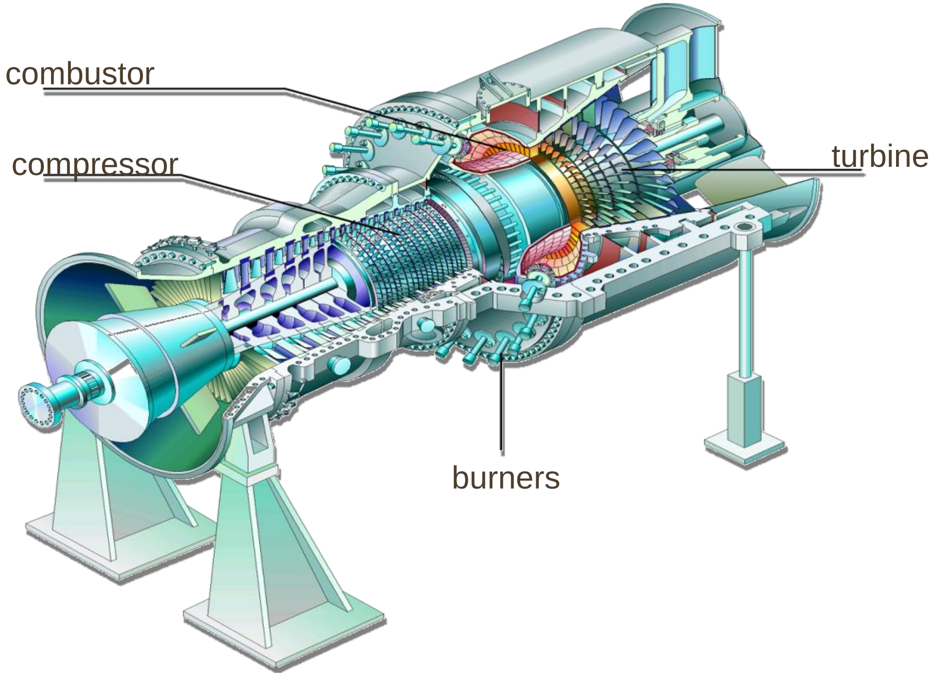
- The aircraft flying in the air at the speed V is subjected to the drag force D
- In order to allow the aircraft flying at the velocity V the thrust T must balance the drag force D.





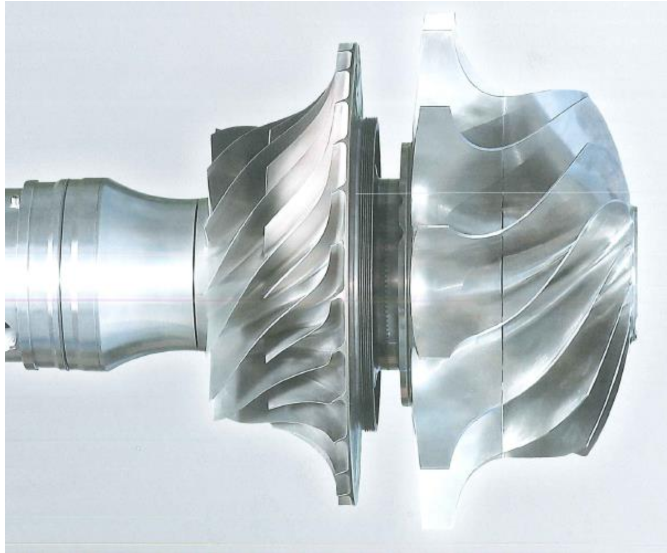
Heavy duty (industrial) gas turbines

- Heavy duty (or industrial) gas turbines are generally characterized by a fundamental and heavy design. In this case, the requirement of low plant cost is more important than the need of small weights and bulks. Generally they are designed for a compression ratio β closer to the maximum work than the maximum efficiency level, with a limited number of stages to reduce the assembly costs.
- A different approach is instead used in aero-derived gas turbines, that are derived with minor changes from aircraft units. They are characterized by lower weight and better efficiency, use higher β and T_3 values but they are more expensive.



Micro-cogeneration gas turbines

- The distributed generation of energy is becoming more and more interesting from the economical and environmental point of view for the possibility of installing, nearby the site of use, small generation units that can provide at the same time electric and thermal energy that can be used directly for civil heating or cooling or for industrial processes. This is called micro-cogeneration.
- The main advantages of micro-gas turbines are:
  - Very high global efficiency (up to 75% including electrical and thermal energy)
  - Low emissions (CO, NO_X, CO_2)
  - Long useful life (> 60.000 hours)
  - Low cost
  - Simple installation
  - Simple maintenance
  - Simple operation
  - Simple and remote control
  - High reliability



Design data

Generator power output	100 kW
GT gas turbine pressure ratio	Beta = 4.5
Turbine inlet temperature	950 C°
Air flow rate	0.8 kg/s
Gas Turbine efficiency	0.30
Air fuel ratio	110
Rotational speed	70.000 rpm
Compressor diameter	130 mm

Energy conversion power plants

Hydraulic Plants

Specific work and power of hydraulic plants

- Hydraulic energy power generation (hydropower) has been used since ancient times to grind flour and perform other tasks. Today hydropower is the most widely used form of renewable energy accounting for about 16 percent of global electricity generation. Modern hydraulic power plants use the potential energy of water to operate turbines driving electric generators.
- If 1 and 2 designate the extremity inlet (upper) and outlet (lower) sections of the plant layout, the work exchange (per unit mass) in the open system is:

$$W_{12} = (h_1 - h_2) + (c_1^2/2 - c_2^2/2) + g\,(z_1 - z_2)$$

- Since enthalpy (h) and kinetic energy ($c^2/2$) variations are generally negligible, the work can be written:

$$W_{12} = W = g\,(z_1 - z_2) = g\,H'$$

where H′ is the geodetic head, i.e., the difference in height between the source and the water outflow

- Actual power P is given by:

$$P = M \cdot W \cdot \eta = \rho \cdot Q \cdot g \cdot H' \cdot \eta$$

where:

ρ = water density = 1000 kg/m³

Q = volume flow rate

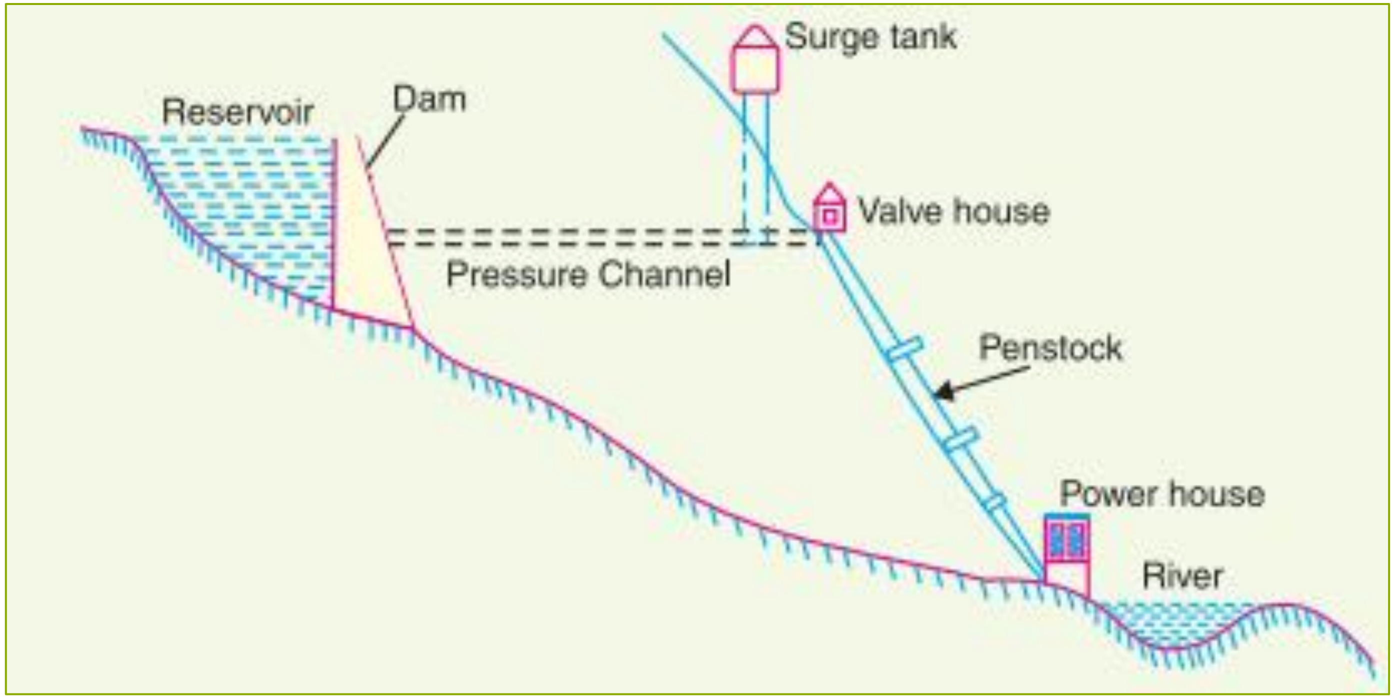
η = overall efficiency (taking account of circuit pipes and turbine losses)

Types of hydraulic plants and turbines

- There are three main types of hydropower facilities:
  - **reservoir (impoundment) plants**: they mainly use the position energy of the water collected (naturally or by a dam) in a basin or lake, at high elevation in the mountains.
  - **water flowing (run-of-river) plants**: they channels a portion of a river through a canal or penstock. They may not require the use of a dam. The water coming from upstream must be used for generation at that moment, or must be allowed to bypass the plant.
  - **pumped-storage plants**: they are similar in structure to reservoir plants and move water between reservoirs at different elevations. At times of low electrical demand, the excess generation capacity of the grid is used to pump water from a lower reservoir to an upper reservoir. During periods of high electrical demand, the water is released back to the lower reservoir and turns a turbine, generating electricity. Pumped-storage schemes currently provide the most commercially important means of large-scale grid energy storage.
- The hydraulic turbines are power generating fluid machines that convert the energy of water supplied by a hydraulic plant into mechanical work.
- Hydraulic turbines may be classified into:
  - **impulse turbines** (Pelton), where the pressure of the fluid along the rotor channels is constant
  - **reaction turbines** (Francis, Kaplan), where the pressure of the fluid drops along the rotor channels

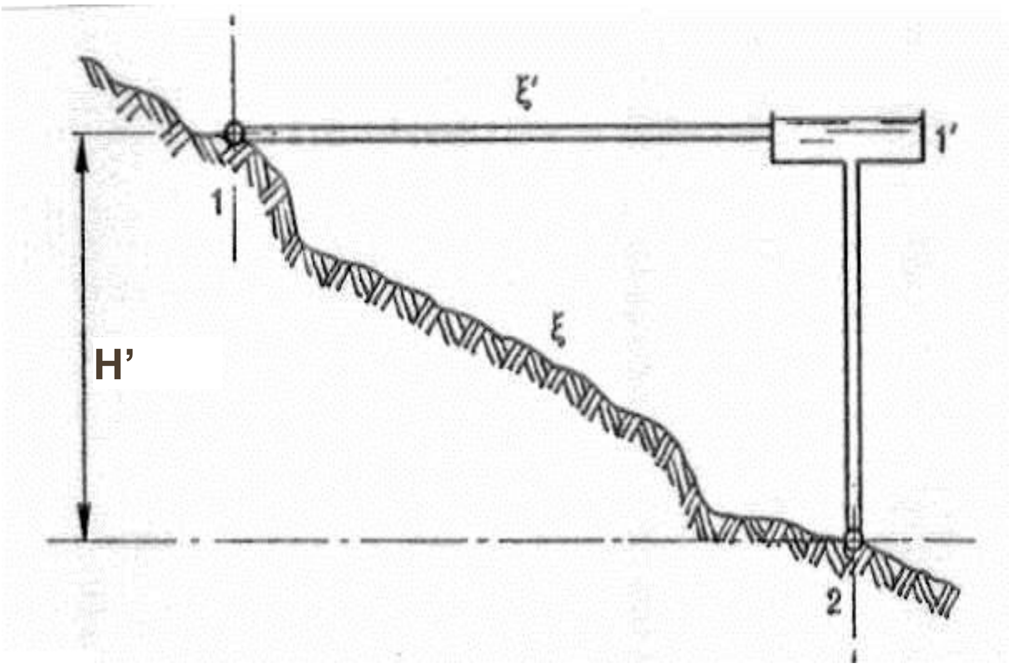
Reservoir plants

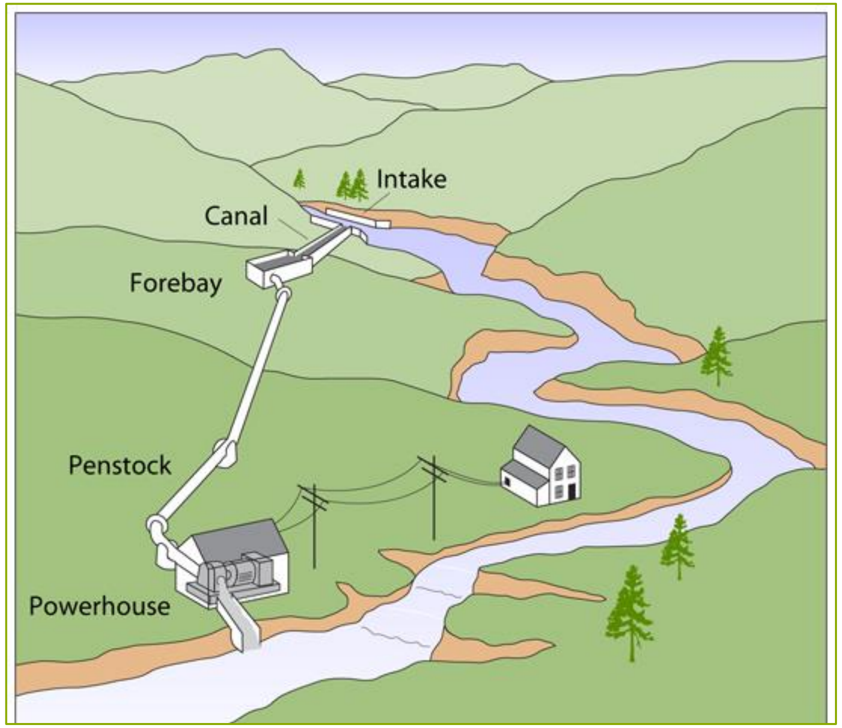
- The level differentials available are normally high (H' = 500-1500 m), while the water volume flow rates are usually quite low (Q = 0.5-50 m^3/s).
- Pelton and Francis type hydraulic turbines are generally used in this type of plant.



Water flowing (run-of-river) plants

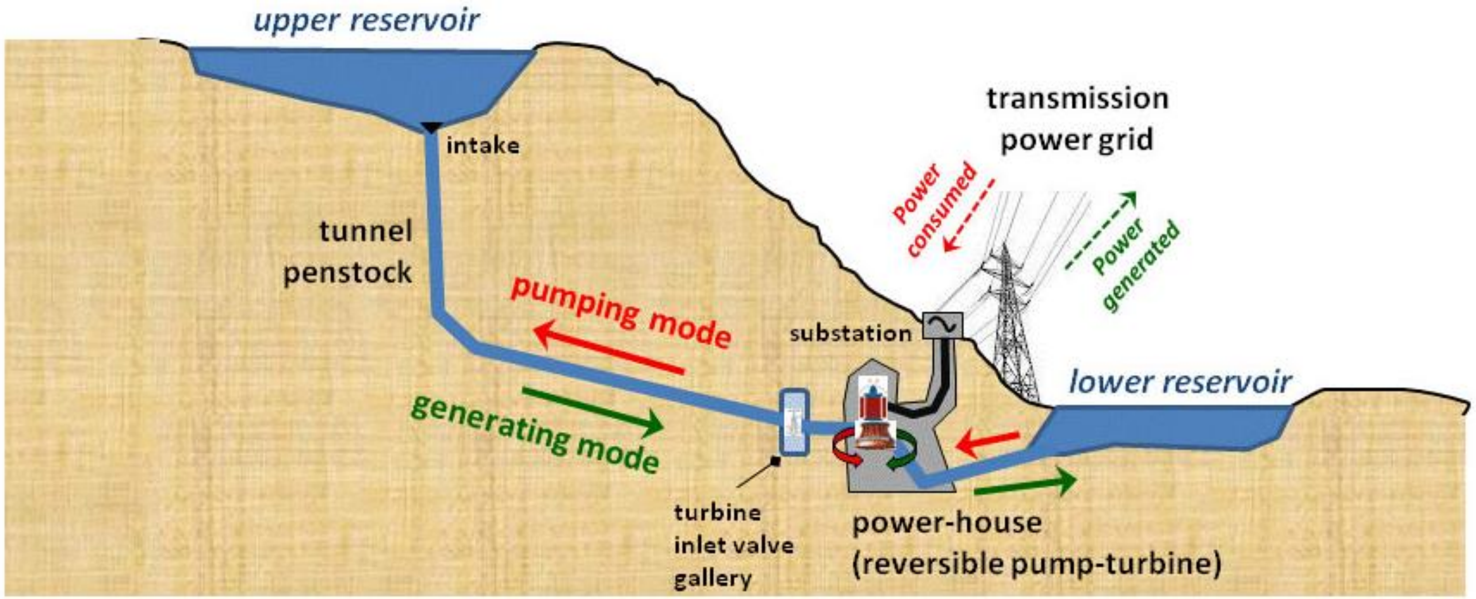
- In this case the geodetic heads are normally low (H’ = 5-50 m) while the water flow rate range is extensive (Q = 5-500 m^3/s).
- Different hydraulic turbines can be used, mainly depending on the water flow rate.
- A portion of the river flow rate is diverted to an artificial canal with lower loss coefficient (ξ') than the natural one (ξ).





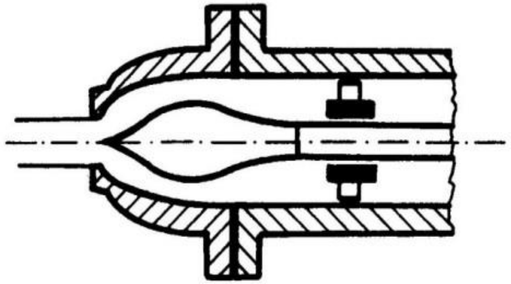
Pumped-storage plants

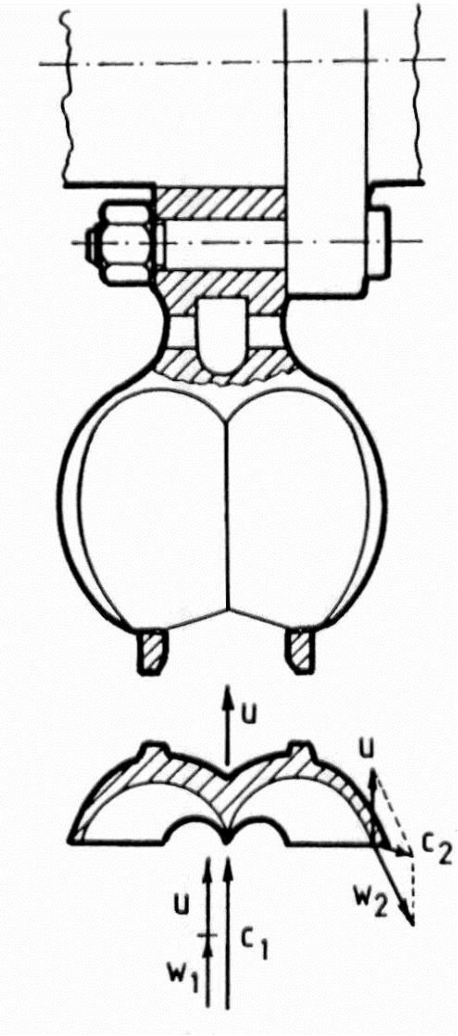
- Pumped-storage plants store energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost off-peak electric power is used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power.
- Although the losses of the pumping process make the plant a net consumer of energy overall, the system is economically profitable since it allows to sell more electricity during periods of peak demand, when electricity prices are highest.



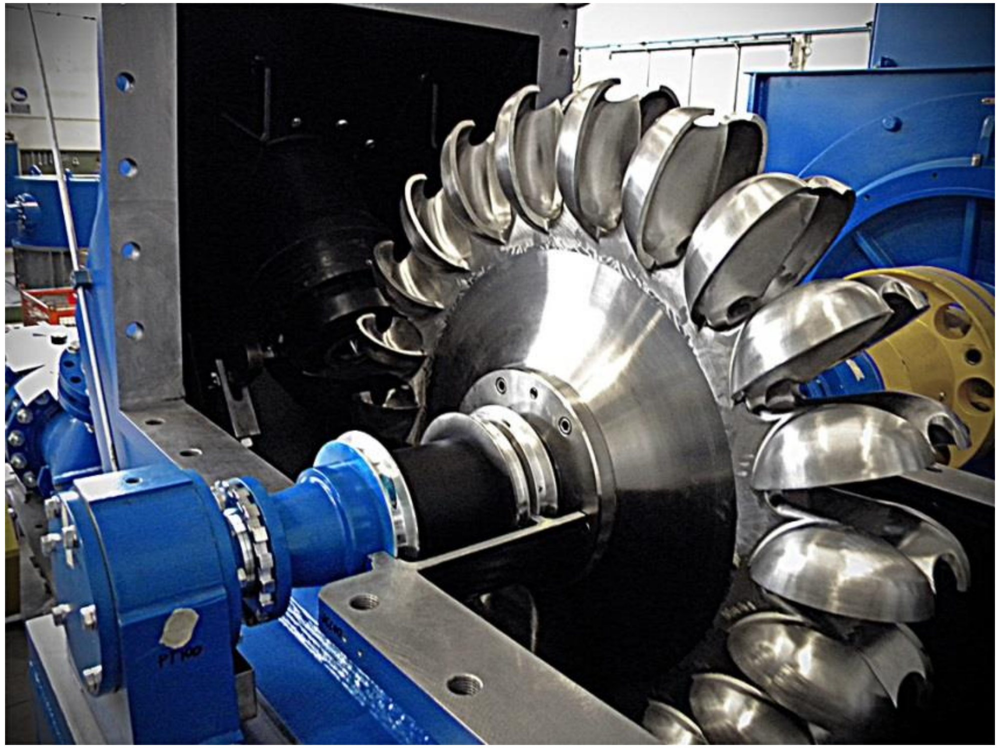
Pelton turbine (1/2)

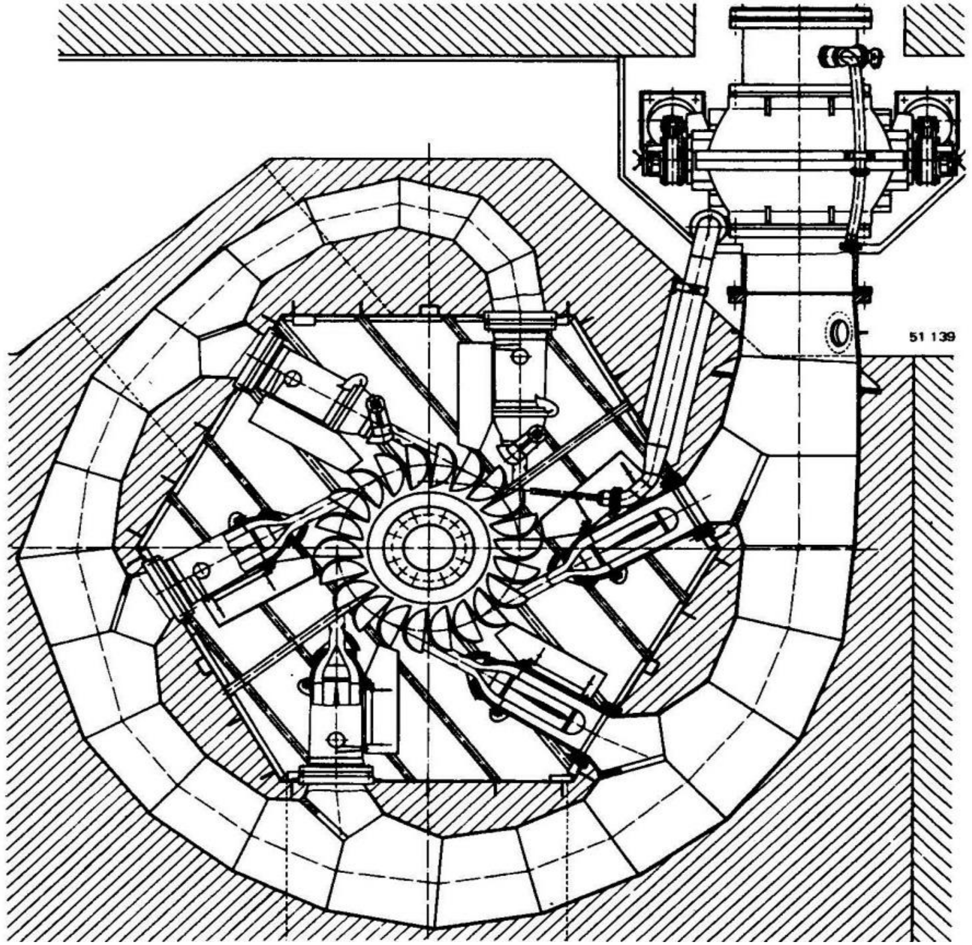
- The Pelton is an impulse type turbine. The Pelton wheel consists of a rotor, with double-spoon buckets mounted at its periphery.
- The water is transferred from a high head source through penstock pipes.
- Each branch duct from the penstock pipe ends in a nozzle, through which the water flows, controlled by a moving needle.
- All the available energy is converted into kinetic energy in the nozzle.
- The water kinetic energy is converted into mechanical work in the rotor



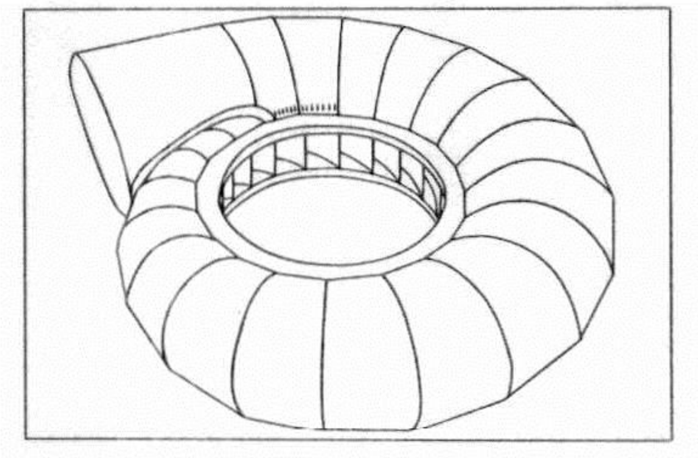


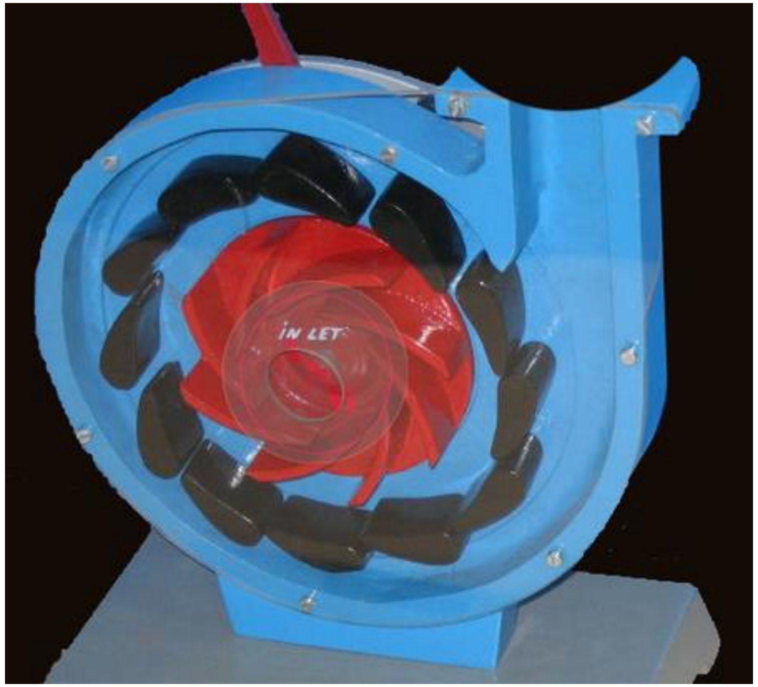
Pelton turbine (2/2)

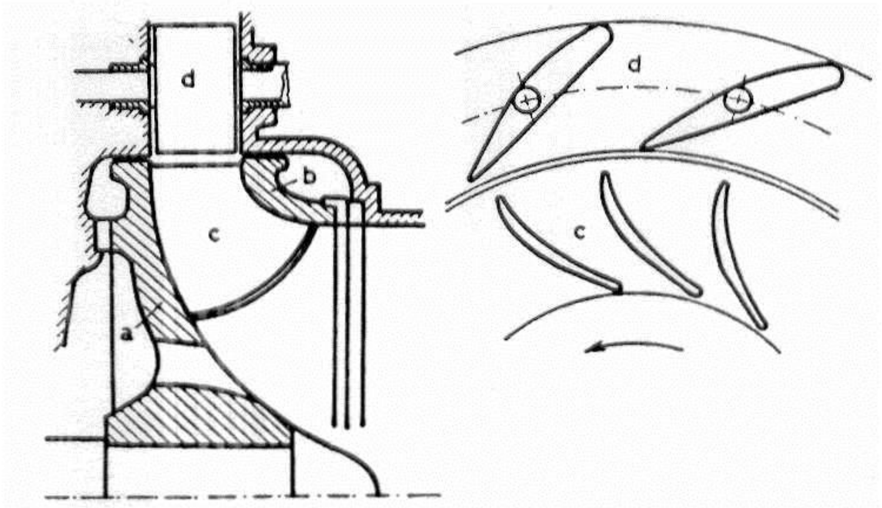




- Reaction turbines (mainly Francis and Kaplan) are used when the geodetic heads are relatively low (H' < 150-300 m) and the water flow rates are high (Q > 10-30 m^3/s).
- The Francis turbine is a radial inflow turbine in which a spiral casing provides a uniform distribution of water around the distributor (stator) circumference. The water, from the spiral casing, is guided into the runner (turbine rotor) by a number of distributor blades.

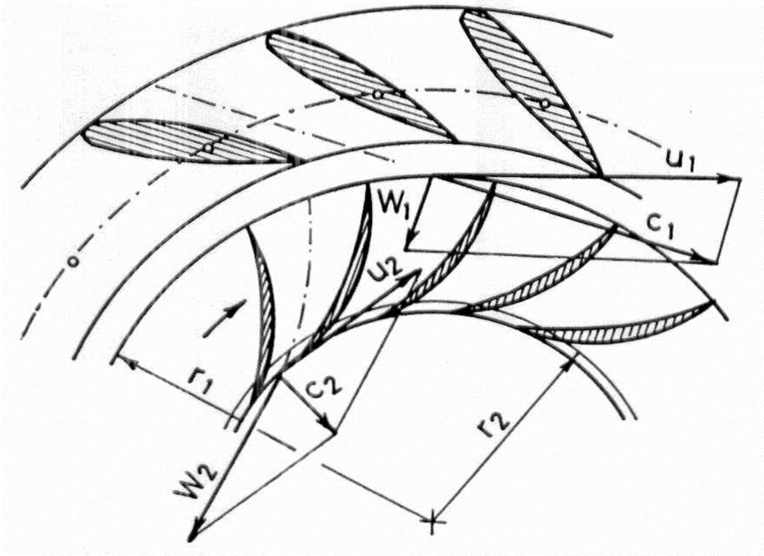






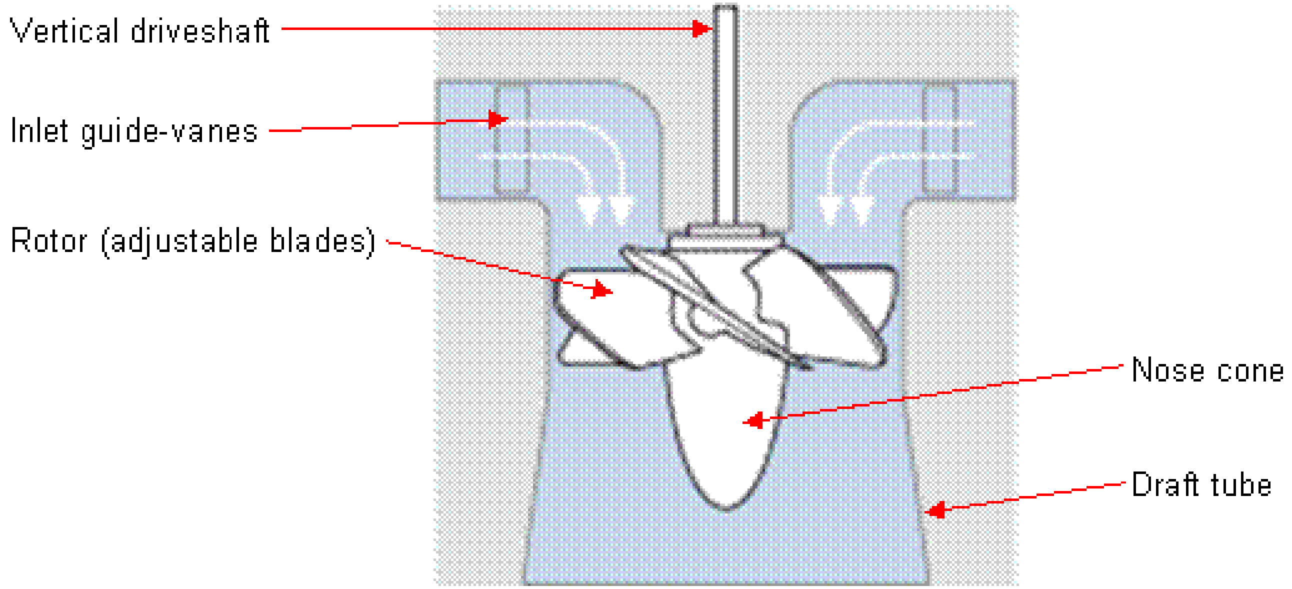
Francis turbine (2/2)

- Flowing through the distributor vanes, the water is accelerated transforming part of its pressure energy in kinetic energy and reaching a correct velocity directed tangentially to the rotor blades.
- The distributor blades can be rotated about fixed pivots by a servo-mechanism, so that the volume flow rate can be controlled. At any load, the distributor blades are turned at the best angle, so that the flow enters the runner without any impact.



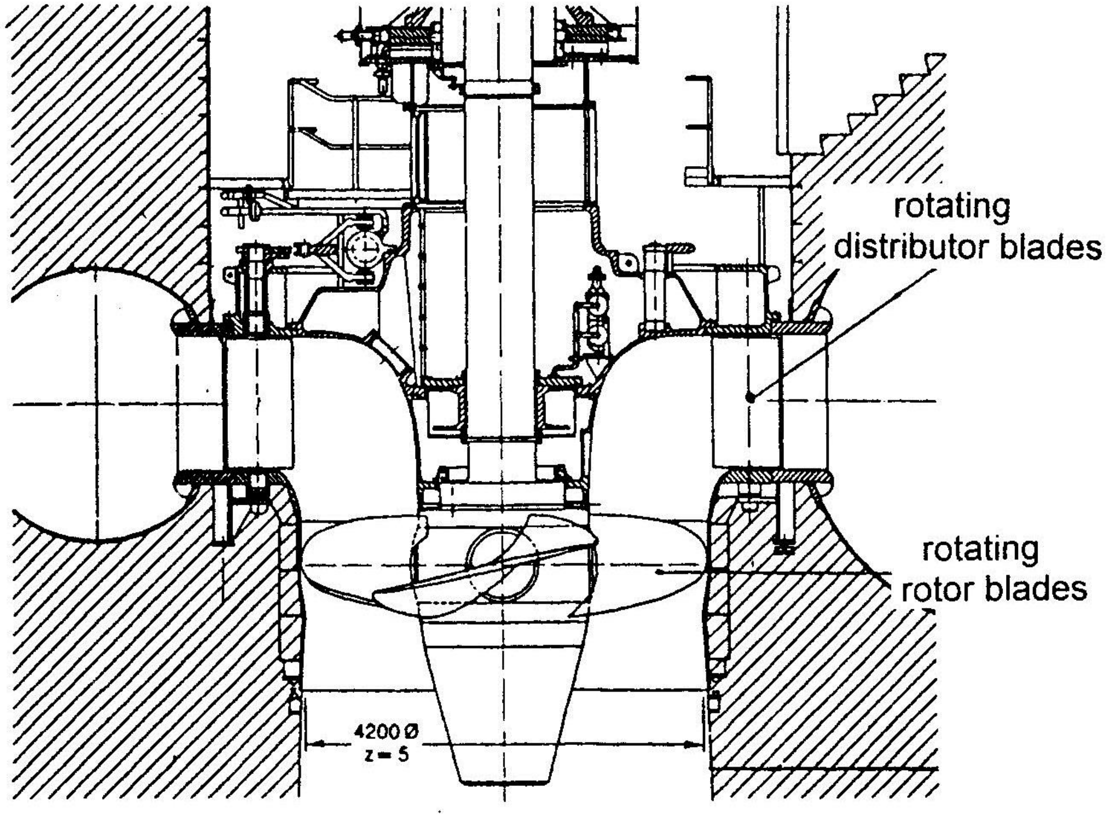
Kaplan turbine (1/2)

- Increasing the volume flow rate and decreasing the geodetic head, the shape of Francis turbine rotor changes: the radial development of the rotor blades decreases while their axial extent increases, in order to handle higher flow rates.
- For the highest water flow rates, Kaplan reaction turbines are used. In this case, not only the distributor blades are rotating , but also the rotor blades are adjustable and can be turned about pivots fixed to the runner, so that the triangles of fluid velocity are optimised at any turbine load.



Kaplan turbine (2/2)

- Kaplan turbines are used for small geodetic heads (H' = 5-40 m) and very high water flow rates (up to 50 m^3/s). Power output ranges from 5 to 200 MW.



Thank you for the attention!

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