Background

1 - General principals

Two main types of machines are used to move fluids or create rotary movement:
- piston machines,
- machines that we generally call "turbines".

Piston machines work based on the principle of the volume contained inside a cylinder changing when a piston travels from one end to the other and back again. This movement compresses or expands a fluid, generally a gas.

Piston engines are equipped with mechanisms that transform a straight-line motion into a rotary motion and vice versa. These generally complex mechanisms usually consist of connecting rod assemblies, but there are other systems such as camshafts, swash plates, and so on.

The pistons in these machines create friction as they rub against the cylinder wall. In order to withstand the pressure that develops in these cylinders, they are equipped with compression rings.

In most cases, including in compressors and internal combustion engines, the pistoncompression-ring-cylinder assembly has to be cooled in order to preserve the quality of the lubrication oil and keep the friction created between the various components to a minimum.

Turbines consist of a rotor equipped with blades turning in a stator. Therefore, there is no need for a mechanical system that converts a straight-line movement into a rotary movement.

Turbines cannot operate at high pressures because they do not have a system capable of varying the volumes between the blades. That is to say, the turbine is not what we call "volumetric".

But they do have one major advantage: the blades do not rub against the stator to create friction.

2 - Introduction to *TURBIVO*
The "Technology" section below explains how the advantages of the piston machines can be brought to the turbine, i.e. by creating a machine:
- without a straight-line to rotational conversion system, like a turbine,
- whose components do not cause friction, like a turbine,
- which can be used to generate volume and pressure variations, like a piston machine,
- in which the seal is created by controlled pressure losses.

Background

2 - Specific examples

2.1 - Thermodynamics of heat engines

2.11 - The laws of thermodynamics

Thermodynamics are based on the following principles:
- energy cannot be created from nothing or destroyed;
- the different forms of energy can only be converted:
- stored energy (fuel, gas, et cætera) into heat,
- heat into kinetic energy;
- heat is never fully converted into work, one of the reasons being that energy is lost by the friction that is generated when parts in movement come into contact;
- none of the natural and technical processes involved in the conversion of energy can be reversed. They all travel in the most probable direction, for instance heat only passes freely from a warmer to a colder body;
- the reverse effect, ie cold passing from a colder to a warmer body, can only be achieved by inputting energy.

2.12 - Types of transformation

Thermodynamic conversions are defined by the conditions in which they take place. Therefore, a conversion:
- at constant pressure is called an isobaric conversion;
- at constant volume is called an isochoric conversion;
- at constant temperature is called an isothermal conversion;
- without heat exchange is called an adiabatic conversion;
- without heat exchange and without friction is called an isentropic or reverse adiabatic conversion;
- with a general change of condition is called a polytropic conversion.

When studying the theoretical cycles of ideal gases, the laws governing the changes that take place use the constant developed by L. J. Gay Lussac (1778 - 1850): $PV = RT$. The constant he developed is $PV = R\ (267 + t)$, very close to $PV = R\ (273.15 + t)$.

A few years later, the Gay-Lussac law coupled with the Boyle-Mariotte law would lead to the law of "ideal gases", the state equation for which is $PV = nRT$ or $PV = NkT$, and forms the basis for simple modeling of gases in thermodynamic systems.

2.13 - Operating principle

The stored energy contained in the fuel is transformed into heat by a process of combustion which requires the presence of oxygen. This energy is converted into work using mechanical components that, when assembled together, we call the heat engine.

2.14 - Classification of heat engines

When this combustion takes place inside the engine, it is called the internal combustion engine. The work process can then progress in one of two ways and in both cases the circuit is open:

- either the work process is cyclic and each time a fresh load of fuel has to be injected and the burnt gases discharged. This is the case in so-called reciprocating piston engines;
- or the work process is continuous and the fuel load is replaced without interruption. This is the case for gas turbines.

When combustion takes place outside the engine, we talk of external combustion. In this case, the work process is continuous and takes place in a closed circuit. This is because the engine fluid can remain chemically unchanged while undergoing changes to its condition, but without having to be replaced.

Preparation of the air-fuel mixture outside the combustion chamber helps to create a more uniform mixture. We call this external or uniform mixing.

Mixing inside the combustion chamber is less satisfactory. The mixture is less uniform. We call this internal or non-uniform mixing.

When combustion is ignited by an electric spark, we call this applied ignition, but if the mixture ignites when it reaches the spontaneous ignition temperature, we call it auto-ignition.

2.15 - Thermodynamic cycles

Heat energy can only be transformed into kinetic energy if the engine fluid changes condition.

These changes are generally shown by diagrams that express two values for each condition:
- temperature increase or decrease;
- pressure increase or decrease;
- volume increase or decrease.

The diagram coordinates generally express these relationships:
- pressure-volume in a p-V diagram;
- temperature-entropy in a T-S diagram;
- enthalpy-entropy in a H-S diagram.

The study of thermodynamics has led several scientists to put forward engine cycles. We will only mention those that are still used today:
- Beau de Rochas (1815 - 1893) invented the 4-stroke compression cycle in 1862. This is the basic cycle used for modern-day four-stroke petrol engines.
N.A. Otto built an engine based on this cycle in 1867, but had to abandon his work when he was attacked in the courts for breach of patent rights.
- J. Joule 18 . . (1818 - 1889) invented the constant pressure cycle. This is the reference cycle for gas turbine engines.
- Sabathé whose forename is unknown to us, was the first to recommend a mixed cycle making use of both the A. Beau de Rochas and R. Diesel cycles. This is the reference cycle for the so-called diesel engines.

Background

2.16 - Fuel quality standards

Three categories of fuels are used in engines. Each category is suitable for use in a specific type of engine. These are:
- fuels for use in uniform mixture and controlled ignition engines;
- fuels for use in non-uniform mixture and auto-ignition engines;
- fuels for use in gas turbine engines requiring a continuous flame.

Among the fuels used for uniform mixtures are leaded petrols, lead-free petrols, liquefied petroleum gases.

These fuels have to be extremely volatile so that the air-fuel mixture is as uniform as possible. However, this volatility has itself to satisfy certain characteristics such as:
- a boiling curve giving the percentage of fuel that is transformed into a spray in relation to the temperature;
- the vapour pressure;
- the vapour-to-liquid ratio used to determine the tendency of the fuel to form vapour bubbles;
- the density of certain types or components of fuels;
- the maximum lead content;
- the octane rating indicating the anti-detonation power of petrol.

These are standardized characteristics for fuels.

Among the fuels used for non-uniform mixing is diesel, also called DERV (Diesel Engine Road Vehicle fuel) in some countries.

This is a mixture of different hydrocarbon oils whose boiling point is between 180° and 360°C.

The main characteristics used to specify a diesel fuel are:
- the density;
- the boiling curve;
- the cinematic viscosity;
- the flash point ;
- the cetane number.

These characteristics are also standardized.

The main requirements of gas turbine fuels concern:
- their viscosity;
- the quantities of any impurities, especially sulphur, sodium, vanadium and lead.

External combustion engines have the least demanding fuel characteristics. This is because the engine fluid and the combustion gases are generally different. The only requirement is that the fuel burns fast enough without leaving a residue.

2.17 - La combustion
Combustion takes place in two different ways:
- cyclically in reciprocating piston engines, after each replacement of the fuel load;

Background

- continuously in gas turbine engines.

Cyclic combustion presents most difficulties for the engineer because it has to take place with as little lag as possible. Hence, the cycle in a four-stroke engine running at 6000 rpm will take place in: 1/(6000/2/60) = 1/50 = 0.02 sec.

However, as the cycle includes suction, compression, expansion and discharge phases, and combustion can only occur during the expansion phase, this may only last: 0.02/4 = 0.005 sec.

These times are divided by around 3 in a two-stroke engine.

The ignition time is practically constant in uniform mixing and controlled ignition engines and only depends on the composition of the mixture, whereas the release of heat is primarily determined by the shape of the combustion chamber and the position of the ignition point.

The burning rate itself is determined by the diffusion process at the edge of the flame, the intensity of the turbulence and the temperature changes in the part of the fuel that has not burned.

As the duration of ignition is constant and has to take place before the expansion phase, a system has to be provided for adjusting the moment of ignition so that the energy stored in the fuel is at a maximum when it is converted into kinetic energy, ie. during the expansion phase.

Auto-ignition in engines with non-uniform mixing of the fuel and oxygen takes place just before the end of the compression phase. The fuel is then injected into the highly compressed air and heated to between 700° and 900°C.

Combustion takes place in two phases, demonstrating that this is combustion according to the Sabathé cycle:
- a phase during which the fuel injected before ignition burns: this is the input of isochoric heat according to the A. Beau de Rochas cycle
-a phase during which the fuel injected after combustion has started burns: this is input of isobaric heat according to the R. Diesel cycle.

The main requirement of combustion in gas turbine or external combustion engines is stability and regularity.

Background

2.18 - Thermodynamic efficiency

The thermodynamic yield of a heat engine depends on the quantity of heat dissipated which is, consequently, lost. It's equal to:

$$\eta = (\theta' - \theta'') / \theta''$$

Where η is the thermodinamic yield,

θ' is the quantity of heat supplied and

θ'' is the quantity of heat dissipated.

2.2 - Types of heat engine

2.21 - Reciprocating four-stroke and two-stroke petrol engines

The reciprocating petrol engine requires a uniform air-fuel mixture and uses spark ignition.

The fuel is generally petrol (gasoline (US)), but can also be a substitute product such as liquid petroleum gas.

The fuel is mixed in either the carburator, indirectly in the inlet manifold, or directly in the cylinder into which it is cyclically injected.

The mixture is periodically compressed in a working cylinder up to a pressure varying between 15 and 25 bars.

The compression temperature which is created and varies between 400° and 600°C remains below the auto-ignition threshold. Therefore, the mixture needs to be ignited in order to transform the fuel into heat energy.

Spark ignition takes place almost instantaneously. It leads to an increase in the pressure equal to approximately seven times the pressure at the end of the compression stroke, although the effective mean pressure is roughly equal to the pressure at the end of the compression stroke.

These values cannot be calculated accurately due to the number of variables that come into play simultaneously. This is one of the reasons why the manufacture of the petrol engine is largely empirical.

In a four-stroke petrol engine the fuel charge to the cylinder is injected through inlet valves. In a two-stroke engine it is injected through orifices arranged close to the bottom dead center.

The work generated is transformed into engine torque by a connecting rod mechanism at the end of the crankshaft. This connecting rod assembly is complex and requires engine idling speeds between 800 and 1200 rpm in order to prevent the engine from stalling. In turn, this leads to high fuel consumption, especially in stop/go congested traffic.

Therefore, we can observe that:
- the relationship between the maximum fatigue of the mechanical components subjected to the peak pressure and the mean fatigue of these same components is equal to p_{max} / p_{me} ;
- these components are designed to withstand a peak pressure plus a safety margin, and not the effective average pressure, which would lead to largely oversized components.

Advantages of the petrol engine:
- design mastered for decades;
- the vehicle industry's economic structures are based on this engine;
- the piston/cylinder configuration performs better at high pressures.
- requires sophisticated fuels;
- has a poor p_{max} / p_{me};
- is relatively inefficient: only approximately 30 % of the heat energy stored in the fuel is transformed into kinetic energy;
- generates relatively high toxic emissions of NO, HC, CO;
- is noisy;
- requires a gear box.

2.22 - Four and two-stroke reciprocating diesel engines

The reciprocating diesel engine uses a non-uniform air-fuel mixture.

Mixing takes place in the cylinder or in a "chamber" arranged in the cylinder head and opening into the cylinder. The Ricardo chamber is an example of this arrangement.

The engine operating cycle is comparable to the petrol engine, except that:
- the air is compressed up to 30 to 55 bars;
- the compression temperature varies between 700° and 900° centigrade in order to exceed the ignition threshold;
- injection takes place slightly before the top dead center;
- the peak pressure can sometimes rise to 200 bars, but is more generally around 150 bars, although pressures of 240 bars plus have been obtained in certain laboratory engines;
- the effective average pressure does not exceed 30 % of the pressure obtained at the end of the compression stroke in atmospheric diesel engines whereas it is limited to the pressure at the end of the compression stroke when cooling of the supercharging air is used.

Diesel engines have to operate with a higher margin than in petrol engines to take account of auto-ignition misfiring which increase the peak pressures during the next rotation.

Therefore, the high compression pressures in diesel engines due to high pressure peaks caused by spontaneous ignition require a relatively heavy power plant.

Engines with non-uniform mixing of the fuel and air have to operate with a large air surplus, therefore diesel engines have a relatively low power density even at full load.

Advantages of the diesel engine:
- design mastered for a long time;
- commercial structures are based on the use of this engine;
- the piston/cylinder configuration can withstand high pressures.

Background

Disadvantages of the diesel engine:
- high cost price on manufacture;
- poor to very poor p_{max} / p_{me} ratio;
- low power density with the cubic capacity of a diesel engine generally 1.5 times greater than a petrol engine with the same power output;
- inefficient: only approximately 30 % of the heat energy contained in the fuel is transformed into kinetic energy;
- polluting emissions: soot and burnt residues;
- noisy to very noisy;
- requires a large gear box.

2.23 - Gas turbines

The gas turbine uses a non-uniform fuel/air mixture and a continuous flame.

It is a multi-fuel engine that can accept either liquid, gas, or emulsified fuels.

The fuel/air mixture is prepared in a separate combustion chamber where an injector distributes fine droplets of the fuel into the combustive air so that the mixture maximizes the burnup rate.

Compression takes place and the work is performed by turbine blades which rotate without rubbing against their respective housings.

This configuration can be used to obtain very high engine speeds in which the gas flow reaches and sometimes exceeds the speed of sound. Even so, the design is based on maximum gas velocities of about Mach 0.8 to 0.9.

The intake air is first compressed between 4 to 6 bars, then passes through the heat exchanger in which its temperature rises, reaches the combustion chamber in which it combines with the fuel to form a gas whose temperature further increases during combustion, thus expanding. The gases use part of their energy in the turbine, another part in the heat exchanger, with the remainder dissipated into the atmosphere.

As the engine operates at relatively low pressures, powers can only be generated at engine regimes which are directly related to the size of the turbine. Thus, a gas turbine used for an automobile would run at between 8000 and 70 000 rpm.

Advantages of the gas turbine:
- multi-fuel operation;
- smooth running,
- good p_{max} / p_{me} ratio;
- favourable emission values without other equipment.

Disadvantages of the gas turbine:
- poor efficiency with less than 30 % of the fuel energy transformed into kinetic energy;
- low working pressures;
- engine speeds often much too high;

- high manufacturing cost;
- high fuel consumption;
- unsuitable for low powers;
- noisy due to the gas velocity generated;
- requires expensive gearing systems.

2.24 - Lubrification

The most widespread engine in use today has the most complex lubrication system.

Indeed, the reciprocating engine has many lubrication points, in particular the piston-compression-ring-cylinder assembly or cylinder sleeve. This is the most difficult to lubricate for two reasons:
- for as much of the fuel to burn as possible combustion has to take place at temperatures of 2000 K+;
- to prevent the piston from seizing up, the temperature of the oil used to lubricate the piston should not exceed 125°C.

In this respect, the gas turbine is more practical since the blades do not come into contact with their respective housings.

2.25 - Cooling

Burning oils lose their power of lubrication. Therefore, the reciprocating engine parts that are exposed to the heat generated by combustion have to undergo intensive cooling to prevent the oil from losing its lubricating capacity.

This cooling function evacuates more than 30 % of the heat energy contained in the fuel, which means we remove part of the heat we had input elsewhere.

2.25 - Exhaust fumes

In reciprocating engines, more than 30 % of the energy contained in the fuel is dissipated through the exhaust:
- either in the form of heat because the expanded volume of the depressurized gas being equal to the compression volume it is not greater than the compression volume in a ratio proportional to the quantity of the heat input during combustion;
- or in the form of partially or completely unburnt hydrocarbon residues, because the time-lag required for the fuel to entirely change its state is too short. 0.002 to 0.01 secs are not sufficient and the air-fuel ratio is not always favourable to satisfactory oxygenation.

In gas turbines, the time lags for the combustion to take place are too short to allow expansion and cooling to occur, and limit the losses through the exhaust. It follows that 70 % to 80 % of the energy stored in the fuel is dissipated in the form of heat, unless this heat is partly transferred to the compressed air by a heat exchanger.

Background

2.3 - Summary and conclusion

2.31 - Summary

This summary is presented in the form of the comparative table below:

Aspect compared	Reciprocating petrol engine	Reciprocating diesel engine	Gas turbine
Expansion volume / work volume ratio	equal to 1	equal to 1	more than 1
Heat exchange	impossible	impossible	possible
Choice of fuels	standardized	standardized	unrestricted
Method of combustion	cyclical	cyclical	continuous
Performances at pressure	high	high	average
Ratio p_{max}/p_{me}	poor	poor	favourable
Heat energy conversion into kinetic energy	30 to 35 % depending on circumstances	30 to 35 % depending on circumstances	20 to 30 % depending on circumstances
Losses by the cooling system	30 to 35 % depending on circumstances	30 to 35 % depending on circumstances	none
Losses by the exhaust system	30 to 35 % depending on circumstances	30 to 35 % depending on circumstances	70 to 80 % depending on circumstances
Gas emissions	toxic	toxic	acceptable
Noise level	high	high	high
Friction in the work volume	yes	yes	no
Lubrication in the work volume	dangerous	dangerous	not required
Cooling	mandatory	mandatory	not required
Gear box	mandatory	mandatory	
Speed reducer			mandatory

Background

2.32 - Conclusion

The arguments in favour of the heat engine can be summarized as follows:
- they are external combustion engines with least fuel requirements. In fact, the engine fluid and the combustion gases are often different. All that is required of a fuel is that it burns quickly enough without leaving residues;
- continuous combustion in gas turbine engines or external combustion engines has to be smooth and regular. This is the principle requirement for these engines.

Advantages of the petrol engine:
- a piston/cylinder configuration that can withstand high pressures.

Advantages of the diesel engine:
- a piston/cylinder configuration that can withstand high pressures.

Advantages of the gas turbine engine:
- multi-fuel;
- smooth operation;
- good p_{max} / p_{me} ratio;
- good emission values without special equipment.

Faced with these options, the following will be retained for our ideal engine specification. It has to be:
- an external combustion engine;
- with multi-fuel operation;
- working at high pressures and high temperatures;
- smooth and quiet;
- good p_{max} / p_{me} ratio;
- good emission values without special equipment, therefore without exhaust system;
- without lubrication in the work volume;
- without cooling of the work volume;
- without a gear box;
- without a movement converter.

The "Technology" and "Applications" sections demonstrate how this ideal specification can best be met.