UNIVERSITÉ LIBRE DE BRUXELLES

SUMMARY

Piston engines
MECA-Y401

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Appel à contribution

Synthèse Open Source

Ce document est grandement inspiré de l'excellent cours donné par Francesco Contino, Marc Overmeire et Axel Coussement à l'EPB (École Polytechnique de Bruxelles), faculté de l'ULB (Université Libre de Bruxelles). Il est écrit par les auteurs susnommés avec l'aide de tous les autres étudiants et votre aide est la bienvenue ! En effet, il y a toujours moyen de l'améliorer surtout que si le cours change, la synthèse doit être changée en conséquence. On peut retrouver le code source à l'adresse suivante

`https://github.com/nenglebert/Syntheses`

Pour contribuer à cette synthèse, il vous suffira de créer un compte sur *Github.com*. De légères modifications (petites coquilles, orthographe, ...) peuvent directement être faites sur le site ! Vous avez vu une petite faute ? Si oui, la corriger de cette façon ne prendra que quelques secondes, une bonne raison de le faire !

Pour de plus longues modifications, il est intéressant de disposer des fichiers : il vous faudra pour cela installer LaTeX, mais aussi *git*. Si cela pose problème, nous sommes évidemment ouverts à des contributeurs envoyant leur changement par mail ou n'importe quel autre moyen.

Le lien donné ci-dessus contient aussi un `README` contenant de plus amples informations, vous êtes invités à le lire si vous voulez faire avancer ce projet !

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Merci !

Contents

Chapter 1

Introduction

1.1 Classification

We find a large amount of engines in the market, small, large, different types, ... But some are dedicated to specific applications. First of all, an engine is an **energy converter** and has to satisfy some requirements (cheap, long lifetime, quick start, ...). According to the type of engines, some of them are better fulfilled. Piston engines are on average rather good for all them.

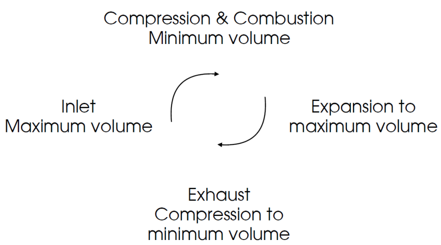


Figure 1.1

The basic principle of an engine is based on the periodic production of mechanical work, using the reaction of fuel with the oxygen of air in a confined space, which produces heat and the pressure in a variable volume produces work:

$$\begin{aligned} &\text{chemical} \to m_f.\text{LHV} = Q_{in} \to thermal \\ &\to pV = nRT \to mechanical \end{aligned} \tag{1.1}$$

where LHV is the energy content of fuel, the Lower Heating Value. The Figure 1.1 represents the closed cycle for a 4 stroke engine but can be adapted for 2 stroke.

Many classifications can be done following the size, the number of cylinder, ... But the mainly used one consists in 4 criteria:

- **Heat source:** internal or external (heat exchanger and working fluid in closed cycle)
- **Mechanism:** piston-connecting rod-crankshaft, piston-piston rod-crosshead-connecting rod-crankshaft or rotary piston-excenter shaft
- **Ignition:** spark ignition or compression ignition
- **Strokes:** 4 strokes or 2

1.1.1 Heat source

In this course, we only deal with the internal one. In this kind of source, fuel, air and the resulting combustion products are the working fluid. In the external type, the working fluid is in a closed cycle and transfers heat to an exchanger. The advantage of the external one is that we can use almost any fuel, have a more controlled combustion, but it is a more complex system and has less response to load change and there are more losses than the internal.

The internal one is produces more power, there is no need of exchanger and the mechanical part have a temperature lower than T_{max} of the cycle, is low coast and safe. Its disadvantages are vibration, noise, emissions, gases are in contact with the engine and depend on fossil fuel.

1.1.2 Mechanism

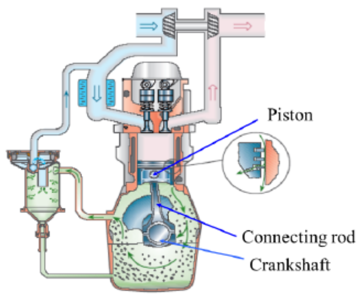


Figure 1.2

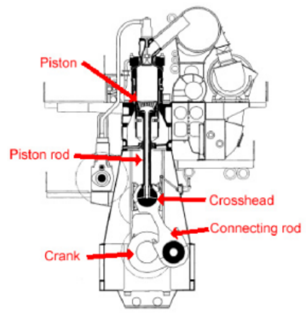


Figure 1.3

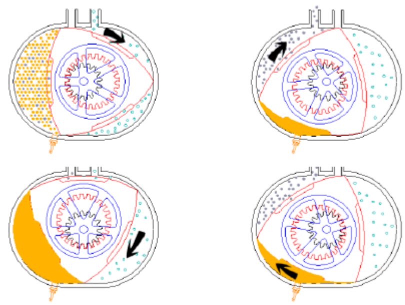


Figure 1.4

- Figure 1.2 - The mostly used mechanism is composed of a **piston** connected to a **crankshaft** via a **connecting rod**. The crankshaft converts the reciprocating movement into a rotating one.

- Figure 1.3 - Another mechanism where we have an additional **piston rod** between the piston and the connecting rod, coupled with a **crosshead**. This avoids the side forces on the piston due to the connecting rod movement. It is commonly used in large engines where side forces would produce too much wear (marine engines for example).

- Figure 1.4 - The third famous mechanism is known as rotary or Wankel engine. It is based on an eccentric rotary motion. The triangular rotor forms 3 combustion chambers that undergo the 4 strokes of a classical engine. So, for one rotation we have 3 power strokes. It is compact and can be operated at higher speed giving a very high power to weight ratio, is smooth and balanced. The challenges relie in the sealing of the combustion chamber, the higher heat transfer, the efficiency, and the emissions.

1.1.3 Ignition

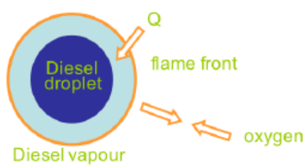


Figure 1.5

The principle of **compression ignition engines** is to auto-ignite the fuel injected into a hot environment by compressing the air. Since the fuel is introduced close to ignition, the combustion is controlled by the mass diffusion of the fuel into the air. So, the work produced is controlled by the mass of injected fuel, air keeping a more or less constant rate. These engines work in lean conditions.

The two major differences of **spark ignition** with compression ignition are the preparation of the mixture before or during the inlet and the ignition by mean of a spark. The combustion is characterised by a turbulent flame propagation. The work is controlled by the amount of air/fuel mixture and these operate in stoichiometric conditions.

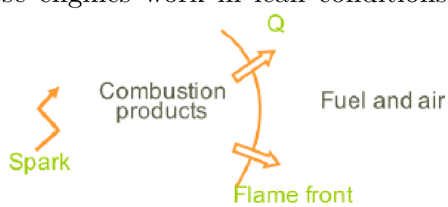


Figure 1.6

1.1.4 Strokes

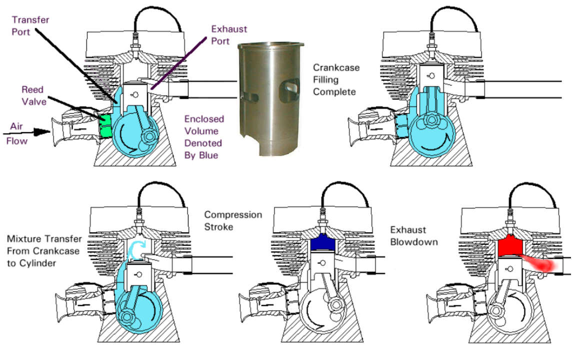


Figure 1.7

In a **two stroke** cycle, there is one work producing stroke every rotation. In the case of spark ignition engine, the scavenging is done through a **transfer port**. The air/fuel mixture is slightly compressed to push the exhaust gas. Once the ports are sealed by the piston, begins the compression followed by combustion and expansion. The exhaust port is first open when expansion. For compression ignition, there is no loss of fuel since the scavenging is done pushing air via a compressor.

The advantages of 2 stroke cycle is that it is more simple, produce more power-to-weight (1 power every rotation) with a more constant torque than the 4 stroke. But we have fuel losses (SI), we need to manage more heat and we must mix oil and fuel for lubrication.

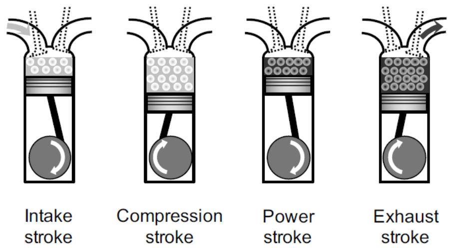


Figure 1.8

The **four stroke** cycle is composed of an intake, a compression, a combustion and an exhaust stroke. This induces one power stroke per two rotations.

1.2 Cylinder arrangements

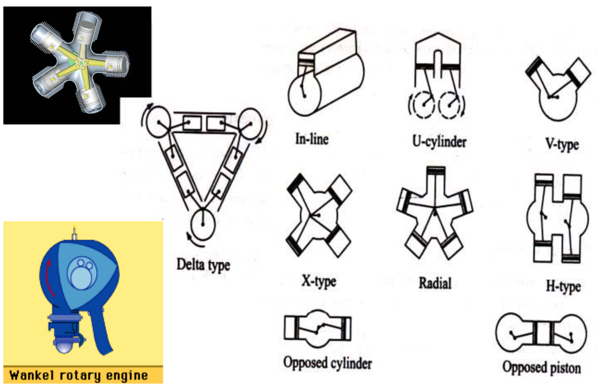


Figure 1.9

There are several arrangement methods. Other than in-line configuration are used in the case of high number of cylinder for the geometry. These are shown on this figure. There is also the W engine. This is in fact composed of two small angle V engine mounted in V type. But what are the advantages and disadvantages of more pistons:

- small degree of speed irregularity due to more power strokes and almost constant torque
- easy to balance, because more force regularity
- saving on R&D and production costs (only copy one piston)
- small dimensions per cylinder → more rpm, power (less inertia)
- cooling, combustion, thermal stresses
- disadvantages: configuration more difficult, more wear (usage), accessibility more difficult (inlet, exhaust).

1.3 Components

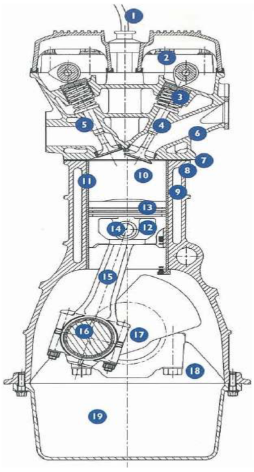


Figure 1.10

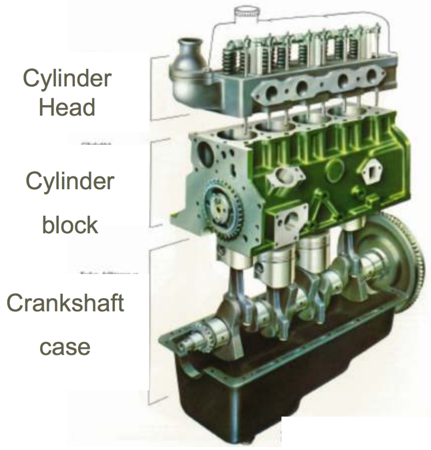


Figure 1.11

1. spark plug
2. camshaft (overhead)
3. valve springs
4. inlet valve
5. exhaust valve
6. cylinder head
7. cylinder head gasket
8. engine block
9. coolant
10. cylinder
11. cylinder liner
12. piston
13. piston rings
14. piston pin
15. connecting rod
16. big end
17. crankshaft
18. mainbearing cover
19. oil sump

- **Cylinder head:** this the enclosure of the cylinder block, contains the combustion chambers and the inlet and exhaust valves.

- **Cylinder block**: very complex part because there are canals within (oil, cooling..), there are also fixing ports. We cast it, we use so iron or aluminum. Iron damps vibrations, is strong, ... (ships). Aluminum is much lighter, so we used it for small cars, disadvantage: is not as strong as iron, too much thermal expansion, that can be a problem, if the dilatation of the aluminium is too large, the piston does not fit anymore and we have leakage.

- **Crankshaft case:** as the name indicates, it contains the crankshaft converting the reciprocating movement into a rotating one and an oil reservoir.

1.3.1 Cylinder

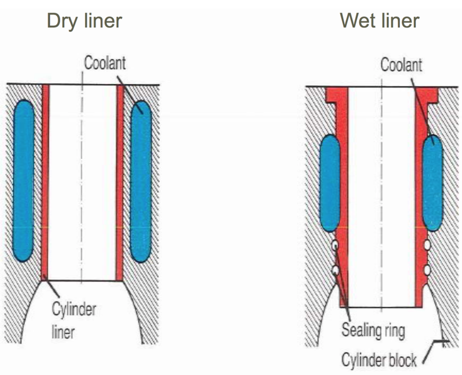


Figure 1.12

Here is a representation of the cylinder, the coolant type more exactly. If we make an engine we have to worry about the lifetime. For ships for example 34 years. We can have liner which is a protection of the insight, we can make it with a special material with special characteristics. We only worry about friction and thermal conduction because the temperature of the piston is high, it must transfer the heat, it transfer it to the piston block. There are also small ports in the liner that can store oil. We also have a coolant, we can have the wet liner or the dry one depending on the position of coolant. Transfer of heat in the wet one is more important but we have leakage risk of the water in the piston chamber from below.

1.3.2 Piston and connecting rod

The piston is a moving part. In the engine the inertia and the mass is important, we will lose power by resistance if it's too high. Piston rings are responsible for avoiding leakage, heat transfer and friction. We also have to worry about leakage behind the rings when the piston goes up and down and the removal of the oil to avoid its combustion. The reason why it's impossible to have 0 leakage in spark engine is that we always have a horizontal movement (Diesel tends to 0).

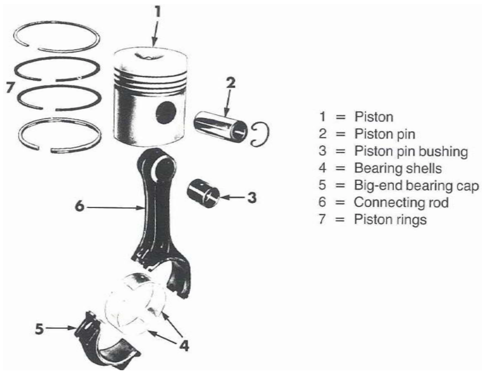


Figure 1.13

This is the moving part, but above this we have cool air or mixture (cool because it will be heated up by the process). The thermal resistance of the piston must be much higher than the engine block, the piston is in aluminum so it expends when heated. We have to manage the thermal behavior to counter this → elliptical geometry when cold and we manage expend to have the good shape when it heats.

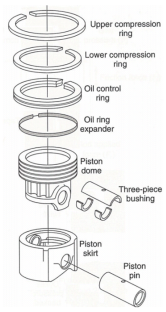


Figure 1.14

The pin has to support enormous force so we use iron, and whole pin because the stresses are bending stresses so we have to remove the weight. The piston is composed of different ring layers. We see that the oil controller ring dispose of an expander to scrape the oil. The compression ring has no expander because the high pressure makes move the ring below then toward the wall when inlet. In practice, one ring is sufficient, but we will have no emergency ring.

1.3.3 Cross section of a piston

Grooves can have different shapes. The efficiency of a spark engine is about 20%, diesel engine 35%. We are looking for increasing this. The skirt is becoming shorter because of the mass.

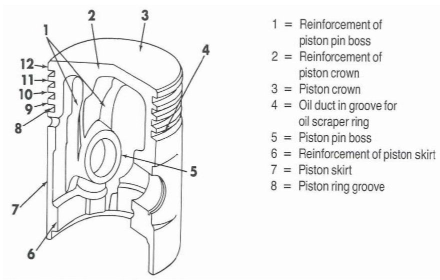


Figure 1.15

1.4 Blow-by due to leakage

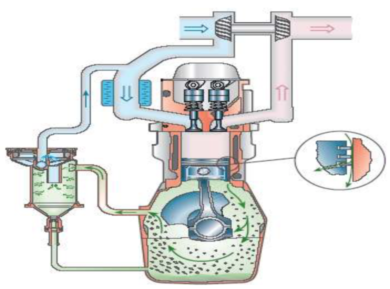


Figure 1.16

What we can have is a gas leakage, that goes into the sump. The consequences are that the fuel mix with oil, reducing its efficiency as the pressure below increases. What we have to do is to evacuate the gases. There is a kind of ventilation. The gases pass through a filter where they are filtered (gas / oil). The gases will be sent to the incoming gas.

Chapter 2

Operating parameters

2.1 Forces on a car

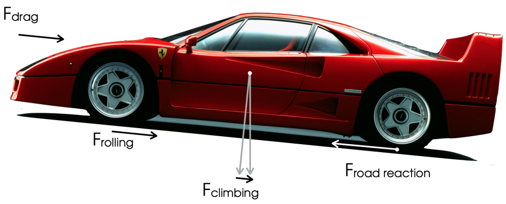


Figure 2.1

The very basic, we need to apply a force to make the car move. Thus our first force is related to acceleration and energy:

$$F = m.a \qquad and \qquad E = F.d \tag{2.1}$$

This force is applied on the contact between the wheels and the road as a reaction to the torque. The three main forces opposed to the movement of the car are **rolling** of the tires, **drag** and **gravity**.

2.1.1 The rolling force

Car tires on field/sand	0.1 - 0.35
Steel wheels on steel rail	0.001 - 0.002
Car tires on concrete	0.008 - 0.015
Truck tires on concrete (higher pressure)	0.006 - 0.01

Figure 2.2

The car weight of the car deforms the tire and the ground. At any time, another part of the tire and ground should be deformed and this requires a force opposed to the movement of the car. The force and the power can be characterized as:

$$F_R = C_R mg \qquad P_R = C_R mgv \tag{2.2}$$

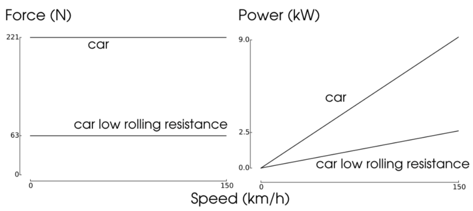


Figure 2.3

where C_R is the rolling resistance coefficient taking into account the effect of the deformation of ground and the tires per unit of weight applied. On Figure 2.2 we can see that the nature of both the tire and ground is important. Figure 2.3 shows the dependence of the power wrt to the velocity, while the rolling coefficient remains constant with speed. Remark that rolling power can go up to 9kW at 150 km/h.

2.1.2 The drag force

This is due to the force induced by the air opposed to the movement of the car. We have to move air particles to ride. The force and power are:

$$F_D = \frac{v^2}{2}\rho_a C_D A_f \qquad P_D = \frac{v^3}{2}\rho_a C_D A_f \tag{2.3}$$

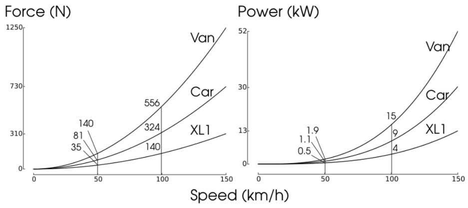


Figure 2.4

where A_f is the frontal area of the car and C_D the drag coefficient, stating how smooth it is to move the air particles. By multiplying the drag coefficient and the frontal surface, we get another equivalent surface that gives an important factor for drag resistance. Figure 2.4 represents the evolution of the force and the power in function of the velocity, we can remark the high non-linear dependency.

At low speed (50-60 km/h), the rolling resistance predominates. As the speed increases, the drag resistance becomes more important. Between 60-80 km/h their respective power is similar.

2.1.3 The climbing force

This one is due to the gravity and can be expressed in function of the angle as:

$$F_C = mg\sin\alpha \qquad P_C = mg\sin\alpha v. \tag{2.4}$$

Let's look to Figure 2.5, 2% inclination can seem to be not important but the effect on the power consumption is already huge. Don't forget that energy and force are linked by the distance, going faster demands more energy.

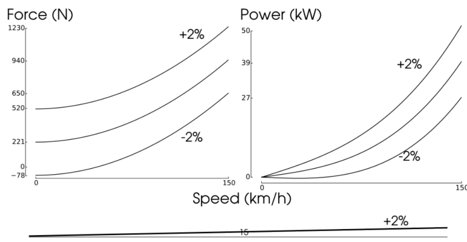


Figure 2.5

There are also some auxiliaries that consume energy (1-3 kW), like opening the windows or air conditioning.

2.2 The wheels

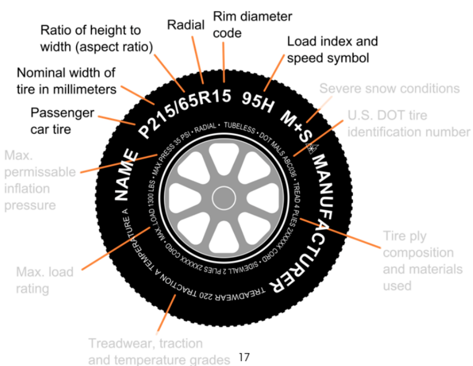


Figure 2.6

To retrieve the rotational speed of the engine from the one of the car the first step is the wheels. Figure 2.6 shows the divers information on the tire. To get the real diameter in cm of the wheel we have to proceed as:

$$\begin{aligned} d(cm) &= (\text{rim diameter})[inch] \cdot 2.54[cm/inch] \\ &\quad + (\text{width})[mm] \cdot 0.1[cm/mm] \cdot (\text{aspect ratio}) \cdot 2 \end{aligned} \tag{2.5}$$

Knowing this, the rotational speed of the wheel is $\omega(rad/s) = \frac{\text{speed (m/s)}}{d/2}$. This is the rpm of the wheel, for the one of the engine, there is the coupling with a gearbox. The power demand is lower than the supply, the **power reserve** is used for climbing and acceleration.

2.3 Geometrical parameters

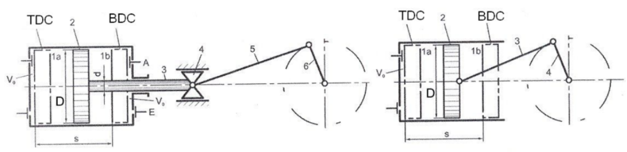


Figure 2.7

We have enormous type of engine that differs from application to application by their characteristics. Figure 2.7 regroups different parts of the piston, but more important are the **dead center** at the top and the bottom which are the position of the cylinder when the velocity is null, the **bore** is the diameter of the cylinder and the **stroke** is the distance traveled by the piston.

Torque	Nm	lb.ft (1.356Nm)
Power	kW	hp (0.746kW)
Specific power	kW/l	
Specific weight	kg/kW	
Fuel consumption	l/100km	mpg
Specific fuel cons.	g/kWh	
Indicated/effective p.	Pa, bar	
Air-fuel/equivalence ratio	-	
Specific emission	g/kWh, g/km	

Figure 2.8

We also speak about the **swept or displacement volume** and the compression ratio given by:

$$V_d = \pi s \frac{D^2}{4} \qquad \epsilon = \frac{V_c + V_d}{V_c} \tag{2.6}$$

where V_c is the minimum volume for valves. We have also the **mean piston speed** which is important for inertia effects, defined as:

$$V_m = 2s\frac{rpm}{60} \tag{2.7}$$

where we remind that for one rpm we have two strokes. The rpm and V_m vary a lot in function of the engine type and the application, mechanical constraints.

2.4 Energy conversion

As a simple model, by neglecting the inertia, friction and gravity, we can say that the energy conservation is expressed:

$$(p_{cyl} - p_0)A\,dx = M_e\,d\theta \tag{2.8}$$

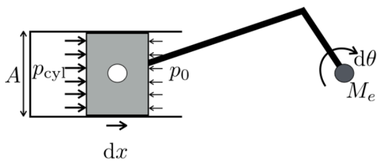


Figure 2.9

where the fuel energy is converted into torque.

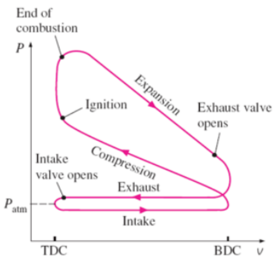


Figure 2.10

What is used to represent the engine cycle is the p-v diagram also called **Watt or indicator diagram**. We see that the exhaust phase is at higher pressure and the intake less pressure than Atm because we have to push and suck the air/fuel. The diagram of traditional engines are approximated with ideal cycles:

- SI: Otto and Beau de Rochas cycle
- CI: Diesel cycle
- Dual and Sabathé cycles to better represent the diagram

2.4.1 Otto cycle

In the Otto cycle, the heat is provided in a constant volume, assuming the combustion to be very fast compared to the piston speed (not realistic). The interest is the efficiency linked to the **compression ratio**:

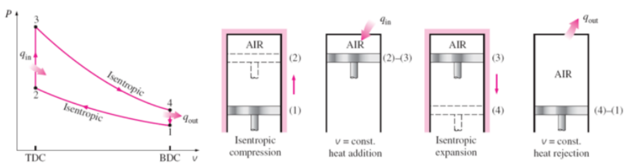


Figure 2.11

$$\eta_{th} = 1 - \frac{1}{\epsilon^{\gamma-1}}. \tag{2.9}$$

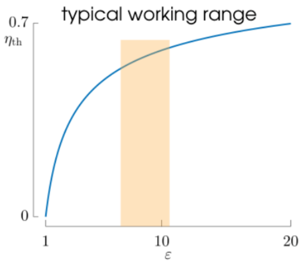


Figure 2.12

We see that by increasing the compression ratio, we increase the efficiency. Unfortunately for spark ignition engines we have an upper limit due to knock. The typical working range is around $\epsilon = 10$.

2.4.2 Diesel cycle

In the Diesel cycle the combustion takes place when the pressure remains constant, assuming a small combustion such that the pressure increase is compensated by volume increase. In that case the ϵ is also important but there is also the **load ratio** α:

$$\alpha = \frac{T_3}{T_2} = \frac{V_3}{V_2} \qquad \Rightarrow \eta_{th} = 1 - \frac{1}{\epsilon^{\gamma-1}} \frac{\alpha^\gamma - 1}{\gamma(\alpha - 1)} \tag{2.10}$$

where T_4, T_1 and α are not independent.

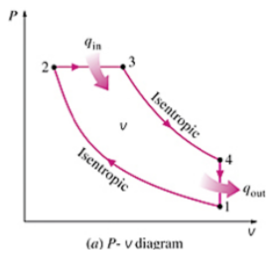


Figure 2.13

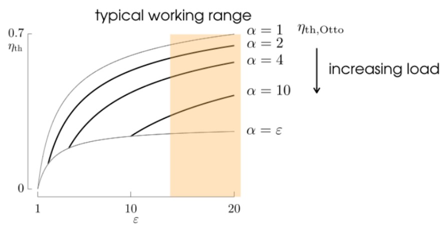


Figure 2.14

We see that when $\alpha = 1$, the efficiency tends to the one of the Otto cycle. When the load increases, the efficiency decreases. For the same compression ratios, the Otto cycle is much efficient than the Diesel cycle. But we operate in much higher compression ratios in the Diesel engine because they are not limited by knock. Therefore, the efficiency of compression ignition engines is higher than the spark ignition engines:

$$\eta_{th,Otto} < \eta_{th,Diesel}. \tag{2.11}$$

2.4.3 Dual cycle

The Otto cycle being too optimistic and the Diesel one too pessimistic, a good diagram should be obtained by combination of the two. However, the additional complexity does not introduce new conclusions.

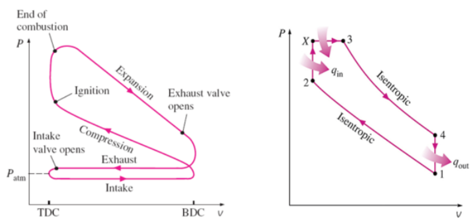


Figure 2.15

2.5 Power conversion steps

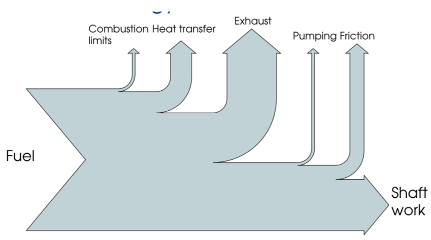


Figure 2.16

Between the energy provided to the crankshaft and the power present at the fuel, there are many losses. A small part is lost in the combustion itself, a bigger part by heat transfer to the walls that are cooled down, the biggest part is lost in with the exhaust gases and we also loose when pumping and friction.

If we compare the indicated work W_i on the p-v diagram with the energy in the fuel, we get the **indicated efficiency** (performance of the cycle):

$$\eta_i = \frac{W_i}{m_{fuel}LHV}. \tag{2.12}$$

If we take into account the different losses, we get the **effective work** W_e. With his we can define the mechanical efficiency and the **effective efficiency** (efficiency to the crankshaft):

$$\eta_m = \frac{W_e}{W_i} \qquad \eta_e = \frac{W_e}{m_{fuel}LHV}. \tag{2.13}$$

This ranges from 30% in SI and 40% in CI.

2.5.1 Industry standards

In the industry, we represent the effective efficiency in the form **specific fuel consumption**:

$$\text{specific fuel consumption} = \frac{\text{fuel mass flow } (g/h)}{\text{effective power}(kW)}. \tag{2.14}$$

This last is inversely proportional to the effective efficiency. Be aware that this depends on the LHV and can change significantly when changing fuels. Note also that the CO_2 emission is directly linked to the fuel consumption, so the efficiency.

2.5.2 Pressure to work and work to torque

As explained, the force on the piston is given by the pressure applied on it:

$$W_i = \oint p\,dV. \tag{2.15}$$

The work is then transferred to the shaft through a torque. It depends on the number of work producing strokes:

$$M_e N\pi = nW_e \tag{2.16}$$

where N=2 or 4 for a two or four strokes engine and n is the number of cylinders. To compare the performance of different engine sizes, we define the **Mean Effective Pressure (MEP)** (does not depend on the size). We have the indicated MEP (IMEP) and the Break MEP (BMEP):

$$IMEP = \frac{\text{indicated work (J)}}{\text{displacement } m^3} \qquad BMEP = \frac{\text{effective work (J)}}{\text{displacement } m^3}. \tag{2.17}$$

This allows to express the torque in function of BMEP:

$$M_e N\pi = nW_e = nV_d\text{BMEP}. \tag{2.18}$$

The power is obtained by multiplying by the number of work producing cycle per second:

$$P_e = M_e 2\pi\frac{rpm}{60} = nV_d\text{BMEP}\frac{2rpm}{N60} \tag{2.19}$$

2.6 Torque as a function of rpm

The engine is generally characterized on a test bench where various parameters are measured. In Otto engine, the throttle change the total mass (air and fuel) while in Diesel engine this change the injected fuel.

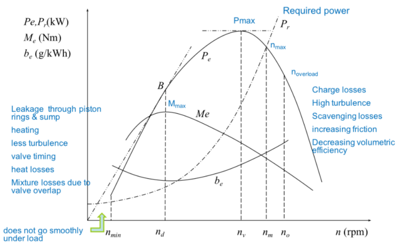


Figure 2.17

On this graph are represented the power and torque shapes for a given engine. We can see that the torque first increases then decreases after a maximum. The power continues to increase after the maximum torque but drops after, close to the maximum speed. The combination of these parameters also gives the fuel consumption map. Most cars are not only designed to reach the maximum legal speed but have much more power than needed.

According to where we are in the consumption map, the consumption might vary a lot. The torque demand comes from the forces applied on the engine. The difference with the maximum torque is the reserve and allow the vehicle to accelerate. Notice that for 2 different speeds, the consumption increase can be less than the demand because the engine speed would be operated in a more efficient way (ex: 70 km/h - 34 g/km and 80 km/h - 37 g/km, +14% speed = +9% consumption).

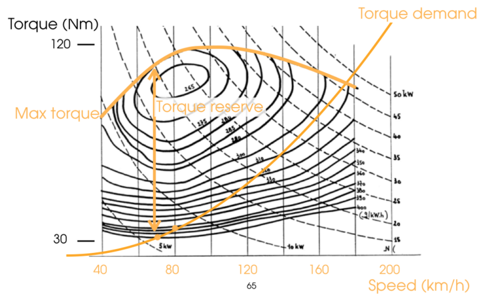


Figure 2.18

The first solution is **downspeeding**, to decrease fuel consumption is to reduce the operating speed by means of gears. Indeed, by shifting gears we try to stay in the region of the graph where we have more torque for lower speeds (Figure 2.19). The second solution is **downsizing**. This means that we reduce the number of cylinder and make smaller engine displacement. This can be dynamically by deactiving some cylinder (Figure 2.20).

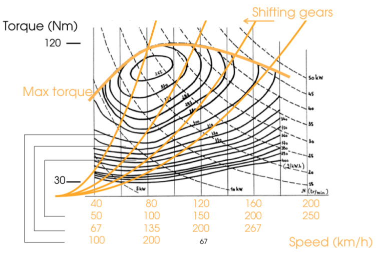


Figure 2.19

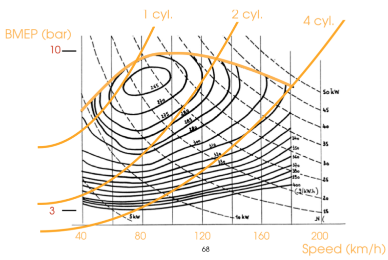


Figure 2.20

The volumetric fuel consumption can be expressed in function of the BSFC:

$$F_{car} = [N] = \frac{1}{3600}\left[\frac{kWh}{km}\right] = \frac{1}{36}\left[\frac{kWh}{100km}\right] \tag{2.20}$$

Knowing that the density of the fuel are:

$$\rho_{gasoline} = 0.72 - 0.78\left[\frac{kg}{l}\right] \qquad \rho_{diesel} = 0.78 - 0.84\left[\frac{kg}{l}\right] \tag{2.21}$$

the volumetric fuel consumption is given by:

$$vfc = F_{car} \frac{BSFC}{\rho_{fuel}} \left[\frac{l}{100km} \right]. \tag{2.22}$$

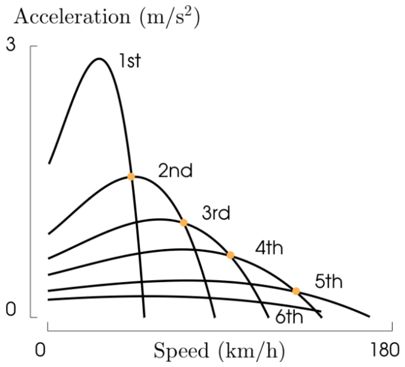


Figure 2.21

But after all this, when is it the best to shift gear? Acceleration is related to the torque and the shape of the curves follows the ones of the torque curves at a given speed. The acceleration is directly linked to the power: $P = mva$, the better is to shift when the power jump is zero, so at the intersection of acceleration curves. When this is not possible, the better is to shift at the maximum speed of the engine. In practice, a cycle or even better, a test on the road would give more realistic results.

Chapter 3

Fuels

3.1 Introduction

Fuels have an influence on the engine design, the torque, consumption, reliability, ... There exists solid, liquid and gaseous fuels, the liquid one being the most used.

3.1.1 Requirements

- High combustion value, more energy, when transport we can store it in a much smaller liter because there are more energy. In the batteries, the energy value is smaller than in fuel for example. For a car it is important but for an industrial use, we don't care.

- It has to be easely and efficiently producible, small carbon footprint. it is easier to produce oil than coal for example.

- The start and end of the combustion should be controllable, spark or compression. In some fuel we cannot control the start of combustion, like in CI engine where the fuel burn by compression.

- Transport is important for vehicles. Diesel is much more safe than petrol for example. Alternative fuel like hydrogen, to store and use it we have a lot of safety issues, much more difficult.

- A lot of emissions, main focus today is to reduce the emissions. CO_2 is causing a global climate change, depending on the fuel it will produce more (diesel) or less (petrol) CO_2. We try to have minimum impact on the environment.

- Life cycle as low as possible.

3.2 Liquid fuels

Crude oil is a mixture of hydrocarbons. The oil has a specific density that decreases with the processes, it depends also on the quality of the oil (depending on the region). First phase, we go over a distillation, the lighter components goes to the top of the distillation tower and the heavier are below. It is easier to sell lighter fuels than the heavier. We take the sulfur out because it is polluting, negative effects: oxidation → sulfur oxide, in the air causes acid rains. Second effect, in compression ignition engine, it stimulates the formation of soude, it is why it is more and more reduced in the fuel.

Type of fuel: at the top of the distillation tower we have **gas** like methane (important greenhouse gas), ethane (LPG) and propane (compressed natural gas). Then petrol and gasoline (spark ignition engine). Kerosene (tractors, airplanes, ...) Gasoil and diesel (compression ignition engine). Heavy fuel (home burners, heavy fuel, high viscosity, we can heat it up and then inject it). Lubrification oil and asphalt are the the one at the very lower part of the distillation.
In fact, all the fuels are mixture of hydrocarbons with different structures and molecular mass. For example, the fuel used in winter and in summer is not the same, they are adjusted to get the best properties.

Here we can see the places in the world where we can find oil. Most fuel are found in Africa, South America and Mexico, United States. Some of the countries has less sulfur in the oil than the others. The oil naps are found by stating gravitational changes in the ground. They introduce some pressure in the ground to exploit the oil. Notice that today we also have ships where the distillation process is executed. Petroleum gas can be used in LPG or in the combustion of the distillation tower.

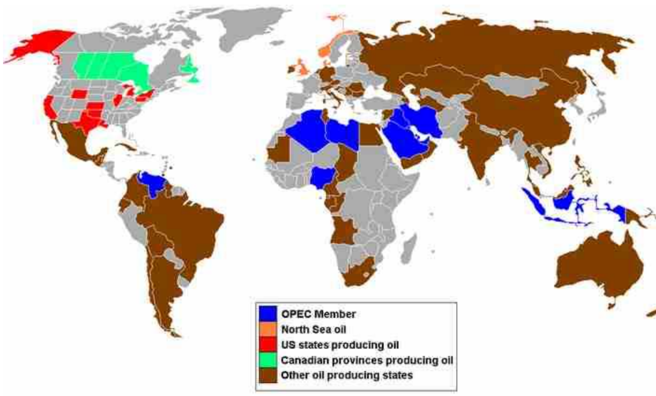


Figure 3.1

Hydrocarbons

Normal paraffines, isoparaffines, olefines, ... If you look to the oxidation reaction, some will react very easily with air, others not. Benzene (**aromatics**) for example resists throw oxidation, it complicates the combustion, this is an advantage to control the combustion (spark ignition for example), but can be undesirable for diesel (compression). Aromatics are undesirable because it is cancerous, so we try to not use it in fuel. **Isoparaffines** combust very well in contact of air. **Making a fuel is mixing hydrocarbons** to get a good combination, if the environment and the condition changes, we have to adapt our composition. For example, in winter the fuel is lighter to make it evaporate during combustion, in summer we have to make it heavier to not evaporate it too rapidly.

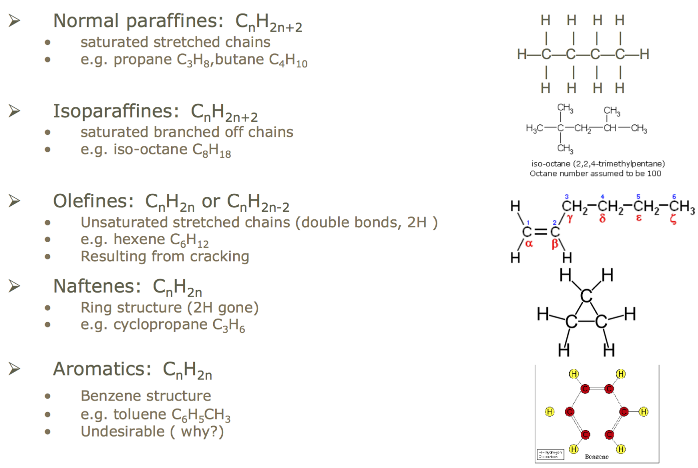


Figure 3.2

3.2.1 Characteristics

Petrol (gasoline)

Fuels are standardized, it is different from the USA to Europe. The boiling traject (30˚C - 200˚C) indicates how easy the fuel evaporates, we have a range of temperature to respect. The composition is also standardized: 60-80% paraffines, 15-30% naftenes, 0-10% aromatics, 0-2% olefines. **Octane number** is the most important characteristic for petrol. Density is limited, so the fuel is lighter than water (0.72-0.775 kg/l).

Diesel (gasoil)

In diesel we have less aromatics (because it is resistant to evaporation) and more paraffines (easy auto ignition), boiling traject indicates that the fuel is heavier (180˚C - 370˚C). The most important number for diesel is Cetane number. For fast running engines (cars) this varies between 45 and 55 while for slow ones it is more than 30 (ships). The density is higher than gasoline but still less than water (0.82-0.86 kg/l).

3.3 Fuel criteria (petrol)

3.3.1 Parameters

Petrol is the first fuel we are studying, spark ignition engine can have 4 or 2 strokes, we have to mix the fuel with oil in the 2 strokes case, but we discuss only the petrol used without oil.

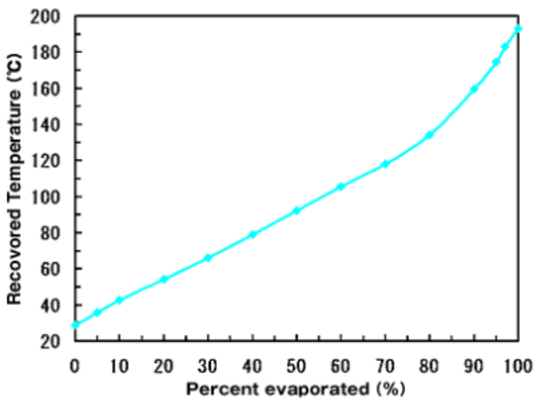


Figure 3.3

- In a spark ignition engine we will mix air and fuel before injection, we should get a precise state before combustion. The important is that when the fuel air mixture is in the cylinder, the fuel must evaporate in the air. At the end of the compression stroke, we want the fuel to be completely evaporated. This is the criterion of **volatility**. The testings are done in lab. For a good cold engine start, we can have 10% of the liquid evaporated and in hot engine 90% (avoids condensation and lubrification oil dilution). If the fuel is too volatile, we will get vapor locks in the fuel supply. Indeed, the fuel is pumped. This process creates heat and if the fuel is volatile, we can have an underpressure at the inlet of the pump, that will block the machinery (Figure 3.3).

- Vapour pressure is the pressure above the fuel itself. We limit it to 60kPa in summer and in winter 90kPa in winter. In summer the fuel is heavier, so it starts to boil at a higher temperature, while in winter it is the contrary. This is why we should have less vapour pressure for summer.

- Vaporization heat: the vaporization needs heat, so the temperature of all other mixtures will decrease. In the air we have water, if the temperature goes down too much we will have icing for example. The 3 last parameters are the criteria before combustion.

- Auto-ignition temperature: we want to control the ignition with the spark. But auto-ignition happens without control, we want to avoid that. So that temperature will be higher for petrol (480-550˚C, 1 Atm) than diesel (330-350˚C, 1 Atm).

3.3.2 Deflagration and detonation

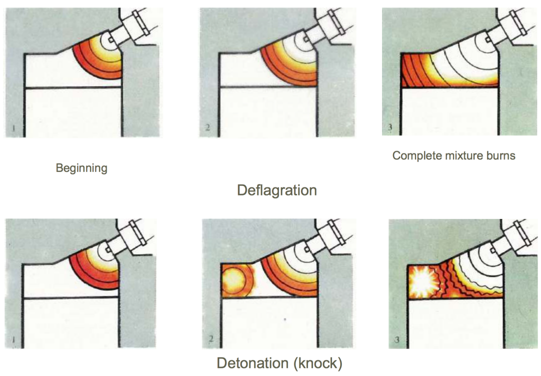


Figure 3.4

Before the compbustion, we have an inlet of air/fuel mixture, which is then compressed and then burned. The normal combustion is the **deflagration**, we have the spark that ignite the fuel in the neighborhood of the spark, if all the condition are good, we start burning, the surrounding fuel mixture will start warming up and then burning and the rest follow. We have some flame going layer per layer, until the progression of the flame front fill the entire combustion chamber. The speed of the flame front is **subsonic**!

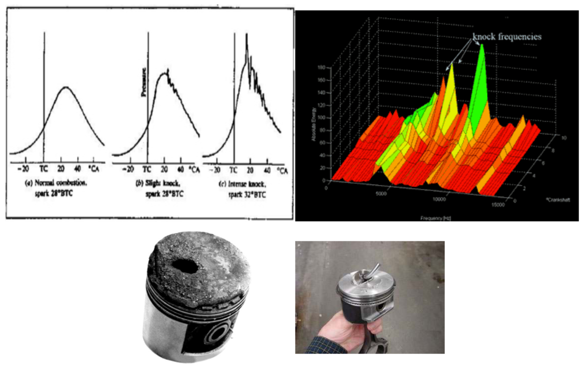


Figure 3.5

Detonation is operated at much higher pressure and much higher speed of flame front. We get the same beginning, the flame front moves, but due to pressure buildup, deposits, ... the far field **auto-ignites**! This is supersonic and goes faster than deflagration. The detonation produces explosions of high pressures that will slow down the piston in its moving, causing vibrations. It can destroy the engine because of the local pressure and large heat production. How can we avoid that? The base parameter is the fuel, so we have to control this process by the fuel. We can see on the figure that the pressure in the combustion chamber normally evolves as a sine, but when there are detonations, this is disturbed.

Fuel criteria

- Fuel is very difficult to ignite and burn if it has not the right mixture of air and fuel. The limits are 1-6.9% of petrol in air. This is performed in a carburetor.

- **Octane number** is the most important number for avoiding auto ignition. If we use a fuel with only iso-octane C_8H_{18}, that fuel is 100% knock free. On the other hand, if we had a fuel composed only of normal heptane C_7H_{14}, we would always have knocks. That is why the Octane number is 0 for normal heptane and 100 for iso-octane. When knock was detected long time ago, they wanted to adapt the fuel to avoid detonation. And the American society said let's make a reference engine and let's do the test on that testing engine (**CFR**), they are still used today. It has never been modified. We canmake some parameters vary to study the fuel. On base of the compression ratio we can calculate the octane number.

We have different kind of Octane numbers: Research Octane Number (RON) which is for normal use in a car, the MON (Engine Octane Number) is used in the USA, the difference can go up to 15, and the last is the Road Octane Number (RdON) which is the one measured in road conditions.

- How do we get a high Octane Number? The main parameter is the hydrocarbon structures, branched, short, unsaturated, cyclic. We can also add some oxygeneous components like alcohols, but the volatility increase can damage the material.

3.4 Combustion in diesel engines

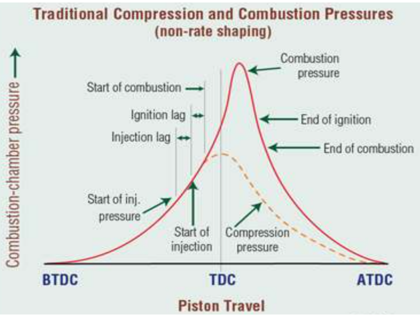


Figure 3.6

Here is represented the evolution of the pressure in the combustion chamber when combustion happens and when not. We see that we go to much higher temperatures and higher pressures when combustion. The injector injects small drops of fuel into the hot air already in the chamber, compressed. In the ideal case, we would like the fuel to burn immediately when injected, but it is not the case, we have an **ignition lag**.

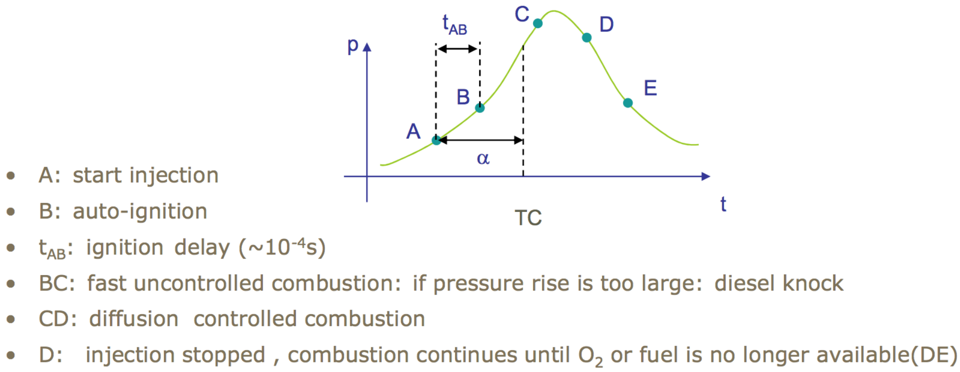


Figure 3.7

We can also have diesel knocks. These ones are influenced by:

- The pre-ignition angle, which is today fully controlled electronically, it influences the amount of fuel injected. Pre-injection consist in injecting a few drops, then waiting it to burn and then doing the main injection. We avoid the knock where too much drop burn together and introduces a high amount of sudden energy.
- The ignition delay is very important because if it's high, the combustion will only start when the piston is already going down. Today, we control that completely electronically.
- If the air is too cold and the pressure too low, it will take too much time to burn the fuel. When the fuel starts to burn, it causes a sudden increase in energy and pressure so diesel knock (vibration). It will not arm the engine directly, because the engine is fitted for high pressures and the knock disappear in a certain time. To avoid this, we warm the engine, heat up the air.

3.4.1 Parameters

- You can imagine that **volatility** is not the main issue of the diesel engine because we inject drops directly in hot air, the large volatility is not required. **Flashing point** is the point of temperature where we can ignite the vapor above the liquid (>55˚C). The **viscosity** is more important than petrol, when we will inject it we will have to apply much higher power.

- Deposits and corrosion are a big problem for diesel engines, we spoke about sulfur, this one is a bigger problem in diesel fuel because it is more heavy. It also causes soude emissions, dangerous for health.

- The ignition delay is as we said the delay between injection and ignition. This can be decreased by increasing the compression ratio, the inlet pressure and temperature. The larger are these values, the closer the auto-ignition conditions are reached after compression. The Cetane number gives information about that.

- Diesel knocks manifest as a too large and fast pressure rise before TC. This can be due to too early pre-injection or too high injection flow rate.

- The Cetane number is the percentage of cetane ($C_{16}H_{34}$) in a mixture of cetane and alpha methylnaphtaline ($C_{11}H_{10}$) that has the same ignition delay as the examined fuel. High Cetane number states good auto-ignition. It is also measured on a CFR engine but diesel. For fast running engines this should be about 50-55, and for slow running engines about 30-35. Low Cetane number means that the fuel favorises the formation of knocks, high pressure and temperature and increased NOX emission, but means thermal stability. While for high Cetane number this means that the fuel has a high proportion of paraffines that are unstable.

- Good starting properties: we have to make sure that the boiling point is low enough to get auto-ignition. Cold resistancy: when temperatures are low, the paraffin cristalizes and can block the filters. To avoid this, we have heated filters.

3.5 Alternative fuels

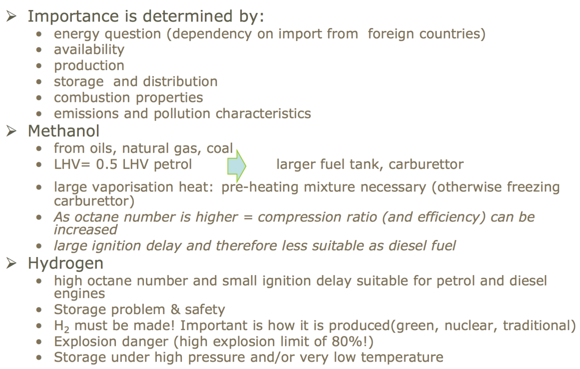


Figure 3.8

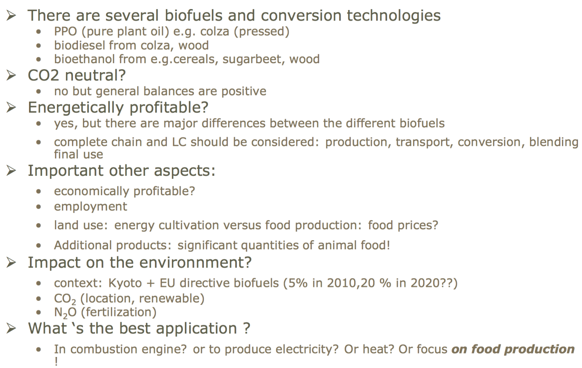


Figure 3.9

Chapter 4

Spark ignition engine

4.1 Mixture preparation in SI engine

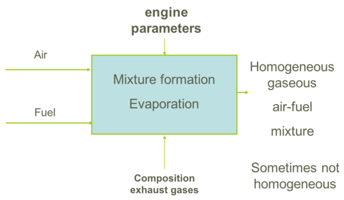


Figure 4.1

The objective is to obtain an homogeneous gaseous composition with the right equivalence ratio. We will see that in direct injection inhomogeneous gas is obtained.

4.1.1 The carburetor

It is now outdated because of the regulation imposed on the exhaust gases and has been replaced by fuel injection except for small engines. As a first approximation we can consider that the carburetor pump the fuel into the air flow using the Bernouilli principle (compressible): when the air velocity increases the static pressure decreases and the fuel flow increases.

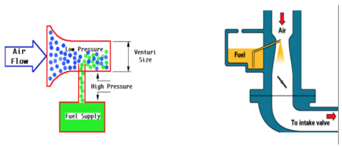


Figure 4.2

Importance of equivalence ratio for combustion

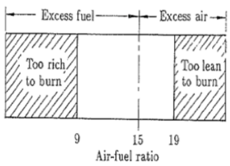


Figure 4.3

The best burning condition is obtained when stoechiometry (15kg air for 1kg fuel). But rich and lean mixture can also burn not in the best conditions. In SI engine the amount of mixture going to the engine is controlled by the throttle. A venturi creates a decrease in pressure for the fuel to be pushed.

The reality deviates from the incompressible model. Indeed, for air velocity increase the pressure drop is more important and the injected fuel is larger as fuel is incompressible (eq. ratio higher in high air flow). In addition the speed in venturi is limited to Mach 1 to avoid shocks and the fuel height pressure has to be compensated in order to have injection, thus for low speeds there is no injection.

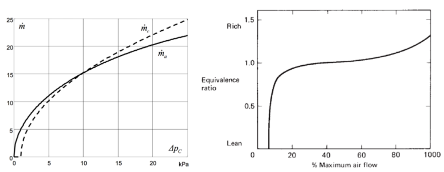


Figure 4.4

Compensating jet

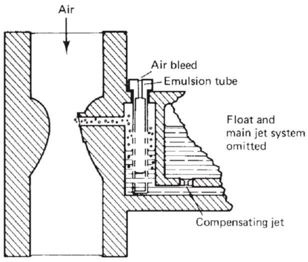


Figure 4.5

This is introduced in order to solve the problem of the increasing equivalence coefficient when air flow increases. The fuel jet is divided into 2 jets, the main directly connected to the venturi and the second connected to the venturi through an **emulsion tube**. As the air flow increases, the one into the emulsion tube too and this decreases the amount of compensating fuel.

Here we can see the effect of this, we have a more constant eq. ratio. As we have decrease the flow of the main jet and the compensating jet is not working at high air speed, the mixture is kept constant. When acceleration, rich mixture is needed. For this an additional system sensing the acceleration provides extra fuel.

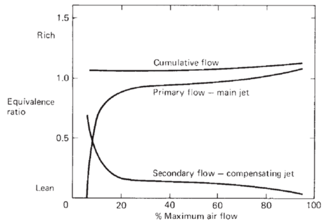


Figure 4.6

Idling fuel line

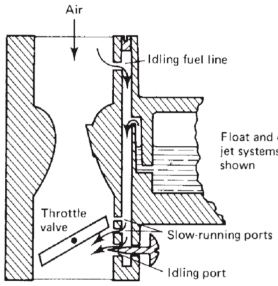


Figure 4.7

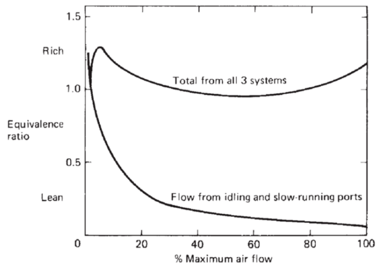


Figure 4.8

The remaining problem is at very low air flow rate because the pressure drop at the venturi is very low. To compensate this, one takes advantage from the flow near the throttle where a local pressure drop is created when nearly closed and uses so the **idling fuel line**. The last trick to include is for **cold start**. The added **choke valve** is situated before the venturi in order to create a choke.

4.1.2 Fuel injection

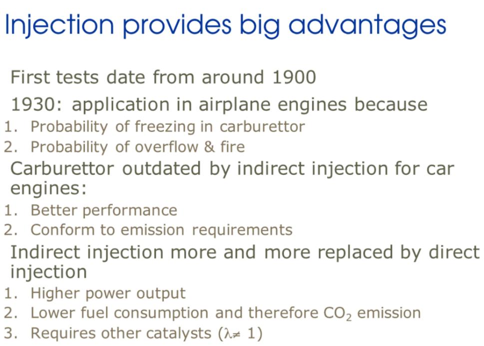


Figure 4.9

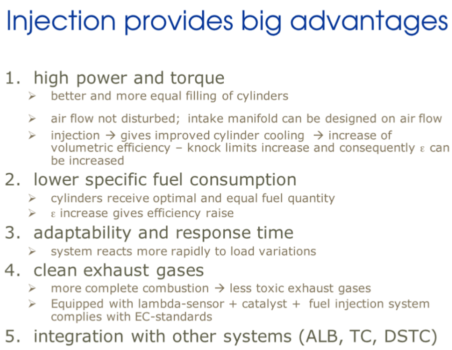


Figure 4.10

The advantages of fuel injection with regard to the carburator is listed above.

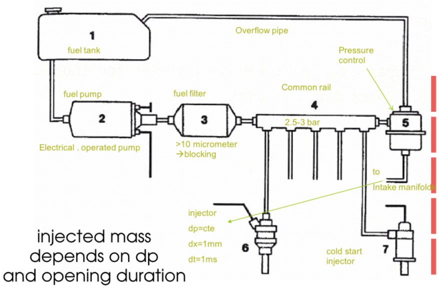


Figure 4.11

The injection is not linked to the air flow, we need thus a control unit in order to control the injection. In the industry, electronic is used for the Engine Control Unit (ECU) based on the input of many sensors, direct or indirect measurement of air flow.

Direct injection

Even if it is more complex, it allows better volumetric efficiency: the fuel is evaporated after injection and thus decreases the air density in the mixture, thus we can intake air at higher load (the cooling is better). In addition, the load is stratified and allow more efficient intake since losses are decreased: lean mixture can be formed and then managed in the piston.

Preparation strategies

There are 3 main categories of guiding the injected fuel to the spark plug: wall-guided, air-guided and spray-guided. The wall-guided consist in using the wall of the piston to get the best mixture, there is for example a small hole. As introduced, it is possible with direct injection to intake inhomogeneous mixture. But we still need an equivalence ratio of 1 for good combustion. To get this condition near the spark plug, the flow conditions can be changed → air-guided.

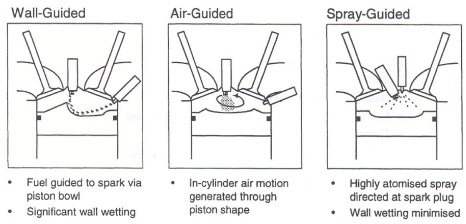


Figure 4.12

The disadvantages of the wall-guided is that it requires good flow conditions and good injection timing, reducing the advantage of improved volumetric efficiency. In addition it is bad for emission. The most efficient but also most complex system is the spray-guided. It relies on the high pressure (no need of high air speed in the chamber) and fast response of the injector to obtain the adequate mixture without interaction with the wall, hence avoiding wall wetting (less emission). The mixture is more homogeneous.

4.2 Ignition

The task of the ignition devices are to:

- In practice, the ignition is not instanteneous and thus we need to introduce an advance delay for the spark ignition.
- In the chamber we have certain pressure, certain temperature, we have to deliver a high voltage in order to create the spark.
- Depending on the layout we have to distribute the spark, if we have a multi-cylinder we have a phase between the different strokes.
- We have to provide enough energy as well as power and duration to ignite.

4.2.1 Spark production

Previously we performed ignition by current interuption with a breaker in the piston, but the breaker was eroded and we need to replace it. This was done with low voltage, limiting the compression ratio. Now, for high voltage ignition we have: coil, transistor, electronic or magneto ignition.

Coil ignition

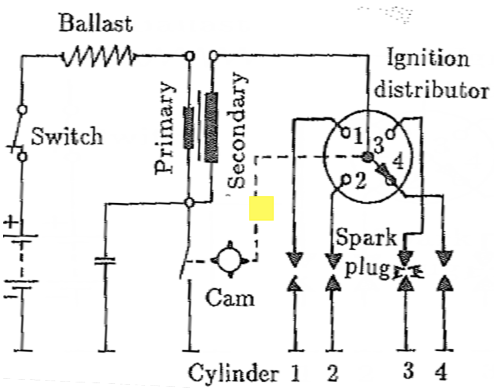


Figure 4.13

The principle of coil is based on the basic electrical relation $V = L\frac{dI}{dt}$ meaning that we will have a huge voltage if we brake the circuit in the primary, that will be converted to a higher voltage in secondary circuit. The problem was the distance to the plug (have to pass from a distributor) and thus the loss of voltage due to humidity. To solve the problem, the distributor and the coil are placed near the plug. The duration of the spark is short.

The big problem with the coil circuit is that as we know, after discharge we need to recharge the coil through a resistance, but this takes some times. This is not a problem for normal circuit but for the engine that must deliver the spark at a fixed time to several cylinders it is. This means that the time constant $\tau = L/R$ must be lower than the switching frequency between cylinders:

$$f = \frac{Nn}{120} \tag{4.1}$$

where N is the stroke and n the rotational speed of the engine (caution: we divide by 60 if it is a 2 strokes engine). How to work on the time constant? If we lower L we will have less energy in the inductance, if we increase R, the current is lower. If the n is going to increase we have less time to produce spark.

Electronic ignition

Today this is used instead of the previous. In the processor we have a number of parameter like rpm, the right position of the crank, etc. We have the exact position on the throttle position. Knocking can also change the pre-ignition angle thus it is also considered.

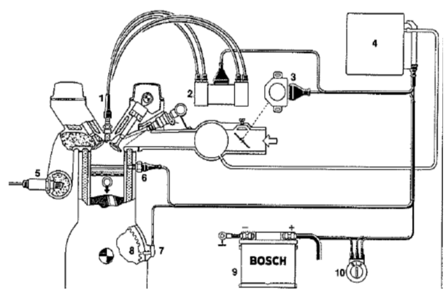


Figure 4.14

4.2.2 Voltage requirements

The voltage we need to apply (kV) is varying with the mixture, we need less kV for $\lambda = 1$ than for lean or rich mixtures.

The kV is also depending on the electrodes distance, if it is enlarged we need more kV and the contrary if the distance is shorter. The problem when shortened is that if some solid deposits form on the plug, the contact would make a short circuit.

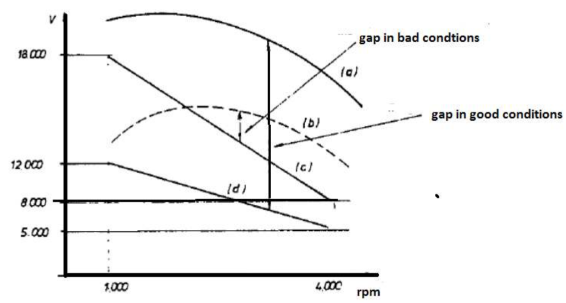


Figure 4.15

Another parameter is the compression ratio ϵ. The higher ϵ the higher the air density and thus the higher the voltage needed. Note that the needed voltage decreases with the rpm because it causes turbulences in the flow of air and thus increase the homogeneity. Too much turbulence is bad. The ignition also depends on the operating conditions. On the figure (a) represents the spark in good condition, (b) in bad condition and (c), (d) are the needed voltage respectively using old and new spark plug. On the figure we have to be careful at start.

4.2.3 Pre-ignition

According to the theory we should ignite when the piston reaches the top dead center. But the ignition process takes time, we will make it ignite before. The condition we want to respect is to have the flame front in contact with the piston when it reaches the top dead center, because before means applying opposite force and after make lose power. If v is the flame front speed and L the chamber distance:

$$T = \frac{v}{L} \qquad \Rightarrow \alpha = \omega T = \frac{n}{60} 360 \frac{L}{v} \tag{4.2}$$

Where α is the pre-ignition angle; the crankshaft angle to deal with. We could also say that L depends on the size of the combustion chamber:

$$L \propto V_c = \frac{V_d}{\epsilon - 1} \qquad \Rightarrow \alpha \propto \frac{n}{60} 360 \frac{V_d}{\epsilon - 1} \frac{1}{v} \tag{4.3}$$

If we look to this formula the two varying parameter are n and v. That flame speed is not supersonic (deflagration). The most important number in fuel is the RON number, a RON 95 is less resistant to the flame than 98 so in principle we have to change the preignition angle if we change the fuel. Now the pre-ignition angle is computed by the computer when running since the rpm is varying. The pre-ignition angle also depends on the load provided by the throttle since the fuel quantity changes. Note that an ignition map can be produced in test bench and the formula would not be necessary.

Leading to knock

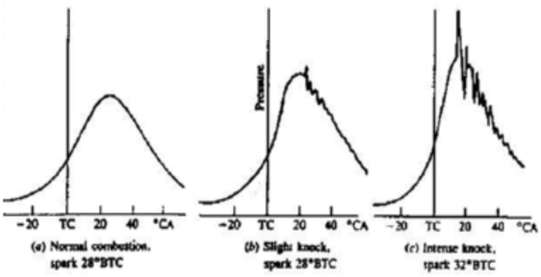


Figure 4.16

If the pre-ignition angle is too large, as the combustion has more time this leads to higher pressure and temperature, auto ignition can happen. On the figure we can see that when the angle increases, waves appear. Knocks are detected by knock sensors by verifying the frequencies (knock = high frequency). This sensor has to be the closest to the combustion sensor since the high frequencies are more damped (viscous model). The configuration of the engine can also make some cylinder more likely to produce knock.

4.2.4 Spark plug

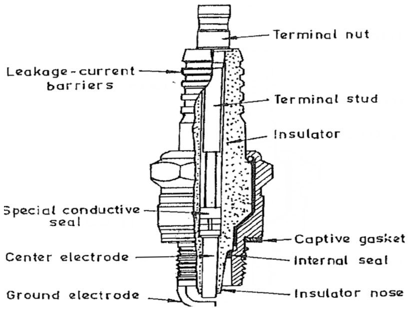


Figure 4.17

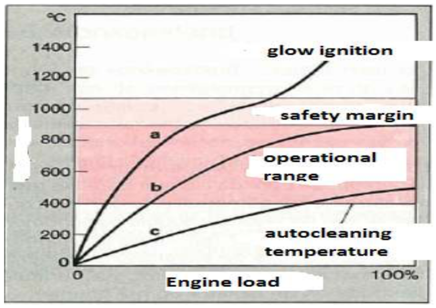


Figure 4.18

The spark plug is composed of the connector (plug wire), ceramic insulator to isolate from the environment and the electrode. An important property is the self cleaning to avoid short circuit. It depends on the engine load. If we go above the safety margin we will have glow ignition, the temperature in this region is not a problem for the plug but even without the spark the ignition will start by itself, we do not control the ignition anymore. When we have a too low temperature, we have no cleaning and the plug get dirty. So we must be in the right range.

We manage the time of spark plug heating, we get 100% high temperature at the bottom and then the other heat are distributed (mostly to the cylinder head, allowing the cooling by air or water in this region). This is managed by playing with the plug shape.

4.3 Combustion

4.3.1 The process step by step

Let's remind that the combustion is an exothermic chemical oxidation reaction. In SI, the gas is premixed and we ignite it in the chamber. Concerning the type, the normal combustion happens with flame propagation, inducing transport of mass and heat (in laminar or turbulent mixture). If the flame speed is subsonic we speak about deflagration, supersonic = detonation (explosion). Auto-ignition happens without spark under certain temperature and pressure.

Creation of the mixture creation in a carburator or in indirect or direct injection. Consists in evaporated fuel in air (homogeneous and gaseous) at stochiometry 14.7 air for 1 mass fuel. The quality is given by L or λ factor: 1 stochiometry, 1.1 minimum consumption, 0.85 power or cold start.

Heating We have some parameter to respect for the preheating of the mixture. We cool the engine in order to avoid auto-ignition and respect aluminum properties, but at regime we should keep a good temperature. Pre-heating is used for cold start: extracting the air of the exhaust system which is already hot. It is not good to have too hot air since it decreases the density and the capacity in fuel. Recirculation is used because in some cases the fuel is not totally burnt, this allows to cool a bit the exhaust gas too (reduces NOx). Bad for the efficiency.

Compression It will make the temperature rise, pressure too. The heating up to 550˚C depends on λ and ϵ. The higher the compression ratio, the higher the temperature. Is it a fixed value? Normally yes, we can play with it by means of the valves (letting the exhaust open for example). The variable one is interesting since we could increase it when cold start and then decrease it. This also depends on the fuel vaporisation (complete is best). There are various hydrocarbons in fuel and some can make the pressure higher by prereaction.

Ignition The ignition is produced by the spark, the energy needed is very small: 0.5-3 mJ needed while 40 mJ provided. It can be calculated by:

$$E_v = cst\frac{d^2}{c}\lambda_m\Delta t \tag{4.4}$$

where c is the flame speed, d the electrodes distance λ_m the conduction and ΔT the diff between mixture and ignition. For the heat to be good distributed we need high c and λ_m. After ignition we have a deflagration.

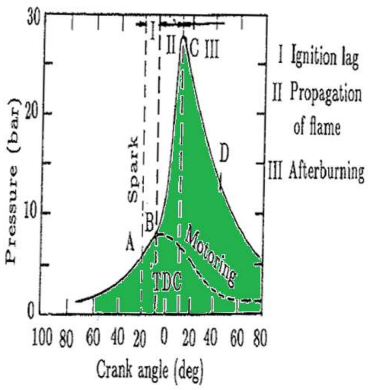


Figure 4.19

Combustion We can see the real curve where there is an ignition lag. Depending on if we are in turbulent or laminar regime we have different flame speed:

$$c_l = f(T)\phi(\lambda)p^{-0.25} \qquad c_t = c_l(1 + \beta c_z^\alpha \lambda^\beta p^\gamma) \tag{4.5}$$

where β is a parameter depending on the shape of the piston and c_z the piston speed. We see that turbulent regime speed is higher.

4.3.2 Influencing parameters

- **Thermodynamics:** the fuel, temperature, pressure and λ value influences. If $\lambda = 0.87$ we have the highest combustion temperature and combustion speed (rich mixture).
- **Aerodynamics:** when the rpm increases, the flow is turbulent and the combustion speed increases.
- **Chemical:** reaction kinetics and propagation mechanism.
- **Geometrical:** the shape of the piston and combustion chamber can increase turbulence.
- **Kinematically:** the motion of the piston.

4.3.3 Abnormal combustion

This is a combinaison of normal combustion and auto-ignition, temperature and pressure are very high. Because of the contact between the two flame fronts we have relatively high pressures (waves) and temperatures leading to high frequency vibrations. Piston destruction is possible.

Influencing parameters

The **knock** is when the auto-ignition happens after the normal combustion somewhere in the piston. **Early ignition** happens before the spark. The meeting of the two flame front leads to high pressure and temperature. The influencing parameters:

- **Fuel**: the RON number gives an indication on the shock resistance, the molecular structure of the fuel, and some additive as lead (former) and now MTBE.

- **Properties mixture**: air/fuel ratio is important since we get the highest temperature with $\lambda = 0.9$, when <1 all fuel does not burn and >1 the air is heated. The inlet temperature is important, higher combustion temperature if inlet hot. The presence of residual gases in the combustion chambers creates irregularities.
- **Operational parameters**: Rotational speed, if it increases, first of all there is less time to fill the cylinder, so we have less mass to burn the temperature will go down, we create more turbulence, the mixture is better but efficiency decreases (temperature too). If the load increases (full throttle) the temperature increases. We can work on the pre-ignition angle, if we decrease it, we ignite later, we will shift to the dilatation part, the combustion will operate when the expansion. If we make the angle smaller the heat will be lower, the pressure too. This is a process that takes time.
- **Compression ratio:** if compression ratio rises, t°and pressure rises $\Rightarrow$ knock.
- **Deposits**: on the wall, they decreases the cooling and thus knock.
- **Shape of the combustion chamber:** play also a role.

Glow ignition

Glow ignition, the phenomena is the same but the origin is different, if one part is too hot, for example the spark plug should not be above some °C, it can ignite without a spark. Same problem with valves and deposits. The characteristics are the same as before for what concerns the effects, the condition too. Outside of the engine we cannot make the difference between the two types of ignition. For deposits, they burn with the knock thus disappear.

After-dieseling is the phenomenon when you switch the engine off, it continues to run because deposits are burning (after heavy loading of the engine $\rightarrow$ carbon deposits).

4.3.4 Design of the combustion chamber

The shape of the combustion chamber is important, the constraints are: avoiding abnormal combustion, volumetric efficiency and structural requirements (strength, cooling, ...). We should have enough space for valves to optimize the volumetric efficiency. We work on the shape of the chamber, shape of piston and the valves. First design rule, we must have small distance between spark plug electrodes and walls of combustion chamber: we try to limit the distance that the flame front has to travel (less knock probability). We must get enough turbulence.

Practical aspects: small bore, the reason is that we limit the distance between the spark plug and the exhaust valve, because we limit the risk of getting an auto ignition there (where the temperature is high). Sufficient cooling of the chamber and sufficient turbulence.

Types of combustion chambers

- **Combustion chamber in the piston head:** side valves, bath tub shaped, wedge shaped, hemispherical.
- **In the piston:** bath tub.
- **In the piston and the cylinder head:** used with direct injection engines.

Figure 4.20

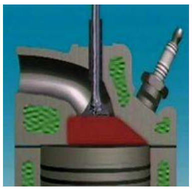


Figure 4.21

Figure 4.22

Figure 4.23

Figure 4.24

Side valve engine Simple construction, but the valve is aside the piston, the distance from the spark to the cylinder walls is larger and the combustion chamber is small, so this design is more sensitive to knocks. We will lower the compression ratio, but this is not good for the efficiency.

Bath tub shaped Short flame distance to the wall, enough turbulence caused by the long oval side and the mixture is compressed in the cylinder head.

Wedge-shaped Short distance and good whirl since the air is pushed from spark plug to the other side.

Hemispherical Good distance to the walls, large space for the valves and good cooling.

Directly injected engines Combination of a roof shaped combustion chamber with a shaped piston, turbulent mixture is pushed to the spark.

Chapter 5

Emissions

When dealing with the emissions there is a strong trade-off between global (greenhouse gases, ...) and local (health, NOx, ...) effects.

5.1 Emission formation

The ideal combustion case is:

$$C_xH_yO_z + O_2 \rightarrow CO_2 + H_2O \tag{5.1}$$

We can see that CO_2 is the product of the combustion at the same level of the H_2O and should not be considered as pollutant. But in reality what happens is:

$$C_xH_yO_z + O_2 + N_2 \rightarrow CO_2 + H_2O + N_2 + O_2 + CO + C_xH_yO_z + C_mH_nO_o + NO + H_2 \tag{5.2}$$

However, the CO_2 contributes to the greenhouse effect when coupled in the atmosphere and its minimization is also important from an efficiency viewpoint. It is not the only greenhouse effect gas, the other have more consequent effects.

Pollutants have several negative effects, for example:

- CO is very toxic (asphyxiation).
- NOx which combined with HC and sunlight produces **ozone**. Ozone can lead to respiratory or cardiac problems.
- $NO + O_3 \rightarrow NO_2$ formation occurs very quickly. It leads to lung malfunctioning, acid rains HNO_3 and formation of Nitro-Pah (carcinogenic).

In fact the smaller the particle the more treatment it requires because it penetrates easily into lungs.

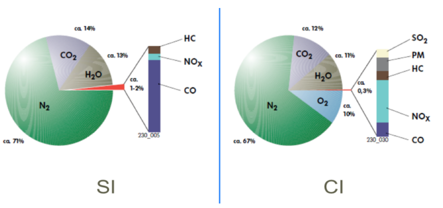


Figure 5.1

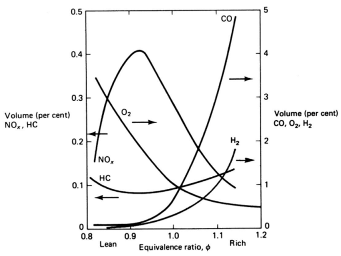


Figure 5.2

Above we can see that SI and CI engines do not have the same emissions and we can also regroup all the parameters leading to emission in function of the equivalence ratio as shown on the plot. In SI engines, the important phenomenon leading to main emissions is the absorption of HC by deposits and cylinder walls that free them at the emission point.

CO Carbon monoxide is mostly produced in SI engine when the fuel is rich ($\lambda > 1$) and is due to incomplete combustion. It is still present in lean fuels because of the dissociation reactions:

$$CO + \frac{1}{2}O_2 \leftrightarrow CO_2 \qquad CO_2 + H_2 \leftrightarrow CO + H_2O \tag{5.3}$$

that happen more easily in high temperature. It is thus possible to reduce it with combustion temperature decrease.

NO The NO production mostly depends on the temperature, this is due to the kinematics of the reaction which shows a dramatic increase in production rate when above 1800 K. The equivalence ratio plays also a role since NO needs oxygen. The maximum is at $\lambda \approx 0.9$ since when higher, temperature increases but less oxygen and the contrary when $\lambda < 0.9$. It also needs times for production and thus is more present at low rpm.

Unburned HC The unburned hydrocarbons are mostly due to incomplete combustion. Other origins: "short circuit" between intake and exhaust valves, slow combustion or flame extinction, absorption desorption of fuel by oil, deposits or crevices.

Soot This emission is mostly due to not optimal combustion (ignition delay, speed) and is mostly observed in direct injection → CI, but also SI direct injection now. It increases dramatically in congested traffic and during idling. We remark also that SI engines produces PM.

5.2 Emission regulation

Emission legislation were implemented because of the concerns for the air quality and the impact on human health. From epidemiological studies, the upper limit before negative effects can be determined. Based on this limit and model on diffusion of pollutants, we can determine what is the limit on a global scale (country) and local scale. From these numbers and other assumptions, we can go back to the limit per source of pollutants, such as vehicles.

Legislation differs from region to region, from the vehicle size, ... The difference between market is difficult with the manufacturer since he has to adapt the vehicle to each market, but they tend to harmonize. The legislation is based on g/km emitted during a test cycle representative for real world driving (previously NEDC as project).

5.2.1 Chassis dyno cycle

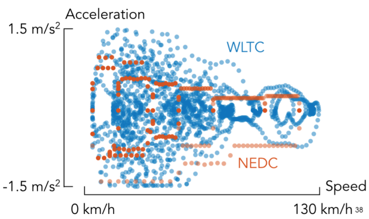


Figure 5.3

The test are performed in a laboratory on a test bench. They are potentially non realistic but the legislators ask for durability of the results. But this is a way of harmonising the legislation as the tests are the same for everyone. To illustrate how dynamic a cycle is, we can plot for every second of the test what is the acceleration and speed of the vehicle. For NEDC, this is illustrated by small acceleration and a very simple pattern. For

WLTC, the range of acceleration and speed is much bigger and variable. However, this is still a predictable cycle, which could be identified.

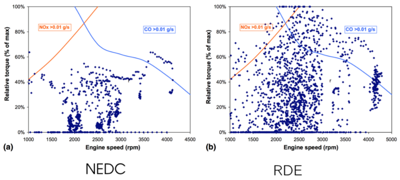


Figure 5.4

The other problem of NEDC is that the entire operating map is not used. Here a comparison between Real Driving Emissions. It provides data with more insight and there is more random point on Figure 5.3 (more difficult to cheat).

5.2.2 Post-processing

As we have a lot of information we have to threat them. The first method is **EMROAD** (moving averageging window). The data is plotted on windows regarding their CO_2 accumulation, then we compute the average mg/km for all pollutants, then we find a value for the entire trip.

The second method is **CLEAR** (Power Binning), the data is ranked in function of the instantaneous power bins. The post-processing is sensible to the windowing used. We use a setup to measure the dynamic profile of PM in GDI (gasoline direct injection), it relies on an impactor that can determine the number of particles of different sizes.

5.2.3 Cheating

- Thermal window defeat device: temperature below the must for test
- Hot restart defeat device: if engine already hot
- Cycle detection defeat device: if we already know the cycle.

For the VW scandal for example, it is easy to prove cheating by change of emission strategy (cycle known). We only have to remake the cycle but backwards, the results should be very similar with non-cheating car. In the VW case they were 6 times higher than the legislation limit.

5.3 Emission reduction

There are many countermeasures for emissions. First in the input of the engine, we could change the fuel composition and lower the aromatics, but then RON decreases and thus lower efficiency. In the engine we could play with ignition time, ... and after engine, we could add catalysis.

NOx treatment NO production is reduced by playing on the temperature and the combustion time. Most of the time this results in a trade-off. For example, delaying the ignition timing decreases the peak temperature and NO but it also decreases the efficiency. Another often used method is the Exhaust Gas Recirculation, this consists in reinjecting part of the exhaust gases, so that the unburned fuel can burn and the inert gases makes the pressure and temperature lower in the combustion.

HC, CO and NOx at eq. ratio 1
→three-way catalyst

HC, CO at eq. ratio below 1
→oxidation catalyst

NOx at eq. ratio below 1
→DeNOx or SCR

Soot
→filter

Figure 5.5

If previous solutions are not enough, we have to treat the exhaust gases. The strategies to reduce the pollutants will depend on the type of pollutant and the conditions in which they are produced (λ, T, ...). For example, CO, HC and soot are oxidised to CO_2 and NOx reduced to N_2, and the way to perform it differs with λ.

5.3.1 The three-way catalyst

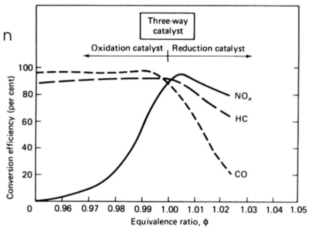


Figure 5.6

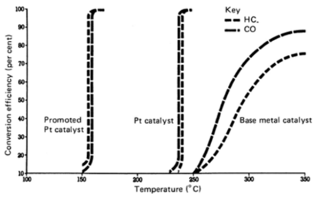


Figure 5.7

The principle of the three-way catalyst is to use the synergy between the oxidation of HC and CO, and the reduction of NOx. To be effective, the catalyst should have a mixture of gases that stays very close to equivalence ratio 1, as shown in the figure. This is typically used in SI engines. For this the ECU measures the λ and adjust the injection. This is a complex and expensive device: use of ceramic or metallic brick with holes and Pt, Rh, Pa catalytic material.

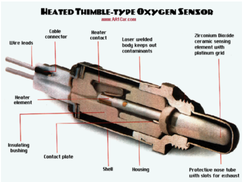


Figure 5.8

Reduction and oxidation processes have an activation temperature, thus this is a problem when cold start. We can use Electrically Heated Cat (EHC), combustion in exhaust or Close Coupled Cat (CCC). On the figure is plotted a **lambda sensor**, the principle consists in having one electrode in contact with air, another with exhaust and produce a voltage proportional to the O_2 difference.

Disadvantages There is a maximum sfc in for lean mixture and maximum power for rich mixture, but we want to stay at $\lambda = 1$. Pumping losses are higher because there is a backpressure from the device. There is a conflict between the exhaust temperature that must be high if we have efficiency and the conversion efficiency. Also between CO_2 production and emission limits.

5.3.2 Filtering

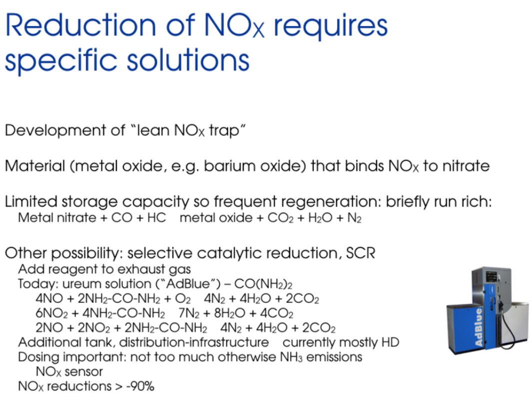


Figure 5.9

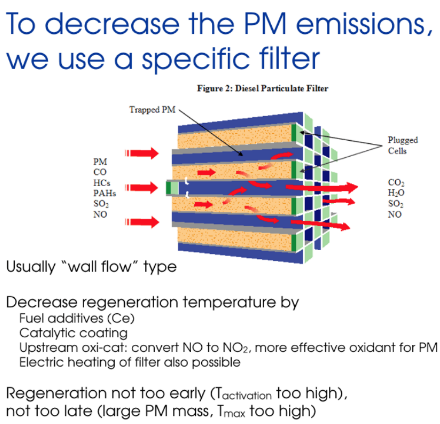


Figure 5.10

The filter principle consists in combining the pollutants with other material to make something better. Since the capacity of catalyst is limited, regeneration is needed. In the process of purification of PM for example, there is also a post-injection to increase the temperature of the exhaust to make the catalytic effect easier. It is possible to combine filtering and catalytic effect in continuously regenerating filters.

As previous case, here are also some trade-off: the reduction of PM and PN is very important ($\approx -98\%$) and it is very effective for nanoparticles, but back pressure and regeneration decrease efficiency.

5.3.3 After-treatment guarantee during life time of the vehicle

When cat ages, the light-off temperature increases, the retention capacity, conversion efficiency decreases and reactivity for different components varies. The aging is accelerated by catalyst poisons like sulphur, this is why we try to keep it minimal in the fuel.

Chapter 6

Combustion in CI engine

Diesel had many contacts in UE. In Belgium they were located in Gent, we get the license to build the diesel engine, and we succeeded to make the more powerful engine in those days (proud of us).

6.1 Classification

They can be classified on basis of the rpm. Fast (500-5000) and slow (100-400) running. The limitation of the rotation speed is due to the much higher compression in the engine, forcing the use of other materials like steel and not aluminum, increasing the inertia, the ignition delay also plays a role in the speed limitation. 2 strokes engines are more efficient (with compressor and with valves), thus we classify also in term of strokes and number of pistons in cylinder. On basis of the combustion chamber, we had a separated combustion chamber for indirect diesel injection. The direct injection is much more efficient. Finally, we differentiate them in functino of the construction mechanism (piston + piston rod + cross head or piston + connecting rod).

Differences with SI We have auto ignition instead of spark ignition. The fuel is different (diesel with Cetane number for the ignition delay) and higher temperature and pressure. Consequences on the material used. We work with lean mixture, excess of air wrt diesel (evaporation in hot air). High efficiency, for a fast running it goes up to 35%, for large engines, slow ones have an efficiency of 40-45%.

6.2 Combustion process

6.2.1 Droplets

The fuel is injected in form of droplets directly in hot air, the size of these is important in the combustion process. The longer the combustion delay, the more time the combustion will take. It depends on parameters: the CN of the fuel, the pressure, the temperature, the amount of turbulence, the size of the droplets, enough oxygen or not.

This is the cylinder, in the middle is an injecter for the droplets that go in the hot air. They will start burning at a certain time, then we continue to inject fuel. When the first droplet starts burning we are still adding fuel, the most important delay is the one of the first droplets since the next ones will be in higher temperature. The combustion chamber is designed to increase turbulence.

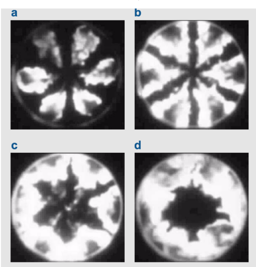


Figure 6.1

To ignite the droplet, we need high temperature and high pressure thus ϵ. The droplet size also influences, if d is its diameter and we qualify $Q_{required} = d^2$ and $Q_{received} = d^3$, we must respect:

$$k_1 d^2 > k_2 d^3 \qquad \Rightarrow d < \frac{k_1}{k_2} \tag{6.1}$$

The diameter must be small to easily ignite. On the other hand, the droplets have to find enough air and this requires larger droplets (they also go further). The diameter is also function of the input nozzle and pressure. The pressure is also important, the size of droplets express a driving force, the more we apply a pressure in the injection, the further it will go in the combustion chamber. We try thus to have the highest input pressure.

6.2.2 Air fuel ratio

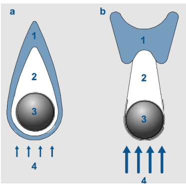


Figure 6.2

If we increase the power, we inject more fuel so we are getting less lean. But the regime of a Diesel engine is lean mixture. Here we have a problem because in SI engine the mixture is more or less heterogeneous but here we can have λ concentrations in the chamber. For example, on a simple droplet λ can go from 0.3 on a region to 1.5 on another region.

On the figure we can see that the droplet is not a simple ball but we have the droplet, the evaporated envelop and the flame zone.

6.2.3 Ignition delay

The droplet must evaporate, realize the cracking process (carbonized particles separate), the time between injection and combustion is called **ignition delay**. This is one cause of the rpm limitation and depends on the Cetane number, the droplet size and the combustion chamber design.

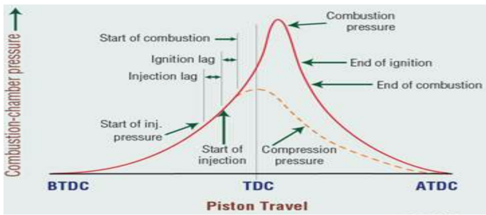


Figure 6.3

Cetane number It gives an information on the ignition delay, the higher it is, the lower is the delay and is about 50 for ordinary diesel and 60-70 for super diesel. Ignition delay becoming shorter, the rpm can be higher. The only advantage to have super diesel is when we start the engine (cold). In ships they use heavier fuel, CN is about 30, engine running at very low speed so we have much more time to ignite the fuel (lower price).

Combustion chamber The combustion chamber in Otto engine should avoid the auto ignition. In Diesel one must promote the auto ignition! To promote the ignition we can create turbulence.

Separate combustion chamber

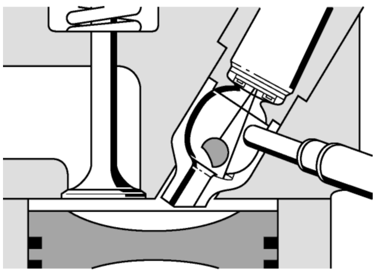


Figure 6.4

Pre-chamber The pre-chamber allows to make a "pre-combustion" to cancel the ignition delay. Since there is low amount of air, the combustion is slow, the pressure too and it increases gradually (high pressure don't needed since the combustion already started). Less emissions of NOx and soot. Less thermal load on the engine. Then the burning droplets are transferred to the combustion chamber. This can lead to diesel knock because of the bulk fuel. We have to pump the fuel in the pre-chamber, increasing the losses. Difficult cold start since it is in the cylinder head and has more thermal inertia (cooling systems).

Figure 6.5

Whirl chamber The idea is the same, but it is not completely detached from the combustion chamber, it is just a passage before going to the chamber. The advantage is that there is a bit less loss than the previous case.

Combustion chamber in the piston

The advantages are that it is a simple construction, the losses are low (high output) and excellent cold start properties. But due to higher temperatures we have more soot and NOx, more vibration, larger ignition delay (lower speed), injection pressure must be higher and nozzle with several holes necessary, the cooling is a bigger issue.

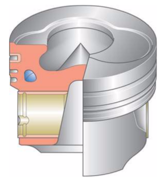


Figure 6.6

Figure 6.7

Glow plug Pre-heating systems are possible to counter cold start by using flame heater or **glow plug**. This is shown on the picture, heating electrode. It is important because at start, the engine is cold, so we have compression losses, large ignition delays leading to knocks.

6.3 The injection system

Its role is to inject the fuel in the adapted quantity as droplets in the combustion chamber at the correct moment. Management of the drop size, penetration (inlet pressure), and quantity. The injection can be performed in one step or in several steps. The second consist in performing a **pilot injection** then inject the real quantity and sometimes a bit more after to burn the soot.

The injection system is composed of the fuel tank, fuel filter, low pressure fuel pump, high pressure injection pump and injection nozzles.

As types of injection, former days we had the: inline fuel injection pump with mechanical regulation and axial piston distribution injection pump controlled mechanically. Now: common rail injection, pump nozzle unit, electronically controlled.

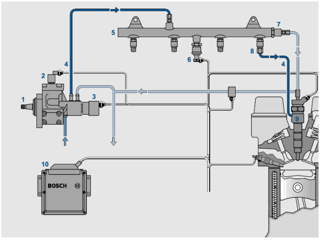


Figure 6.8

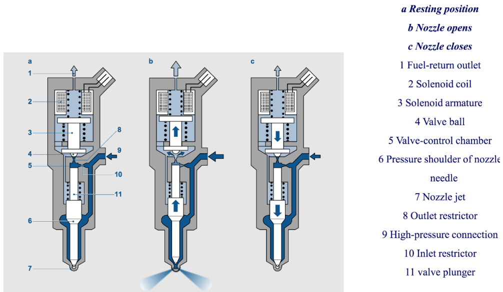


Figure 6.9

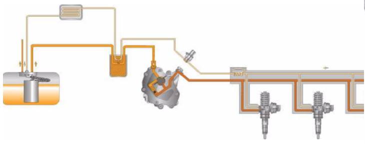


Figure 6.10

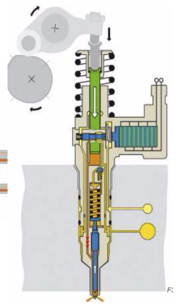


Figure 6.11

Above is plotted the rail injection, the nozzle principle, the unit injector system and unit injector (I don't really understand the difference if you want to explain it here don't hesitate).

6.4 Diesel engine benefits

High torque, operational safety, production cost, economy of operation fuel, Reliability. The major advantages for the efficiency above the SI engine are: higher compression ratio, air excess, no throttle (no loss), lower consumption. Increased compression ratio improves thermal efficiency and lowers specific fuel consumption, but increases pumping, friction and compression/expansion losses. For example, ϵ going from 10 to 20 increases the thermal efficiency from 26 to 40% but decreases mechanical efficiency from 83 to 75%.

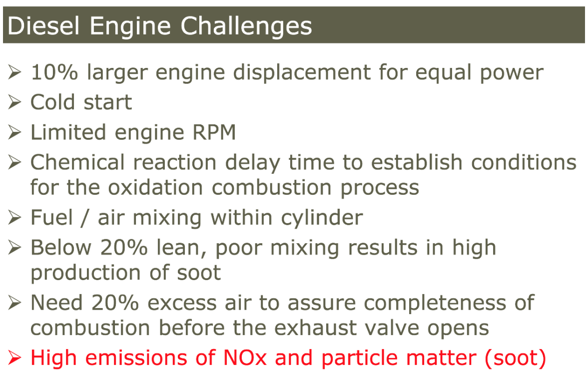


Figure 6.12

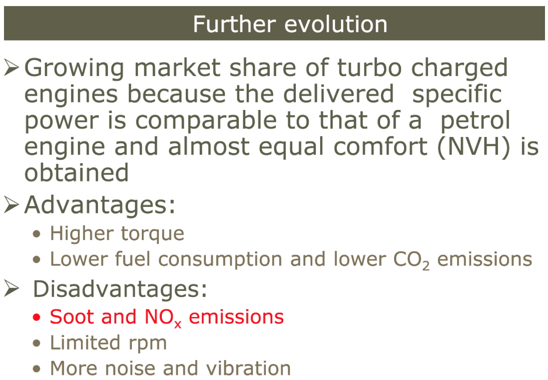


Figure 6.13

Chapter 7

Intake and super/turbo charging

7.1 Torque curve

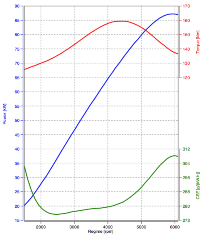


Figure 7.1

The maximum torque and power have this shape. To see why, let's define the **volumetric efficiency**:

$$\sigma = \frac{m_{air,real}}{m_{air,theoretical}} = \frac{p\frac{V_{cyl}}{rT}}{p_{ref}\frac{V_{cyl}}{rT_{ref}}} \tag{7.1}$$

the reference values are chosen as those at the intake.

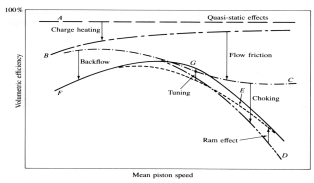


Figure 7.2

This can be represented as A on the graph, but there is many losses: B charge heating because the lower the rpm the more time we heat the gas; C viscosity, D chock at high rpm, E back flow due to overlap, the rest is second order losses. We can see that the shape is very similar to the torque curve, the most we admit mass, the most we have torque. The length of the intake pipe plays also a role. The reason is that consider a cycle, when the valve is closing, the intake is disrupted and this creates a pressure wave in the pipe.

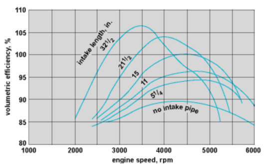


Figure 7.3

This will travel until the other side of the pipe and will be reflected. If the valve is open when the wave reach again the valve, there will be a pressure boost, increasing mass, increasing torque. This is called **engine acoustic**, the wave propagates at speed of air. The pipe design is used to modify the torque curve. This can be used in multicylinder engine but it is more complex since the wave can be used for another cylinder. And we can play with it: change of the length of the pipe (natural frequency), change between 3 cylinder acoustic and 6, allowing to modify the torque shape continuously.

7.2 Valves

The valve is a nozzle that creates pressure losses, so it is designed carefully. Consider the radius R and the lift l, the area can be approximated by a cylinder surface:

Figure 7.4

Figure 7.5

$$A_c = 2\pi R l \qquad \Rightarrow A_e = C_D A_c \tag{7.2}$$

where A_e is the effective area taking into account the corrective factor for aerodynamic configurations C_D (discharge coefficient). The maximum voluetric efficiency is obtained with maximum area, this is why we don't have straight valves in gasoline engine and the combustion chamber is in the cylinder head. The intake valve is the bigger one to make the intake easy, but has to be not too big because of the cooling issues.

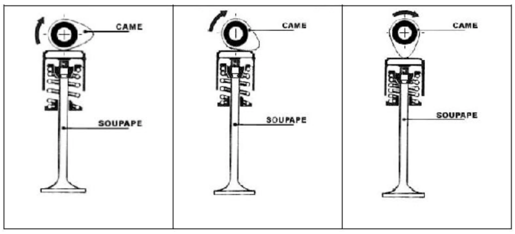


Figure 7.6

The working principle is exposed on the figure, we have **camshafts** turning with the engine that manage the opening/closing. Increasing the number of valves increases the cost since we need more camshaft. We could also use a single camshaft for both input and output valves but the force will be higher and will limit the lift size, thus the efficiency. But having 4 valves makes the torque higher than 2 valves, increasing the cost.

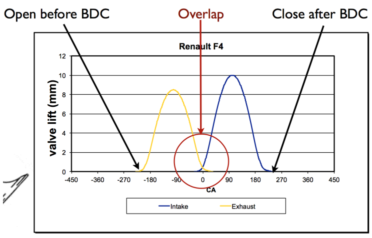


Figure 7.7

The lift law is linked to the camshaft. Valve timing is driven by mechanical stress on camshaft and by pressure waves. There is an overlapping, generally not a problem, but we can play with it for example by trapping the gases in the cylinder after the exhaust (shift of intake on the right). This is called **Internal gas recalculation** (IGR) and it lower the efficiency. If we shift the intake to the left, the gases are flowing from inlet to outlet thus this is only used in direct injection to increase the performances, otherwise fuel to the exhaust. A way to use the acoustic waves is to shorter the compression stroke (Atkinson cycle better efficiency).

7.3 Control of the torque

7.3.1 Gasoline

Figure 7.8

We can compute it as:

$$P_{out} = \eta P_{fuel} = \eta \dot{m}_{fuel} LHV \propto \eta \dot{m}_{air} LHV \phi \quad \Rightarrow T_{out} \propto \eta \dot{m}_{air} LHV \phi \tag{7.3}$$

so we see that we can play on the mass flow of air, this is done by cam profile or by intake pressure. Intake pressure is varying by means of the **throttle**. Impossible to change the equivalence ratio a lot because of the pollutants.

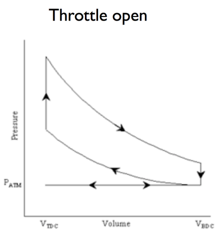


Figure 7.9

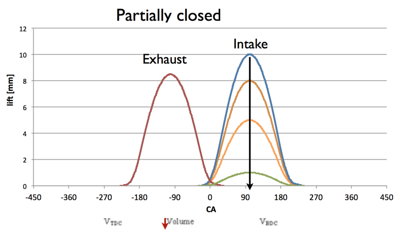


Figure 7.10

The problem with the throttle is that it increases significantly the pumping losses due to pressure losses. At the limit case of idle, we are still consuming because we counteract the pressure loss. Another way of controlling the torque is based on the lift size as shown on the second figure but this is more and more complex.

7.3.2 Diesel

First of all, there is less acoustic waves here because turbochargers kill it and the valve timing is limited by the piston motion. Indeed the compression ratio is much higher than in gasoline case, the piston head must be flat and thus the valve straight. The cylinder head - piston clearance is 0.7 mm, the valve should be closed when at TDC. It is thus very difficult to use waves to play on the shape of the torque, the area for the valve is limited, ... The volumetric efficiency of the diesel engine is limited to 0.7 without turbocharger (against 0.9 for gasoline). We will see that the shape of the torque curve is controlled with the **turbocharger**.

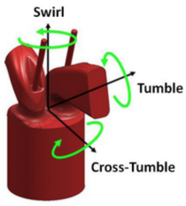


Figure 7.11

There is no camshafting or any fancy device on diesel since we have the turbo. For what concerns the number of valves, with 2 there is not a good swirl (aerodynamic) at every regime and lead to bad combustion. Valves are very important to generate turbulence via high speed air intake. In gasoline the main is **trumble** and for diesel, **swirl** for the mixing.

7.4 Turbocharger

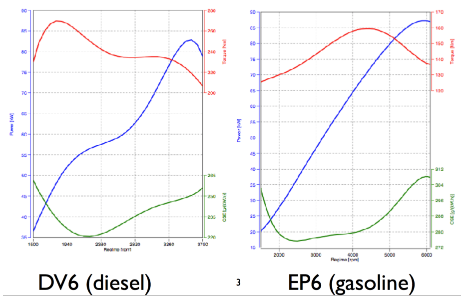


Figure 7.12

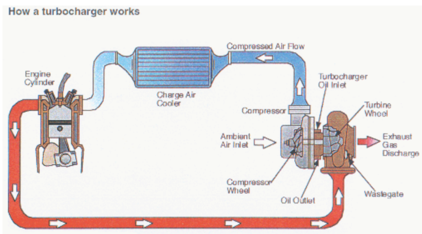


Figure 7.13

One expects that the diesel engine will provide more torque than the gasoline because of the higher pressure ratio. But if we look to the equivalence ratio, due to soot limit $\lambda = 0.7$ for diesel and 1 for gasoline. 30% of the air is not used. The diesel engine should thus provide less torque and power (7.3). **But this is not the case! Because we love turbochargers <3**. This consists in increasing the air mass flow in the same equation, by increasing the inlet pressure (7.1). This is done by transferring the exhaust expansion energy to the compression of the air.

Compressing increases the temperature, we add an **intercooler** to reduce it (keep high σ). To avoid over regimes, the turbo is controlled (rpm between 100 000 - 300 000).

7.4.1 Description

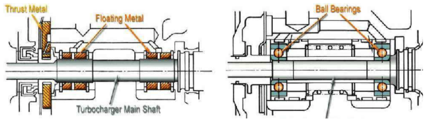


Figure 7.14

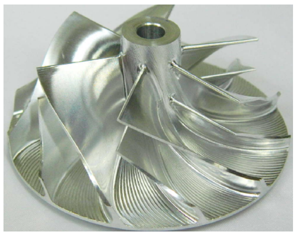


Figure 7.15

Sleeve bearing or ball bearing, the first has more friction for low loads. The turbo is cooled by oil (all the oil flow pass from the turbo). The main axle is linked to the turbine. Since the environment could be corrosive the material has to be chosen carefully (titanium for example) for the compressor represented on Figure 7.15. The turbo can only work on a limited range of rpm (we have to accelerate it). Small ones are easy to accelerate but compress less than a big one, which has more inertia and cannot rotate so fast. We define thus the **turbo lag**:

$$T = I\frac{d\omega}{dt} \tag{7.4}$$

where I increases and the other term decreases for big turbos. We can improve the turbo lag by for example adapting the incoming angle of the flow on the blades of the turbine or control the counter pressure coming from the exhaust. We could also use

- parallel sequential: use a small turbo for low mass flow and add one in parallel when higher
- series sequential: replace the small one by a big one.

This is good for lag but it is difficult to control since there is valves everywhere. We could also try multiple turbos with each their own working range. If we go out of the region, the torque is hardly decreasing because of the stress on the engine.

Industrial engines They are turbocharged which gives them an advantage. They can compensate for hot and high conditions, which is not the case for gas turbine ! No fancy turbo, simple one, matched on the nominal regime. One waste gate and one intercooler, that's all. Since mass flow is higher you can find axial turbine on BIG engines. The maximum torque of the diesel is more constant than the gasoline

7.4.2 Gasoline engines

The main problem for the use of turbos on gasoline engines is the throttle. Indeed, the introduced pressure loss is too high. We can solve this problem by downsizing, which goal is to avoid at maximum the throttle. In fact, we use the turbo as a throttle. We have a smaller engine with smaller torque and instead of decreasing the manifold pressure with a throttle, we increase the manifold pressure in order to get higher torques. But the throttle is still present.

In gasoline the mass flow ratio could go up to 80:1 while 6:1 in diesel, so the matching is more complex. Indeed we could combine variable valve lift, turbo, start stop, ...

Some concerns First of all, the use of turbo increases the knock sensitivity leading to downsizing even more, lower compression ratios and efficiency. Turbo charger has a protection for high rpm, thus we still need to use the throttle when the turbo is turning.

Knock sensitivity can be reduced by reducing the compression ratio, changing the cycle (exhaust valve open during compression start). The turbo protection requires temperature maximum, the exhaust temperature minimal we can get from downsizing is still high. We can decrease it by adding more fuel! But this is lost fuel.

Turbochargers only increase performance and not the overall engine efficiency.

7.5 Compressor

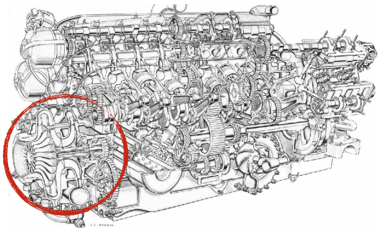


Figure 7.16

This is another way of increasing the input air, before the turbo. It consists in compressing the air but linked to the crankshaft. For aero engine in the 1930s for example there were centrifugal compressors.

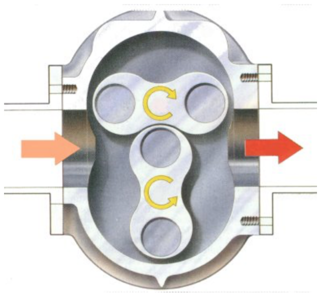


Figure 7.17

The roots compressor Rotation is given by the crankshaft. Since there is no volume change, pressure ratio is limited. Isentropic efficiency is very low and there are leaks, reducing further the efficiency. There is an increase in kinetic energy due to the lobes rotation, then a sudden transition from kinetic to pressure energy which is bad for efficiency, on a turbo the volute is responsible for energy conversion. Always coupled with an intercooler.

Further **helicoidal** roots have been developed, making the transition between kinetic and pressure energy smoother. Its efficiency is as high as the turbo compressor. This is sometimes used in engines nowadays, since there is no change in efficiency but the cost is lower. Since it is linked to the crankshaft rotation, the use of a throttle is tricky. But it needs recirculation, the compression ratio is low and thus cannot be used to boost on diesel. **The main advantage is the very very low response time, allowing to boost the torque at low rpm**.

A turbocompressor (CVT) can also be used, it is a turbo linked to the crankshaft, giving low response time, but rotation speed much lower. The gain in response time can also be performed by electric drive compressor.

In the end ...

	Roots Helicoidal	Turbo	Turbo 2 stages	Compresseur électrique	Compresseur CVT
Cost	average	average/high	very high	very high	average
Efficiency	< 75%	< 80%	< 80%	< 80%	< 80%
Response time	fast	slow	average	(very) fast	(very) fast
low rpm torque	very good	bad	good	good	good
pressure ratio	2.2	3.5	6	3.5	3.5
Catalyst heat up	normal	normal/slow	slow	normal	normal

On industrial engines, only one turbo.

- Roots does not boost enough the performances
- Electric/CVT too costly
- Two is too complex, costly and not reliable

Figure 7.18

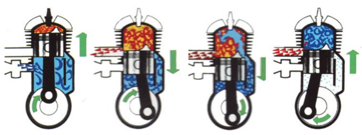


Figure 7.19

The expansion of exhaust gases reduces the temperature and could be not good for the catalyst effect. For a 2 strokes engine the only device to use is the **turbo**. Indeed, since the exhaust is performed by means of the piston motion, it is bad to put counter pressure at the output.

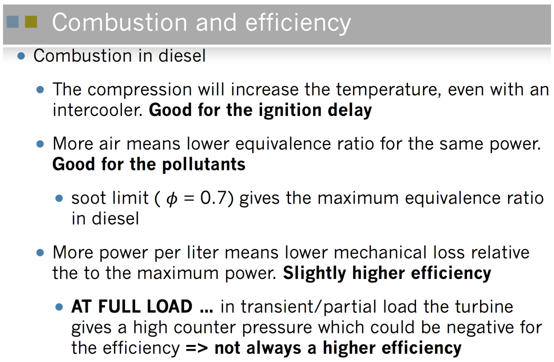


Figure 7.20

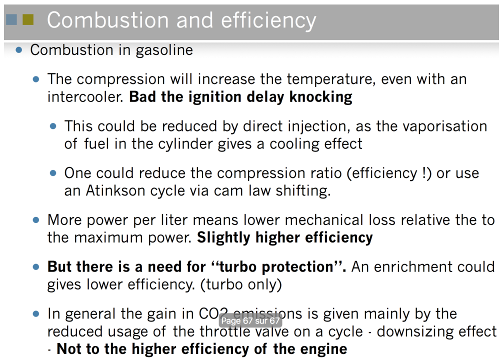


Figure 7.21

Chapter 8

Alternative cycles

8.1 Low temperature combustion

8.1.1 Homogeneous Charge Compression Ignition

The HCCI mode combines the principles of the homogeneous charge of the SI engine combined with the auto-ignition of the CI engine. The objective was to better control 2 strokes gasoline for weak mixture. They arrived to lower the consumption of 29% (Honda Activated Radicals Combustion). The results pushed to make research for the 4-strokes. The main difference with SI engine is that the combustion don't occur with the waiting of flame propagation but the mixture ignite a bit everywhere.

HCCI combines the advantages of diesel and gasoline engines. For example, it can burn any fuel and the NOx emission is reduced consequently. Indeed, since the fuel dilution is higher, the thermal efficiency is higher and thus NOx lower. Additionally, there is no rich zone and this decreases the soot. The drawbacks are that the NO and HC emissions are increased, the load/speed range is is limited and no direct control.

Increasing working region

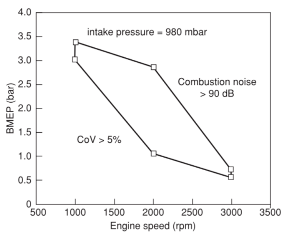


Figure 8.1

There are two main limits for HCCI. The lower limits is due to instability of the auto-ignition, illustrated by the Coefficient of Variation (CoV). The upper limit is described by the high energy release rate which lead to "knocking". For what concerns the controllability, in traditional engines we have the injection and the spark, here not. In HCCI the auto ignition is function of many parameters having influence on the combustion.

Variable compression ratio The compression ratio is directly linked to the temperature at TDC. So if we can control it, we're done with the auto-ignition. But this is very complex.

Variable valve timing This is already very often used on traditional engines, it allows to control the compression ratio through opening and closing of valves.

Charge heating, turbocharging, injection timing, fuel mixture Charge pre-heating is also an option but generally presents a certain inertia which limits to control for each cycle. Injection timing is used in

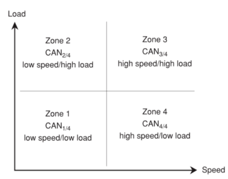


Figure 8.2

alternative low temperature combustion (see below). Turbocharging and control of the inlet pressure is also an effective way of changing the combustion timing. For the mixture, we introduce a new number to characterize combustion in HCCI which is **CAI number (CAN)**. This is illustrated on the figure. We can use the different technologies together but the challenge lies in the transition from one mode to another.

Current research Consult the slides for more info but I don't think it is important. Be aware that Reactivity controlled Compression Ignition is experimented, we use small gasoline quantity in diesel. This method lowers the soot and NOx emission compared to full diesel.

8.2 Other cycles

Atkinson cycle

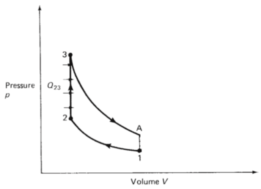


Figure 8.3

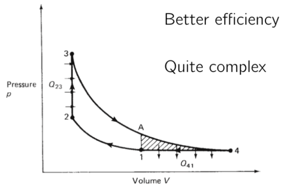
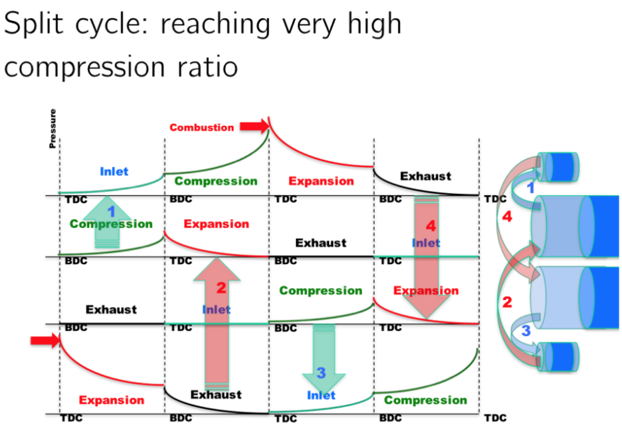


Figure 8.4

The Atkinson cycle is an Otto cycle but with different compression and expansion ratio. Indeed, in Otto cycle, the compression and expansion ratio are the same, but this let a still high pressure at the end of expansion. The Atkinson idea is to take advantage of this last pressure. This would provide indeed more efficiency but this is complex. This is achieved by opening the exhaust later, but then power density decreases (we can compensate by supercharger → Miller), used in hybrid cars (electric for high loads).

Scuderi cycle The idea is to have to combustion chamber, the first one exhaust goes into the other for a second combustion.



End of the story, enjoy!