



UNIVERSITÉ LIBRE DE BRUXELLES

SUMMARY

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**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 Marc OVERMEIRE 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 L<sup>A</sup>T<sub>E</sub>X, 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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# 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.

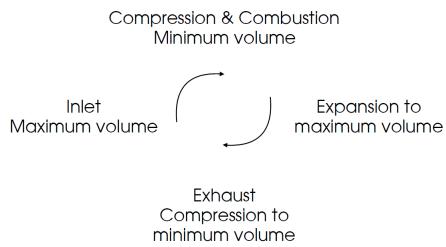


Figure 1.1

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:

$$\begin{aligned} \text{chemical} &\rightarrow m_f.\text{LHV} = Q_{in} \rightarrow \text{thermal} \\ &\rightarrow pV = nRT \rightarrow \text{mechanical} \end{aligned} \quad (1.1)$$

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 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 cost and safe. Its disadvantages are vibration, noise, emissions, gases are in contact with the engine and depend on fossil fuel.

### 1.1.2 Mechanism

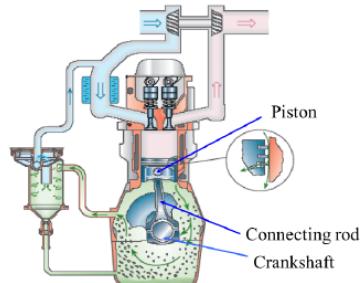


Figure 1.2

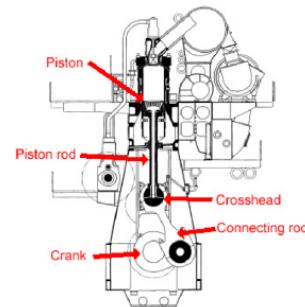


Figure 1.3

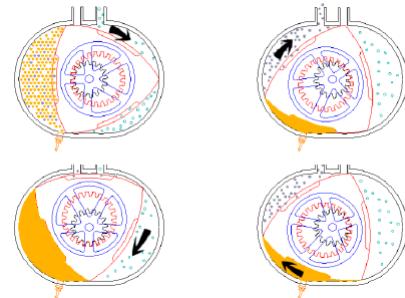


Figure 1.4

- Figure 1.2 - The mostly used mechanism is composed of a **piston** connected to a **crank-shaft** 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 relate in the sealing of the combustion chamber, the higher heat transfer, the efficiency, and the emissions.

### 1.1.3 Ignition

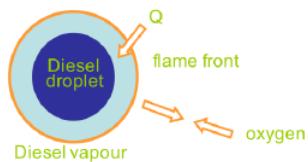


Figure 1.5

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.

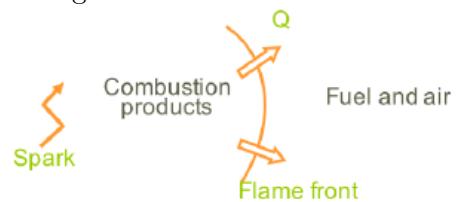


Figure 1.6

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 means 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.

### 1.1.4 Strokes

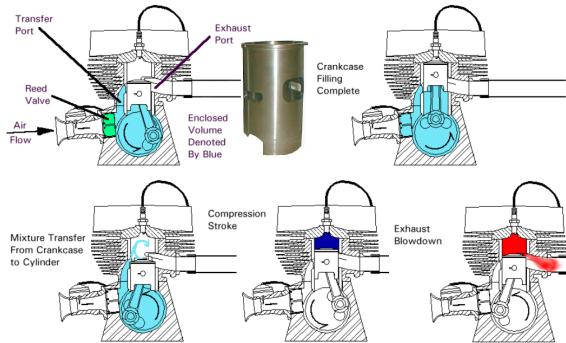


Figure 1.7

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.

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.

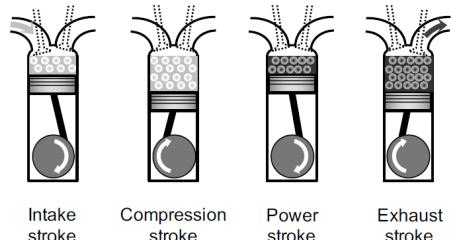


Figure 1.8

## 1.2 Cylinder arrangements

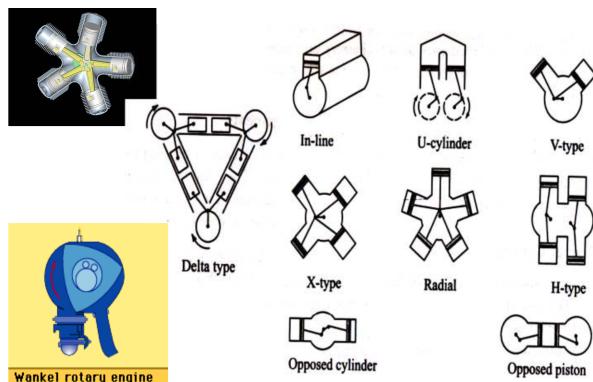


Figure 1.9

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

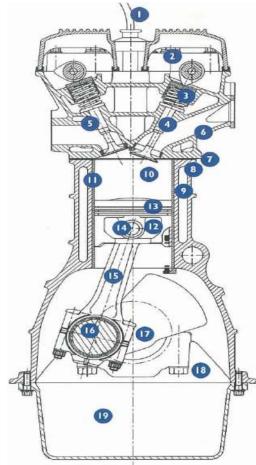


Figure 1.10

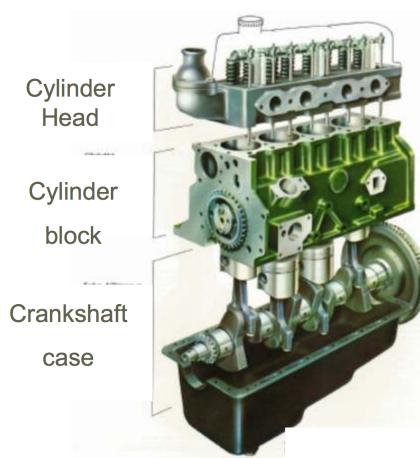


Figure 1.11

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

- **Cylinder head:** this is 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

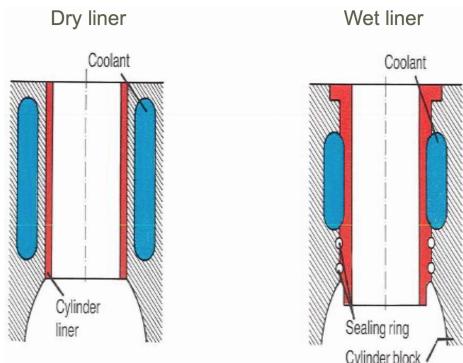


Figure 1.12

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 transfers 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).

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 expands when heated. We have to manage the thermal behavior to counter this → elliptical geometry when cold and we manage expand to have the good shape when it heats.

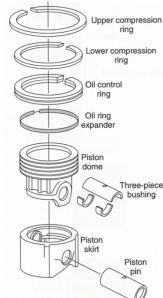


Figure 1.14

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.

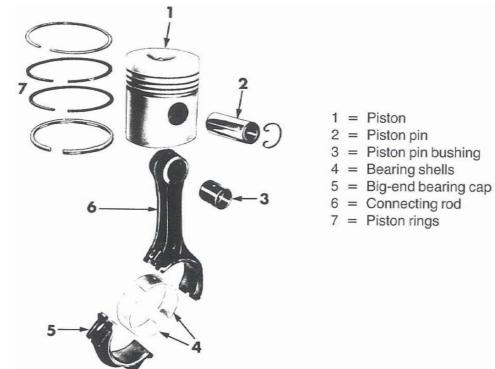


Figure 1.13

### 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.

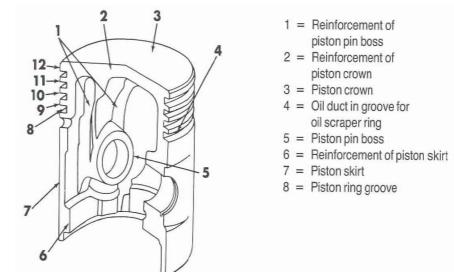


Figure 1.15

### 1.4 Blow-by due to leakage

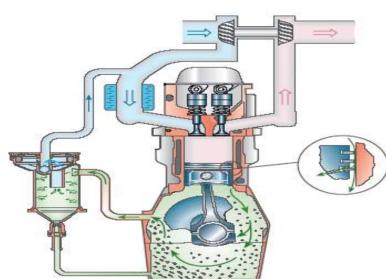


Figure 1.16

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

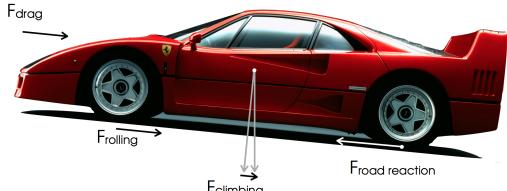


Figure 2.1

of the car are **rolling** of the tires, **drag** and **gravity**.

#### 2.1.1 The rolling force

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:

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

$$F_R = C_R mg \quad P_R = C_R mgv \quad (2.2)$$

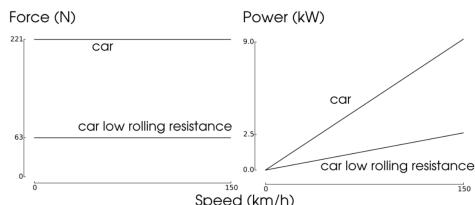


Figure 2.3

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:

$$F_D = \frac{v^2}{2} \rho_a C_D A_f \quad P_D = \frac{v^3}{2} \rho_a C_D A_f \quad (2.3)$$

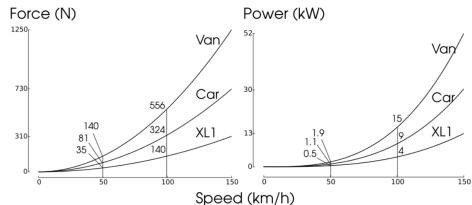


Figure 2.4

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:

$$F_C = mg \sin \alpha \quad P_C = mg \sin \alpha v. \quad (2.4)$$

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.

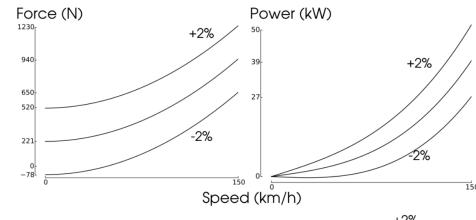


Figure 2.5

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

## 2.2 The wheels

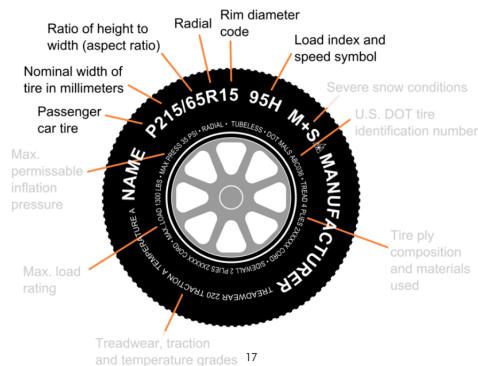


Figure 2.6

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:

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

Knowing this, the rotational speed of the wheel is  $\omega(\text{rad/s}) = \frac{\text{speed}(\text{m/s})}{d/2}$ . 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

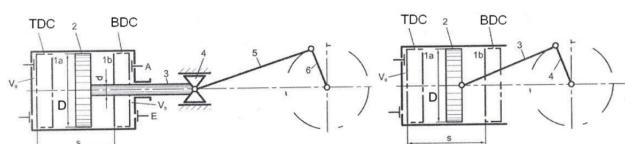


Figure 2.7

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	

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

$$V_d = \pi s \frac{D^2}{4} \quad \epsilon = \frac{V_c + V_d}{V_c} \quad (2.6)$$

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

Figure 2.8

$$V_m = 2s \frac{rpm}{60} \quad (2.7)$$

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:

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

where the fuel energy is converted into torque.

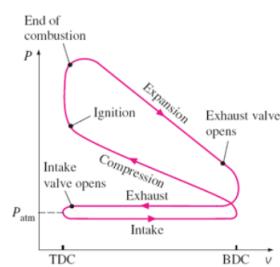
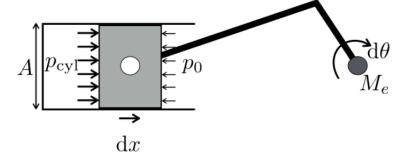


Figure 2.10



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**:

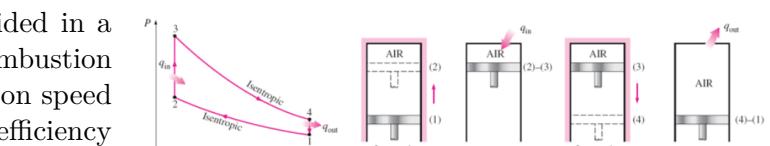
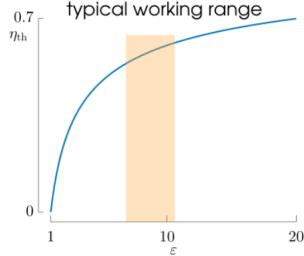


Figure 2.11

$$\eta_{th} = 1 - \frac{1}{\epsilon^{\gamma-1}}. \quad (2.9)$$



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  $\epsilon = 10$ .

Figure 2.12

### 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  $\epsilon$  is also important but there is also the **load ratio**  $\alpha$ :

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

where  $T_4, T_1$  and  $\alpha$  are not independent.

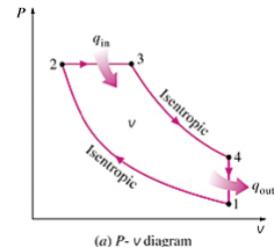


Figure 2.13

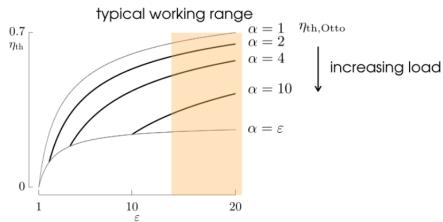


Figure 2.14

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:

$$\eta_{th,Otto} < \eta_{th,Diesel}. \quad (2.11)$$

### 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.

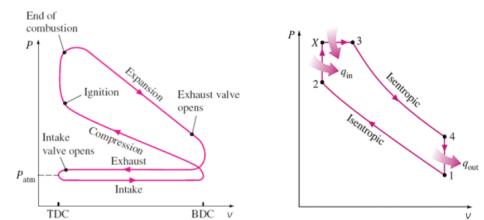


Figure 2.15

## 2.5 Power conversion steps

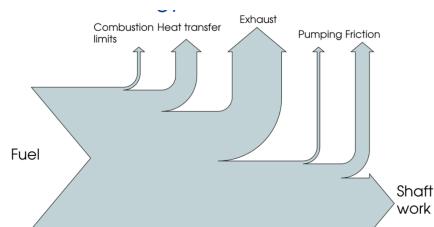


Figure 2.16

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):

$$\eta_i = \frac{W_i}{m_{fuel} LHV}. \quad (2.12)$$

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

$$\eta_m = \frac{W_e}{W_i} \quad \eta_e = \frac{W_e}{m_{fuel} LHV}. \quad (2.13)$$

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**:

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

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:

$$W_i = \oint p dV. \quad (2.15)$$

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

$$M_e N \pi = n W_e \quad (2.16)$$

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):

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

This allows to express the torque in function of BMEP:

$$M_e N \pi = n W_e = n V_d BMEP. \quad (2.18)$$

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

$$P_e = M_e 2\pi \frac{rpm}{60} = n V_d BMEP \frac{2rpm}{N60} \quad (2.19)$$

## 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.

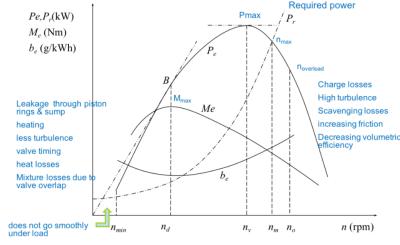


Figure 2.17

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).

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 deactivating some cylinder (Figure 2.20).

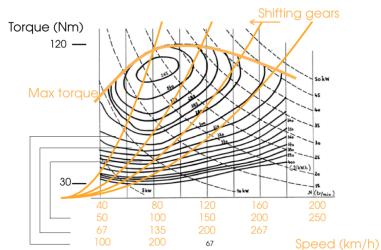


Figure 2.19

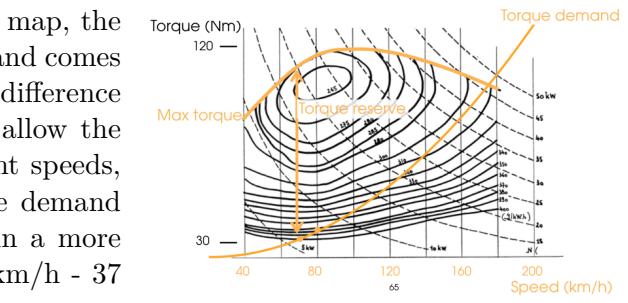


Figure 2.18

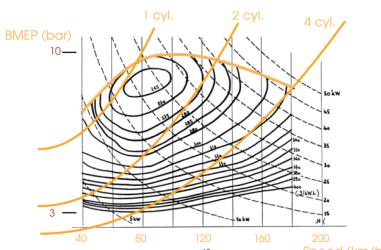


Figure 2.20

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

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

Knowing that the density of the fuel are:

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

the volumetric fuel consumption is given by:

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

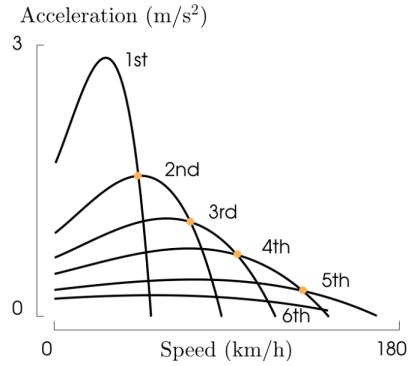


Figure 2.21

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

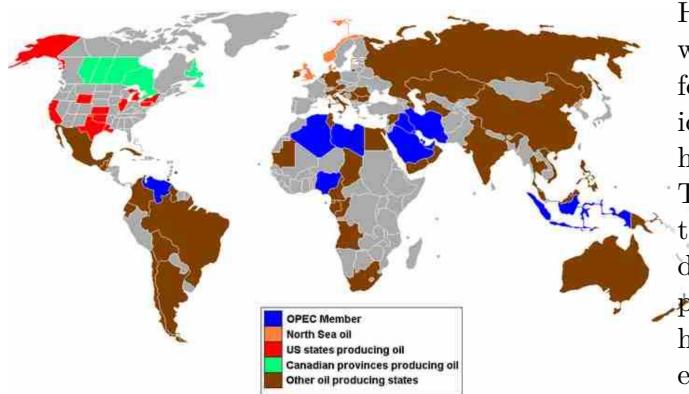
- High combustion value, more energy, when transport we can store it in a much smaller liter because there are more energy. In the batteries, the energy value is smaller than in fuel for example. For a car it is important but for an industrial use, we don't care.
- It has to be easily and efficiently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



tion tower.

Figure 3.1

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 distilla-

## 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.

- Normal paraffines:  $C_nH_{2n+2}$ 
  - saturated stretched chains
  - e.g. propane  $C_3H_8$ , butane  $C_4H_{10}$
- Isoparaffines:  $C_nH_{2n+2}$ 
  - saturated branched off chains
  - e.g. iso-octane  $C_8H_{18}$
- Olefines:  $C_nH_{2n}$  or  $C_nH_{2n-2}$ 
  - Unsaturated stretched chains (double bonds, 2H)
  - e.g. hexene  $C_6H_{12}$
  - Resulting from cracking
- Naftenes:  $C_nH_{2n}$ 
  - Ring structure (2H gone)
  - e.g. cyclopropane  $C_3H_6$
- Aromatics:  $C_nH_{2n}$ 
  - Benzene structure
  - e.g. toluene  $C_6H_5CH_3$
  - Undesirable (' why?')

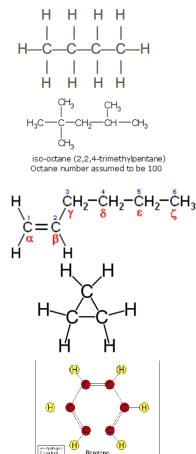


Figure 3.2

### 3.2.1 Characteristics

#### Petrol (gasoline)

Fuels are standardized, it is different from the USA to Europe. The boiling traject ( $30^{\circ}C - 200^{\circ}C$ ) 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 ( $180^{\circ}\text{C}$  -  $370^{\circ}\text{C}$ ). 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.

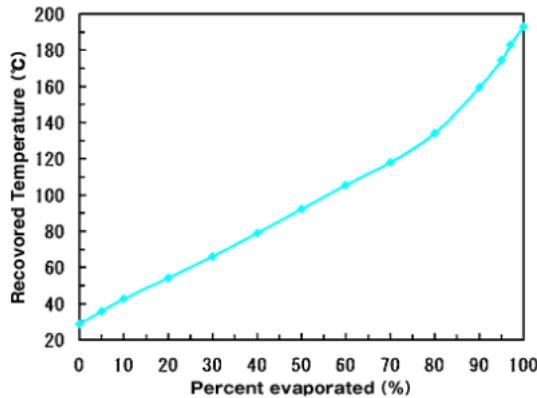


Figure 3.3

- 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 lubrication 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 ( $480\text{-}550^\circ\text{C}$ , 1 Atm) than diesel ( $330\text{-}350^\circ\text{C}$ , 1 Atm).

### 3.3.2 Deflagration and detonation

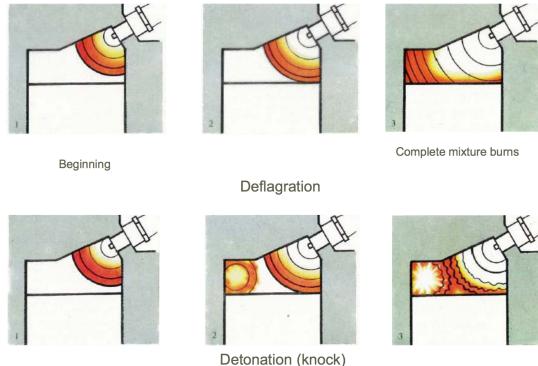


Figure 3.4

**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.

Before the combustion, 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**!

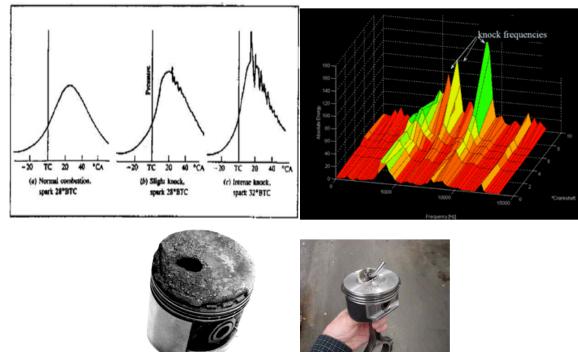


Figure 3.5

### 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 can make 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 oxygenous components like alcohols, but the volatility increase can damage the material.

### 3.4 Combustion in diesel engines

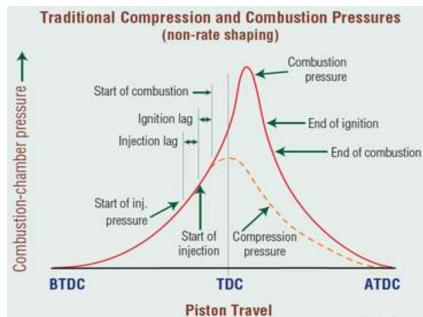


Figure 3.6

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**.

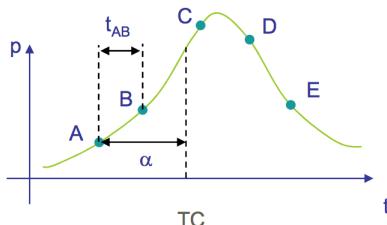


Figure 3.7

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 ( $>55^{\circ}\text{C}$ ). 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 soot 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 methylnaphthaline ( $C_{11}H_{10}$ ) 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 favors 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

- Importance is determined by:
  - energy question (dependency on import from foreign countries)
  - availability
  - production
  - storage and distribution
  - combustion properties
  - emissions and pollution characteristics
- Methanol
  - from oils, natural gas, coal
  - LHV = 0.5 LHV petrol  larger fuel tank, carburettor
  - large vaporisation heat: pre-heating mixture necessary (otherwise freezing carburettor)
  - As octane number is higher = compression ratio (and efficiency) can be increased
  - large ignition delay and therefore less suitable as diesel fuel
- Hydrogen
  - high octane number and small ignition delay suitable for petrol and diesel engines
  - Storage problem & safety
  - H<sub>2</sub> must be made! Important is how it is produced (green, nuclear, traditional)
  - Explosion danger (high explosion limit of 80%)!
  - Storage under high pressure and/or very low temperature
- There are several biofuels and conversion technologies
  - PPO (pure plant oil) e.g. colza (pressed)
  - biodiesel from colza, wood
  - bioethanol from e.g. cereals, sugarbeet, wood
- CO<sub>2</sub> neutral?
  - no but general balances are positive
- Energetically profitable?
  - yes, but there are major differences between the different biofuels
  - complete chain and LC should be considered: production, transport, conversion, blending final use
- Important other aspects:
  - economically profitable?
  - employment
  - land use: energy cultivation versus food production: food prices?
  - Additional products: significant quantities of animal food!
- Impact on the environment?
  - context: Kyoto + EU directive biofuels (5% in 2010, 20 % in 2020??)
  - CO<sub>2</sub> (location, renewable)
  - N<sub>2</sub>O (fertilization)
- What's the best application ?
  - In combustion engine? or to produce electricity? Or heat? Or focus on food production !

Figure 3.8

Figure 3.9

# Chapter 4

## Spark ignition engine

### 4.1 Mixture preparation in SI engine

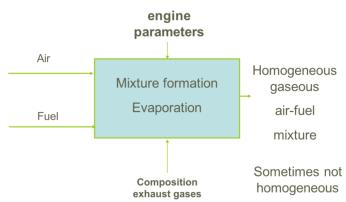


Figure 4.1

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.

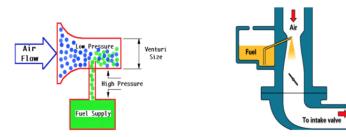


Figure 4.2

#### Importance of equivalence ratio for combustion

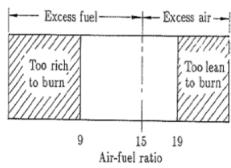


Figure 4.3

The best burning condition is obtained when stoichiometry (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.

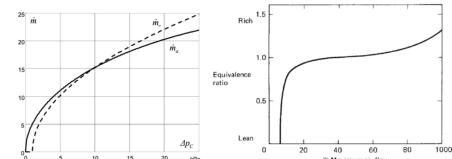
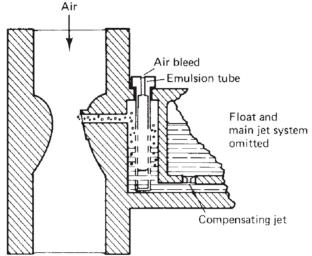


Figure 4.4

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.

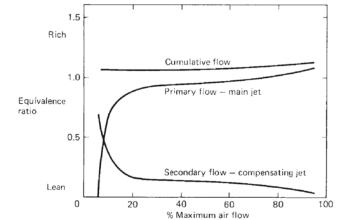
#### Compensating jet



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.

Figure 4.5

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.



### Idling fuel line

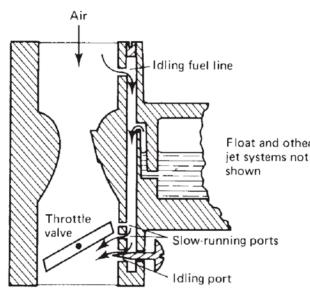


Figure 4.7

Figure 4.6

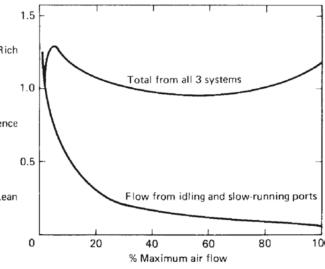


Figure 4.8

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.

## 4.2 Indirect fuel injection