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 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 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.

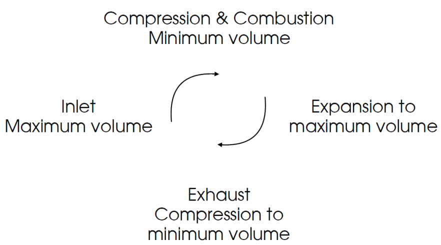

Figure 1.1

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:

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

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

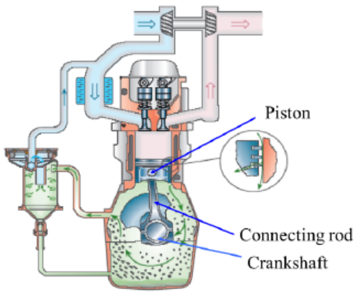

Figure 1.2

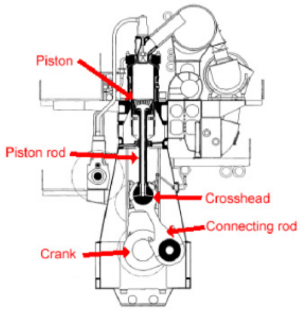

Figure 1.3

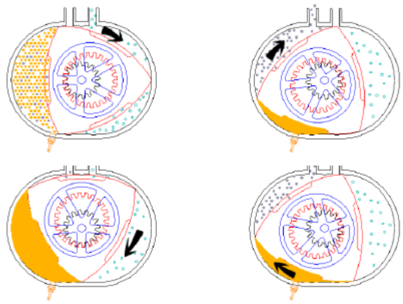

Figure 1.4

- 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

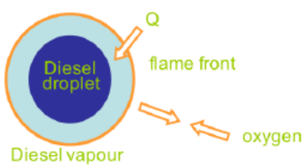

Figure 1.5

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.

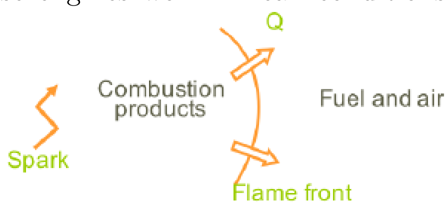

Figure 1.6

1.1.4 Strokes

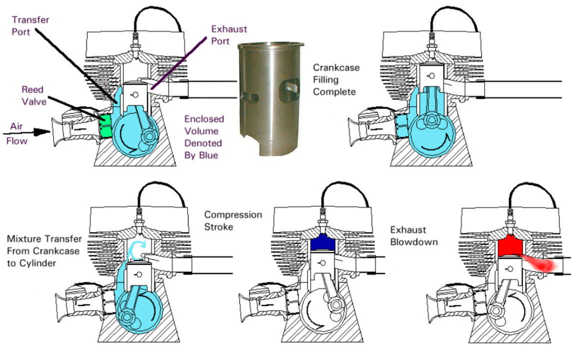

Figure 1.7

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.

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.

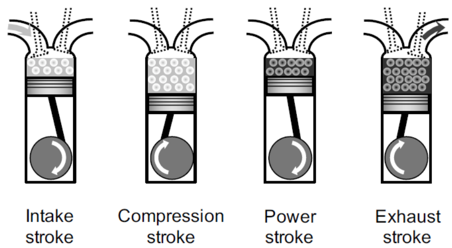

Figure 1.8

1.2 Cylinder arrangements

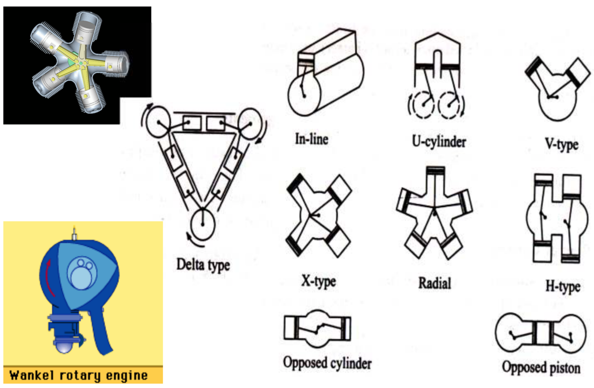

Figure 1.9

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

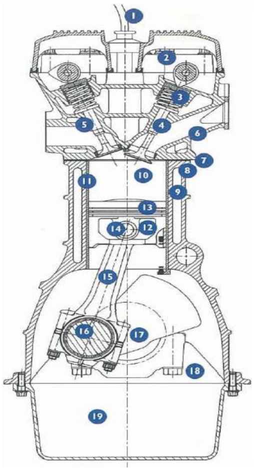

Figure 1.10

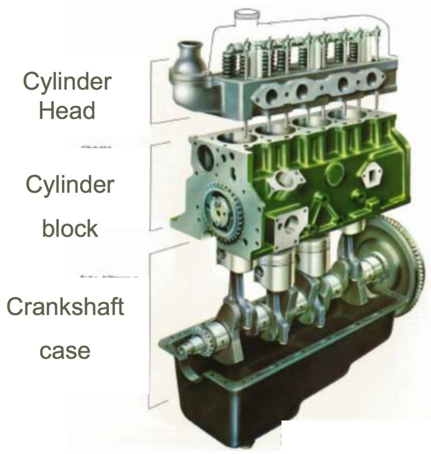

Figure 1.11

1. spark plug
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

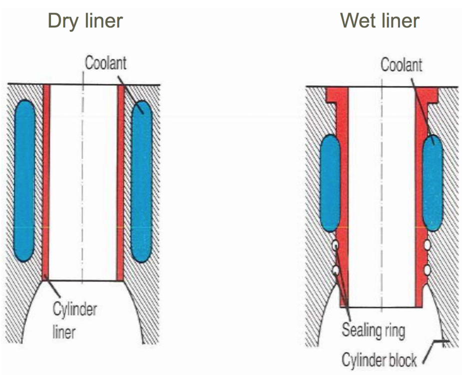

Figure 1.12

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

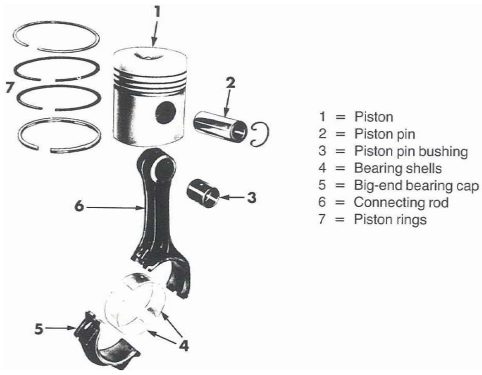

Figure 1.13

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 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.

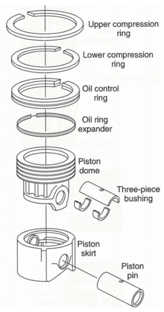

Figure 1.14

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

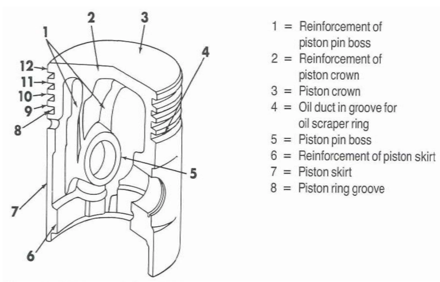

Figure 1.15

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.

1.4 Blow-by due to leakage

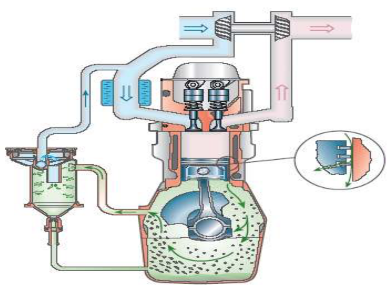

Figure 1.16

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

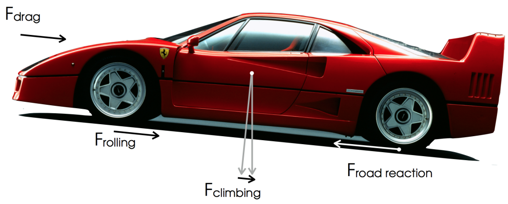

Figure 2.1

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

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

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:

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

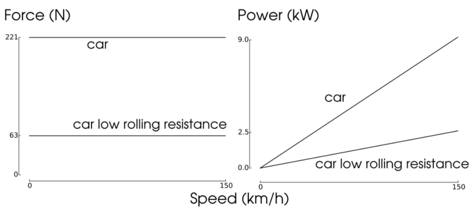

Figure 2.3

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:

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

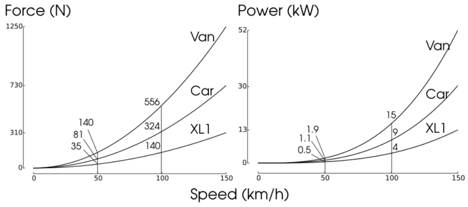

Figure 2.4

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:

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

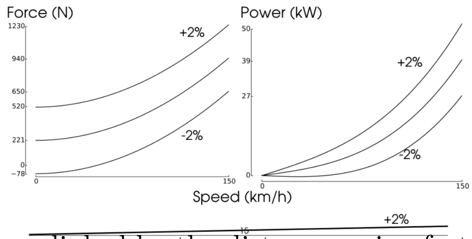

Figure 2.5

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.

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

2.2 The wheels

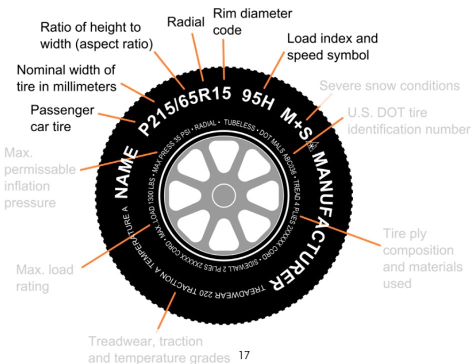

Figure 2.6

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

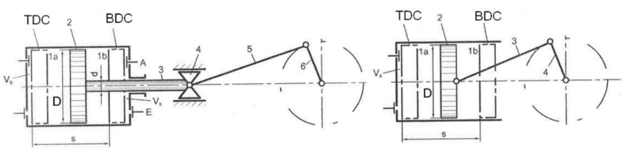

Figure 2.7

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:

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

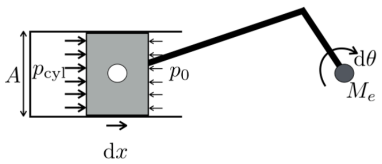

Figure 2.9

where the fuel energy is converted into torque.

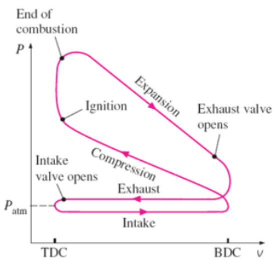

Figure 2.10

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**:

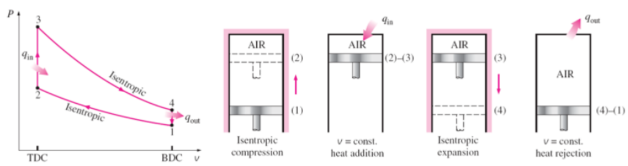

Figure 2.11

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

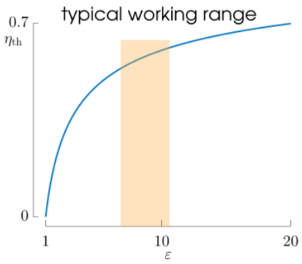

Figure 2.12

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.

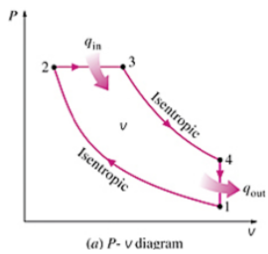

Figure 2.13

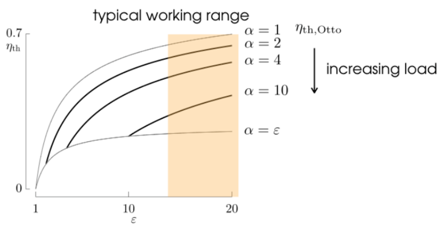

Figure 2.14

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.

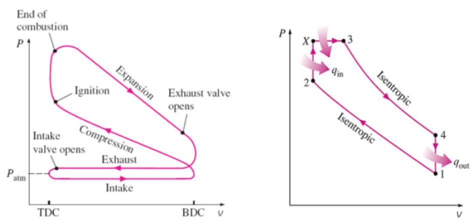

Figure 2.15

2.5 Power conversion steps

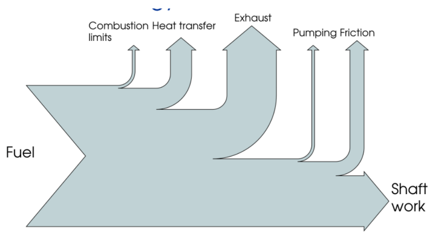

Figure 2.16

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 pressure