Warsaw University of Technology
Mechanical Faculty of Energy and Aviation

Computer Methods in Combustion

Analysis of valve overlap impact on power and efficiency in Diesel-type internal combustion engine

Autor:
Kacper Górka

Project made under the leadership:

dr Mateusz Żbikowski

June 8, 2022

Contents

Abstract

The subject of the project is to perform the analysis of influence valve timing on power and efficiency diesel engine.

1 Introduction

Diesel engines began to be used in automobiles in the 1930s. Mainly used for commercial applications early on, they did not gain popularity for passenger travel until their development in Europe in the 1950s.

The Mercedes-Benz 260 D in the W 138 series was the world's first series-production diesel passenger car. In February 1936 – 50 years after the invention of the petrol-powered automobile by Carl Benz – Mercedes-Benz presented this revolutionary vehicle at the International Motorcycle and Automobile Exhibition in Berlin. Its 2.6-litre OM 138 four-cylinder engine with the Mercedes-Benz pre-chamber system and a Bosch injection pump developed 33 kW (45 hp) at 3200 rpm

2 How does diesel engine work?

Diesel engines, like gas engines, are internal combustion engines that convert chemical energy into mechanical energy. This process moves pistons up and down inside cylinders, which then leads to the motion that turns the wheels of a vehicle.

So how does a diesel engine turn fuel into power?
There are a number of definitions that should be well understood before continuing with the details of the four-stroke cycle. Refer to the image below and the definitions underneath the image.

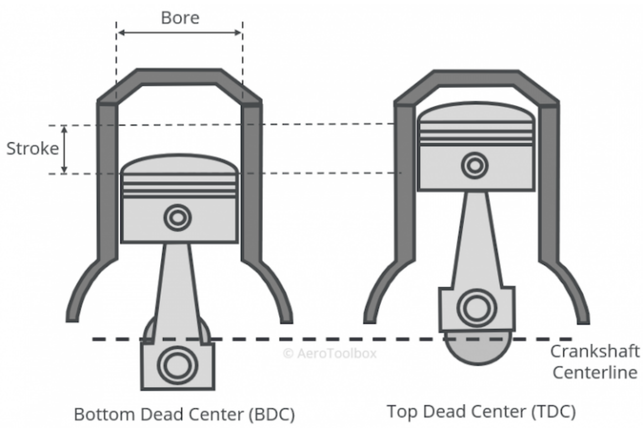

Figure 1: BDC and TDC visualisation

Top Dead Center (TDC) – this refers to the position of the piston when it is at the top of its travel. The piston is situated near the top of the cylinder head and the crankpin is at its uppermost position.

Bottom Dead Center (BDC) – this refers to the point in the cycle where the piston is at the bottom of its travel and the crankpin is at its lowest position.

Diesel engines operate using the same four strokes as gas engines:

1. **Intake stroke**: In this phase, the piston travels from top dead center (TDC) to bottom dead center (BDC). This results in low pressure inside the cylinder. All diesel engines are turbocharged, so air isn't drawn in but is waiting behind the intake valve under pressure. As soon as the valve opens, the air rushes in.

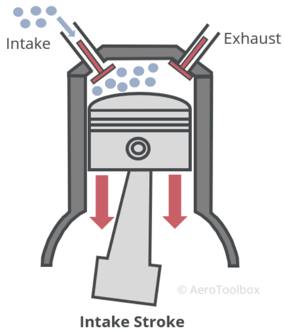

Figure 2: Intake stroke

2. **Compression stroke**: The piston travels from BDC back to TDC and prepares for combustion. The compression creates heat, which ignites atomized diesel fuel. There is no spark necessary — diesel fuel will self-ignite if it is atomized, or sprayed into the cylinder in a fine mist.

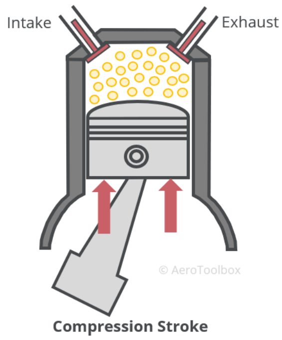

Figure 3: Compression stroke

3. **Power stroke**: In the power stroke, the piston goes from TDC to BDC. The combustion creates pressure to move the piston downward, and this shifts the power to the crankshaft.

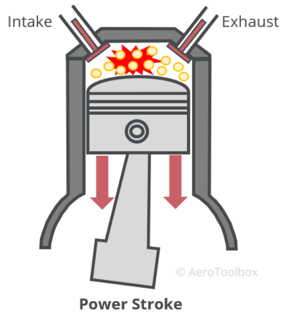

Figure 4: Power stroke

4. **Exhaust stroke**: In the last stroke, the piston travels from BDC to TDC. As it rises, exhaust gases are pushed from the cylinder and through the exhaust valve. They go into the emissions system and are then pushed from the vehicle.

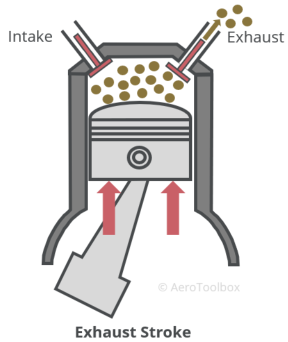

Figure 5: Exhaust stroke

Diesel engines do not use spark plugs to ignite the fuel mixture. The higher compression ratio in the engines produces enough heat to ignite the mixture. Additionally, diesel fuel itself allows for combustion without the use of a spark plug.

3 The main subject – valve overlap

Valve overlap is the period during engine operation when both intake and exhaust valves are open at the same time. Valve overlap occurs when the piston nears TDC between the exhaust event and the intake event.

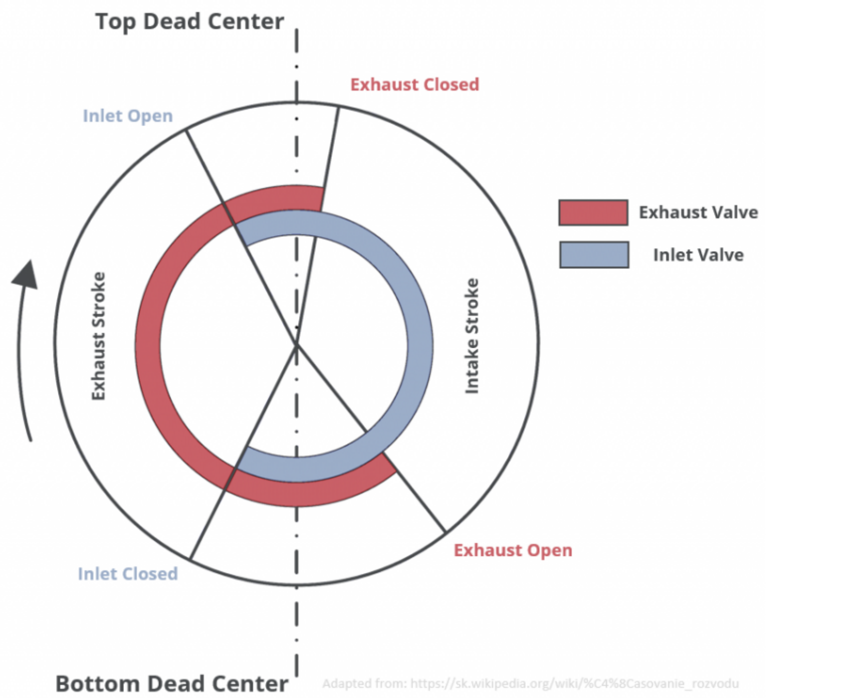

Figure 6: Valve overlap

Duration of valve overlap is between 10° - 20° of crankshaft rotation, depending on the engine design - in sports cars valve overlap is more extensive but it requires hihger idle RPM to stable engine operation. The intake valve is opened during the exhaust event just before TDC, initiating the flow of the new charge into the combustion chamber.

4 Theory and preparations

4.1 Combustion process

In order to analyze it, we must start from the basics, i.e. from the very phenomenon of combustion in the cylinder.

Fuel in my considerations wiil be the petroleum diesel, also called petrodiesel or fossil diesel, is the most common type of diesel fuel. It is produced from the fractional distillation of crude oil between 200 and 350 °C (392 and 662 °F) at atmospheric pressure, resulting in a mixture of carbon chains that typically contain between 9 and 25 carbon atoms per molecule.

I would like to simplify the ingridients to Dodecane which is an oily liquid n-alkane hydrocarbon with the chemical formula $C_{12}H_{26}$.

the combustion reaction is as follows:

$$C_{12}H_{26} + 18.5(O_2 + 3.76N_2) => 12CO_2 + 13H_2O + 69.56N_2$$

4.2 Tools to perform simulation

The model was created using python and some tools and packages to perform scientific and mathematical operations:

- ***Cantera*** which is an open-source suite of tools for problems involving chemical kinetics, thermodynamics, and transport processes.
- ***NumPy*** comprehensive mathematical functions, random number generators, linear algebra routines, Fourier transforms, and more
- ***SciPy*** provides algorithms for optimization, integration, interpolation, eigenvalue problems, algebraic equations, differential equations, statistics and many ...

5 Model

5.1 Input parameters and setting up engine functions

To perform the analysis, the one cylinder engine with eight crankshaft revolutions was considered.

$$n_{rot} = 3000\,RPM \qquad \text{engine speed}$$
$$V_H = 500\,cm^3 \qquad \text{displaced volume}$$
$$\varepsilon = 20 \qquad \text{compression ratio}$$
$$d_{piston} = 0.083\,mm \qquad \text{piston diameter}$$

In the program many parameters were described, but the most important are:

Timings were described as degrees of crankshaft rotation angle after the beginning of full cycle. One engine cycle has 720^o crankshaft rotation. This is because of four stroke engine.

- Fuel mass, injector open and close timings

$$injector_{open} = 350^o \qquad \text{injector open timing}$$
$$injector_{close} = 365^o\,cm^3 \qquad \text{injector close timing}$$
$$injector_{mass} = 0.032\,g \qquad \text{the amount of fuel injected in one engine cycle}$$

In the analysis were considered a few different valve open and close timings

- Inlet, outlet valve friction coefficient, open and close timings

Valve timing [^{o}]				
	Inlet		Outlet	
LP.	Open	Close	Open	Close
1	-3	183	537	3
2	-8	188	532	8
3	-13	193	527	13
4	-18	198	522	18
5	-23	203	517	23
6	-28	208	512	28
7	-33	213	507	33
8	-38	218	502	38

Valve timing summary [^{o}]			
	Open duration		
LP.	Inlet	Outlet	Overlap
1	186	186	6
2	196	196	16
3	206	206	26
4	216	216	36
5	226	226	46
6	236	236	56
7	246	246	66
8	256	256	76

- Crankshaft angle (time)
  Function that converts time to crank angle.

$$crank_{angle}(t) = \frac{2 \cdot \pi \cdot n_{rot}}{4 \cdot \pi}$$

- Crankshaft angle (time)
  Approximate piston speed with sinusoidal velocity profile

$$piston_{speed}(t) = \frac{1}{2} \cdot 2 \cdot \pi \cdot n_{rot} \cdot \sin\left(crank_{angle}(t)\right)$$

5.2 Setting up Reactor Network

Cylinder was modeled as a reactor using Cantera. It was essential to set up the basic parameters such as temperature, pressure and composition on intake and ambient air. The most important set ups are shown below:

- **Cylinder** modeled as ideal gas reactor
- **Inlet and outlet valves** as valves which open and close in exact time
- **Injector** as a mass flow controller, the fuel state is gaseous
- **Piston** as a moving wall

5.3 Running the simulation

To simulate the engine operation, the time have to be converted to actual crankshaft angle. In the simulation some data are collected such as mass flow rate and mechanical power.

$$\frac{dW}{dt} = (P_{chamber}(t) - P_{ambient}) \cdot A_{piston} \cdot piston_{speed}(t)$$

Simulation was performed with step equal 1^o of crank angle, so $dt = \frac{1}{360 \cdot n_{rot}}$.

6 Results

6.1 Integral Results

The main objective of analysis was to check how the valve timing set up influences the performance of the engine.

The ordinary numbers in tables and plots refer to the cases of valve timing set up, which are presented in 5. section.

Simulation summary				
	Inlet		Outlet	
ON	$\dot{Q}\,[kW]$	$\dot{W}\,[kW]$	$\epsilon\,[\%]$	$CO\,[ppm]$
1	34.8	18.2	52.2	33.0
2	34.6	18.3	53.0	16.8
3	31.7	18.4	58.2	11.5
4	34.7	18.5	53.3	8.8
5	36.3	18.6	51.2	7.3
6	35.5	18.6	52.4	6.5
7	35.7	18.6	52.1	6.0
8	36.0	18.6	51.5	5.9

With respect to the calculation results, it can be seen that timing has the greatest influence on the CO emission. The wider the valve overlap, the lower the CO emission. The heat from chemical reaction and efficiency also clearly depend on timing. The smallest differences are in mechanical power.

6.2 Plots

The next five graphs refer to case 3, where the valve timing of the system is presented as:

Valve timing: Case 3			
Inlet [^{o}]		Outlet [^{o}]	
Open	Close	Open	Close
-13	193	527	13

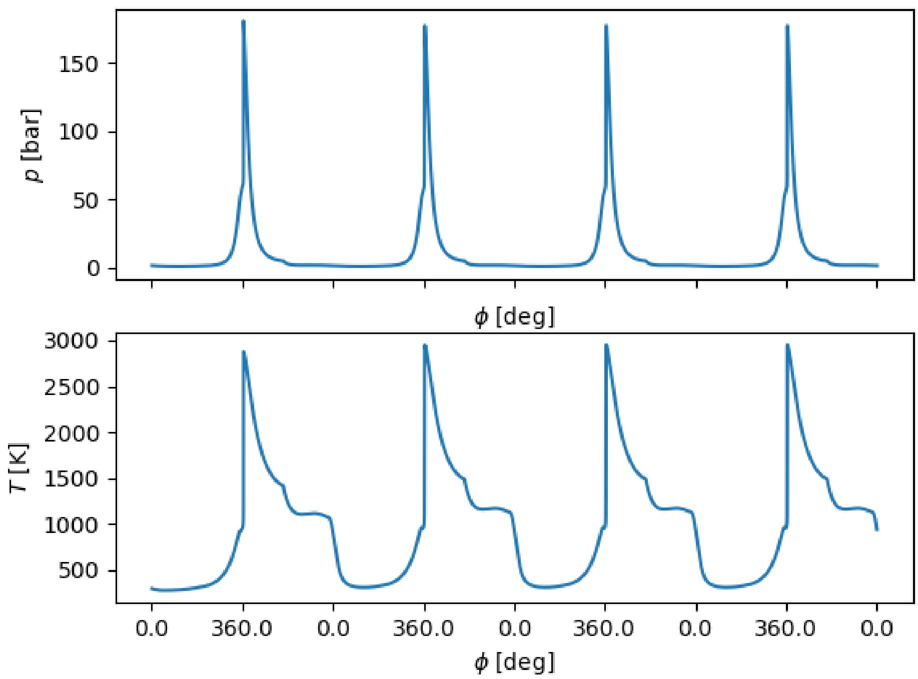

Figure 7: Pressure and Temperature depending on crankshaft angle

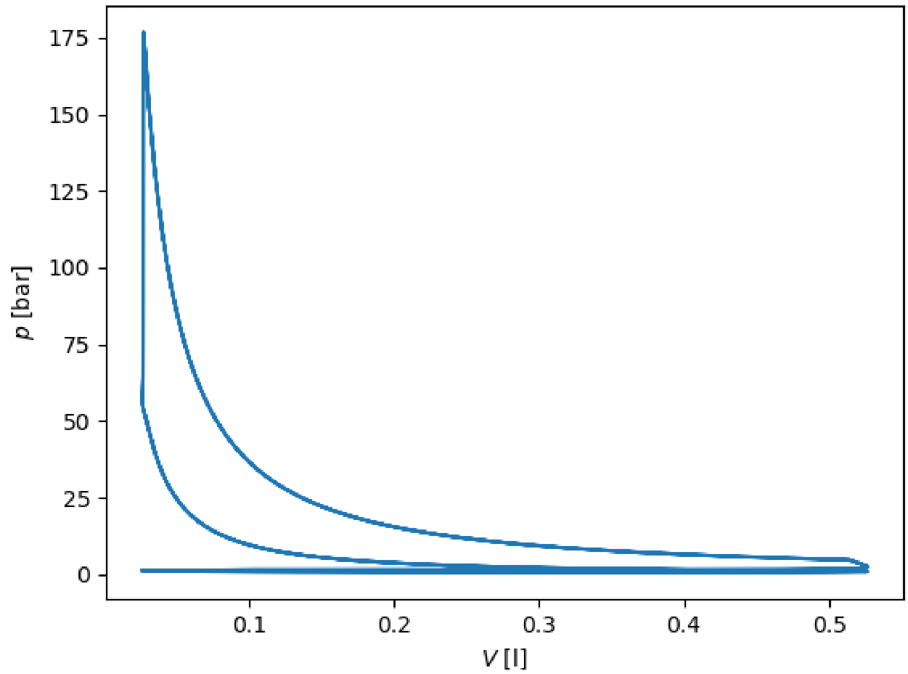

Figure 8: p(V) diagram

The diagram is more like the Otto Cycle than Diesel cycle. This is due to simplifications in the simulation, where only one specific component is used as fuel. What is more, mixing occurs very quickly.

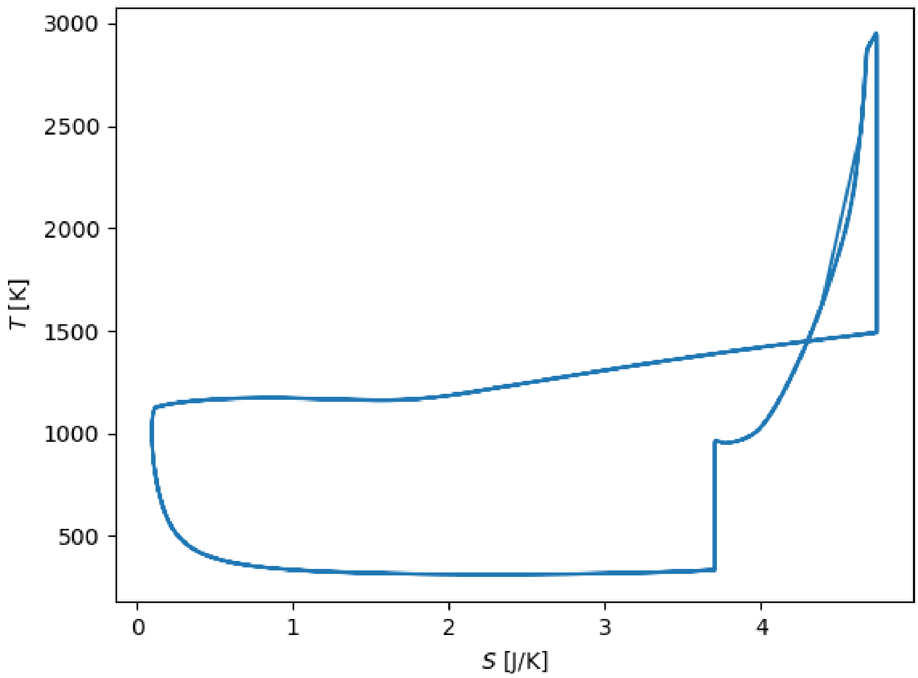

Figure 9: T(S) diagram

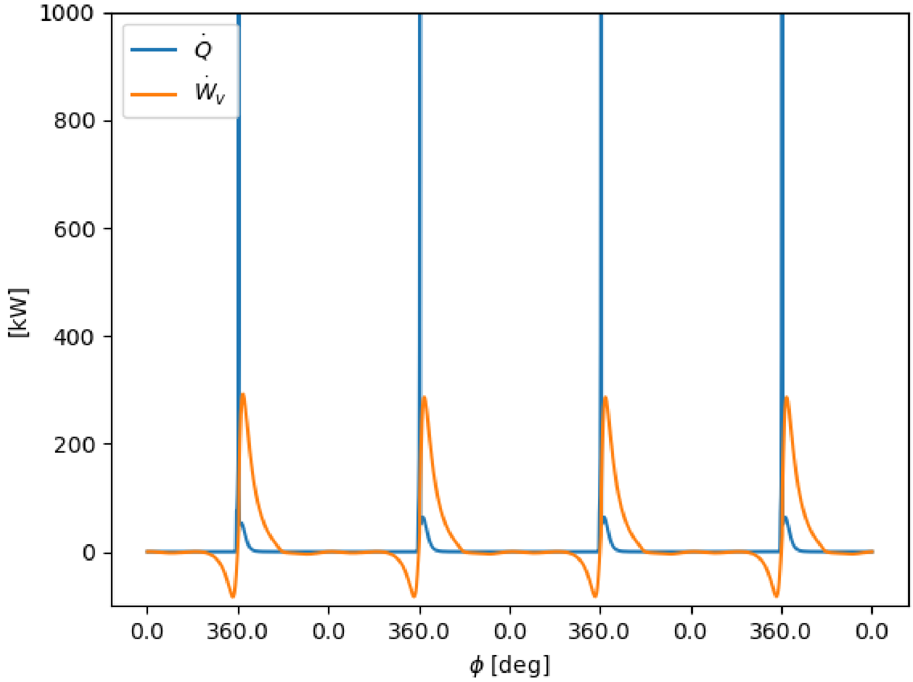

Figure 10: Heat stream in combustion chamber depending on crankshaft angle

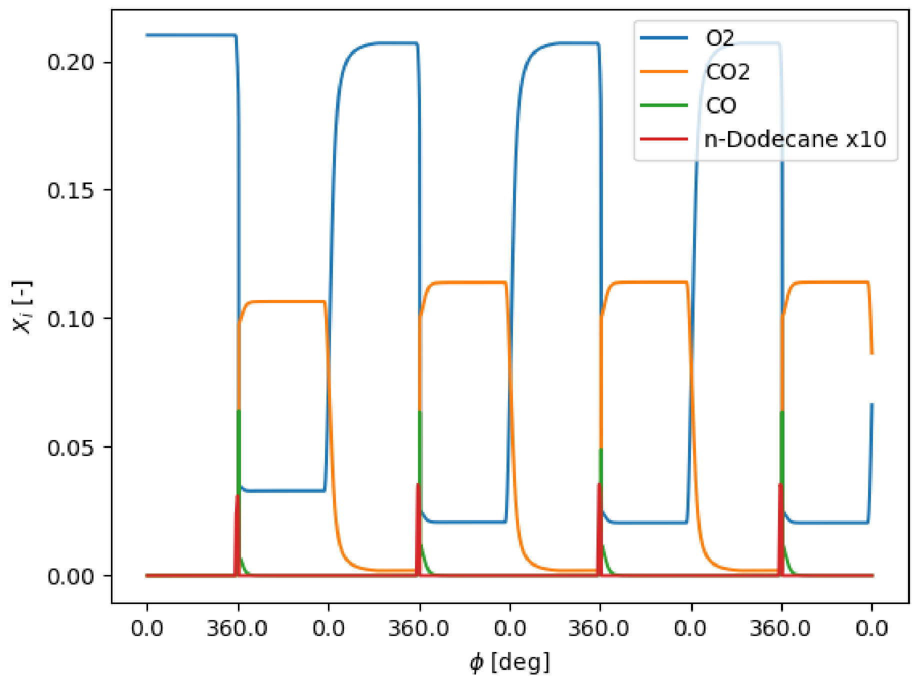

Figure 11: Gases composition depending on crankshaft angle

Below are presented the integral results, where the different valve timing cases are compared.

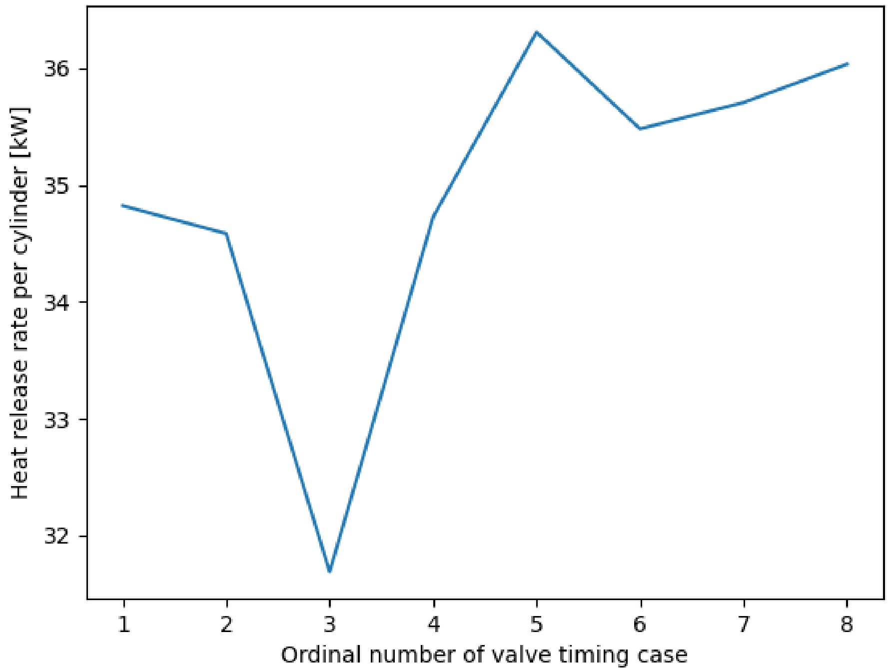

Figure 12: Heat release rate per cylinder depending on valve timing set up

As it can be seen, the valve timing has a great influence on the heat flux, which is caused by the better gas exchange in the cylinder. The relationship is not linear, because it depends on other things. It has the lowest value for case 3, and the highest for case 5.

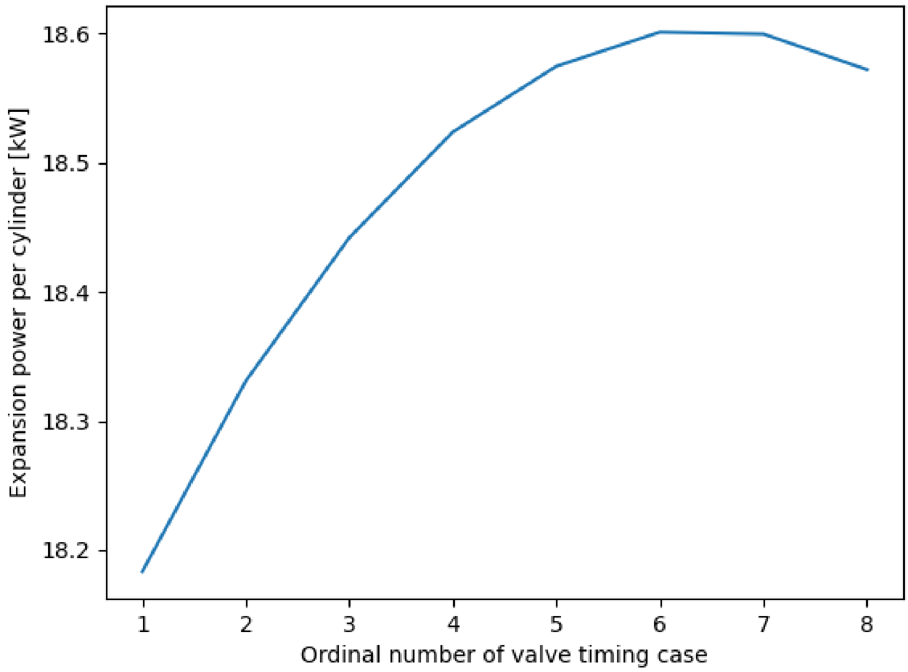

Figure 13: Expansion power per cylinder depending on valve timing set up

A parabolic distribution is visible. If the user of this engine wants to be as powerful as possible, he should choose 6. valve timing system.

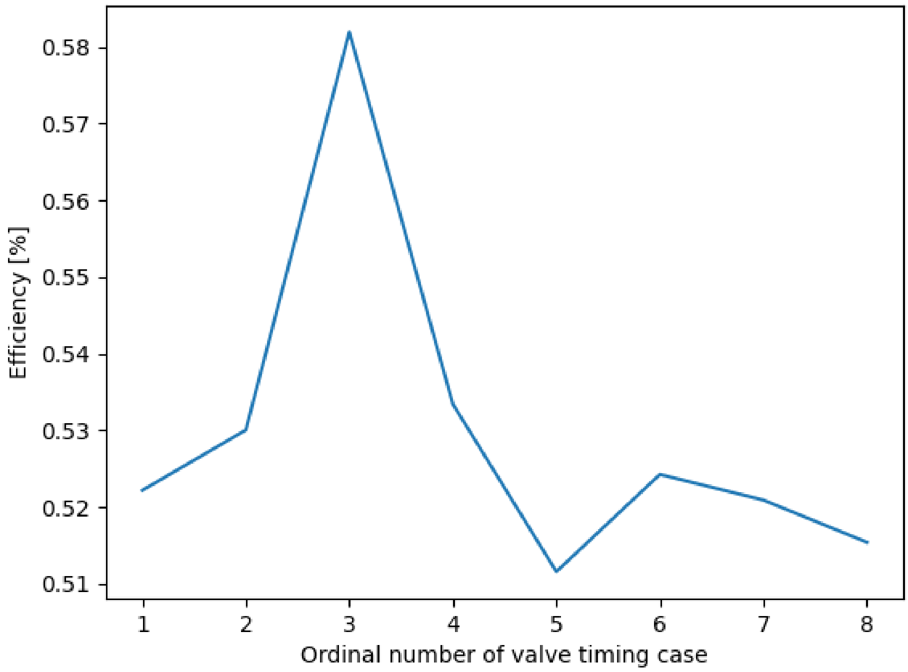

Figure 14: Efficiency depending on valve timing set up

Undeniably and unequivocally, it can be seen that the engine is the most effective for the third case. The difference is huge (+11.5% compared to average of the remaining results). This means that a car or machine with a 3rd timing system will burn the least fuel compared to other cases when doing the same job.

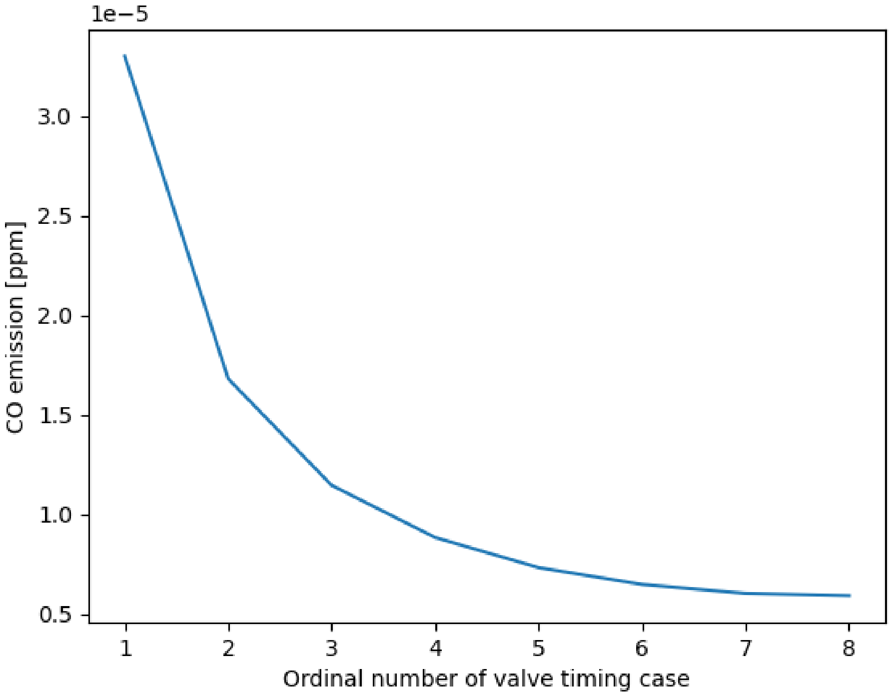

Figure 15: CO emission depending on valve timing set up

The longer the valve cover time, the lower the CO emission.

7 Conclusions and summary

The simulation results should be treated only in an illustrative way, which is not entirely in line with reality. Many simplifications have been adopted.

Based on the simulation, it can be seen that timing has a significant impact on the efficiency, performance and operation of the engine. In terms of quality, the results of the calculations are in line with reality, because we obtain greater efficiency and a more economical engine for low valve overlap. In sports cars, on the other hand, we use a much larger valve overlap due to more efficient gas exchange in higher speed ranges.

References

[1] Cantera, *Internal combustion engine simulation*;
https://cantera.org/examples/python/reactors/ic_engine.py.html

[2] Mercedes-Benz Group Media, *February 1936: the diesel engine celebrates its premiere in the passenger car*;
https://group-media.mercedes-benz.com/marsMediaSite/en/instance/ko/February-1936-the-diesel-engine-celebrates-its-premiere-in-the-passenger-car.xhtml?oid=9915149

[3] Marcin Polkowski, *LaTeX – strona tytułowa*;
http://morony.pl/?p=187

[4] Wikipedia, *History of the diesel car*;
https://en.wikipedia.org/wiki/History_of_the_diesel_car

[5] Universal Technical Institute, *HOW DOES A DIESEL ENGINE WORK?*;
https://www.uti.edu/blog/diesel/how-diesel-engines-work

[6] AeroToolbox, *The Four Stroke Engine Cycle*;
https://aerotoolbox.com/four-stroke-engine/

[7] Wikipedia, *Dodecane*;
https://en.wikipedia.org/wiki/Dodecane

[8] Wikipedia, *Diesel fuel*;
https://en.wikipedia.org/wiki/Diesel_fuel