

THERMOPTIM®

Diesel engine example

JAVA VERSION

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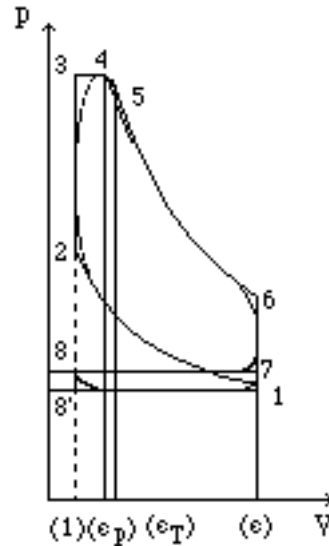
Reciprocating internal combustion engine cycle

Let us study a reciprocating internal combustion engine whose corresponding theoretical cycle takes into account a multi-step combustion process. We shall in this example analyse the diesel engine.

After a 0.9 isentropic efficiency compression, start a combustion that unfolds in three phases:

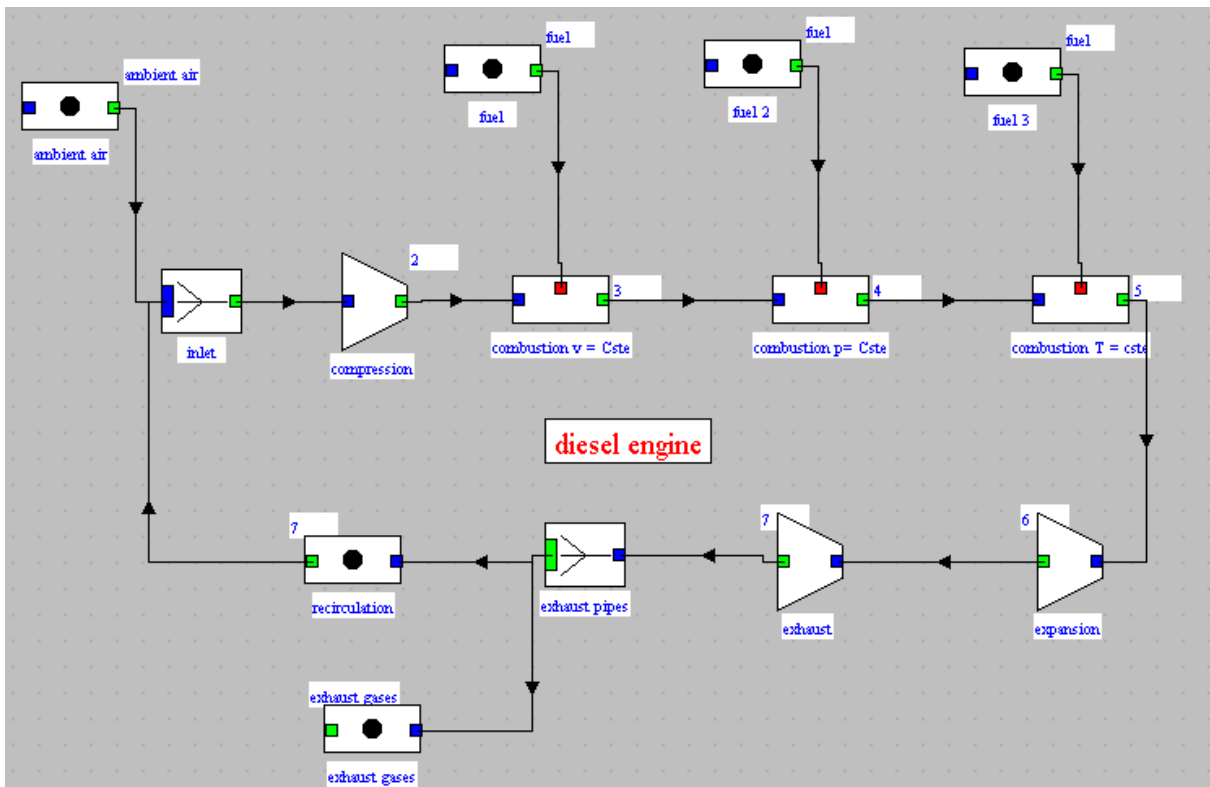
- the first one, at constant volume, allows the pressure to reach its maximum in the cycle,
- the second one, at constant pressure, leads to the maximum temperature
- the end of the combustion takes place at constant temperature.
- gases are then expanded to the bottom dead center (bdc), with an expansion isentropic efficiency equal to 0.95

Due to the clearance volume, 3.3% of the burnt gas mass are assumed to recirculate.



ε compression ratio
 ε_p isobaric cutoff ratio
 ε_T isothermal cutoff ratio

This cycle corresponds to the following diagram which can easily be built in the graphical editor:



Solution of the problem

Almost totally (except for intake and exhaust phases), this example deals with closed systems.

We will suppose that the composition of exhaust gases is known in order to be able to determine the mass taken in. If this is not the case, it is necessary to iterate. With the clearance ratio being small, the influence of this exhaust gases remains moderate. Similarly, the outlet expansion temperature will be initialized at 589 °C (862 K) and 1.1 bar. As the system is coupled, the values that you will get may be slightly different from the ones presented here. The fuel is a car fuel included in THERMOPTIM, whose formula is $C_{7.2}H_{13.42}$ and LHV is approximately equal to 42 MJ/kg.

Once the diagram built, transfer its components in the simulator and start setting the parameters of the various elements.

The mixer that provides the intake temperature connects the two processes-points representing intake air and recycled gases. The admission pressure is set equal to 0.95 bar.

process name	m abs	T (°C)	H
ambient air	0.967	15	-9.87
recirculation	0.033	587.46	624.75

Intake conditions are thus obtained (37 °C, 0.95 bar) and the compression can be studied. It is a closed system compression process. Set the volumetric compression ratio equal to 14, and the isentropic efficiency value to 0.9.

parameter	value
inlet T (°C)	36.97414
inlet p (bar)	0.950012
inlet h (kJ/kg)	12.17
inlet quality	1
outlet T (°C)	626
outlet p (bar)	38.5616
outlet h (kJ/kg)	635.78
outlet quality	1
flow rate	1
Delta_U	454.47
Q	0
compression ratio	14
isentropic efficiency	0.9

At point 2, at the compression outlet, the temperature is 626 °C, and the pressure 38.6 bar. For 1 kg of intake mass, the compression work is equal to 454 kJ.

Then begins the first phase of the constant volume combustion, until the maximal pressure of the cycle is equal to 80 bar. The combustion process looks as follows:

It connects points 2 and 3 and is a closed system combustion, at a set volume equal to that of the inlet point. The fuel is included in the database, and one can consider some dissociation (7% of the CO₂, quenching temperature equal to 1500 °C). A thermal efficiency of 0.81 is chosen to take into account the heat transmitted to the cylinder walls and removed by the engine cooling water.

It remains then to calculate the air factor such that $p_3 = 80$ bar, which can be made only by iteration. The value obtained is $\lambda = 2.19$. The outlet combustion temperature is then equal to 1590 °C.

The volume is constant and there is no useful work ($W = 0$). The heat of combustion is distributed between losses (19%) and the fluid internal energy variation $\Delta U = 1006$ kJ. The mass flow rate has increased, due to the fuel injection, to reach 1.0306 kg/s at point 3.

The constant pressure combustion phase is represented in a similar manner: the oxidizer is determined by the preceding process ("prod diesel 1"), and the fuel is the same. In order to keep track of the different fuel flow rates according to the combustion phases, it is necessary to create several corresponding processes-points (as in the case of this example).

It connects points 3 and 4. It is a closed system combustion, at a set pressure equal to that at the inlet point. The 0.81 thermal efficiency is maintained, as well as the quenching temperature. The CO₂ dissociation degree has been set here to 8%.

It remains then to calculate λ , such that the outlet combustion temperature is equal to 2100 K, or 1826.85 °C. To do that, select checkbox "Calculate lambda" and click on "Calculate".

During the combustion, the heat liberated by the fuel is used three ways: heating the fluid, whose internal energy increases ($\Delta U = 380$ kJ), work provided to the crankshaft of the engine, the volume having increased at constant pressure ($W = 75$ kJ), and finally heat losses through the cylinder walls. The mass flow rate continues to increase, and reaches 1.041 kg/s at point 4.

process	combustion p= Cste	type	combustion	<	>	Save
energy type	purchased	<input type="checkbox"/> set flow	links	Suppress	Close	
inlet point	3	flow rate	1.04097	<input checked="" type="checkbox"/> closed system	<input type="checkbox"/> observed	
	display	Delta_U	379.77	<input type="checkbox"/> open system	Calculate	
T (°C)	1,590.81	W	74.75			
p (bar)	80.0866	fuel	fuel 2	display		
h (kJ/kg)	1,876.44	<input type="checkbox"/> CHa type				
quality	1	<input checked="" type="checkbox"/> dissociation	dissociation degree	0.08		
outlet point	4		quenching temp. ...	1,700		
	display		combustion eff.	0.95129		
T (°C)	1,826.85		chamber efficiency	0.81		
p (bar)	80.0866	<input checked="" type="checkbox"/> Calculate lambda	lambda	3.5252		
h (kJ/kg)	2,223.71	<input type="checkbox"/> Calculate T	T (°C)	1,826.85		
quality	1	<input type="checkbox"/> Set the fuel flow rate				
		<input checked="" type="checkbox"/> set pressure				
		<input type="checkbox"/> set volume			<input checked="" type="checkbox"/> by the inlet point	
		<input type="checkbox"/> set temperature			<input type="checkbox"/> by the user	

The constant temperature combustion phase is similarly represented: the oxidizer is determined by the precedent process ("prod diesel 2"), and the fuel is the same.

process	combustion T = cste	type	combustion	<	>	Save
energy type	purchased	<input type="checkbox"/> set flow	links	Suppress	Close	
inlet point	4	flow rate	1.04301	<input checked="" type="checkbox"/> closed system	<input type="checkbox"/> observed	
	display	Delta_U	126.58	<input type="checkbox"/> open system	Calculate	
T (°C)	1,826.85	W	116.58			
p (bar)	80.0862	fuel	fuel 3	display		
h (kJ/kg)	2,223.71	<input type="checkbox"/> CHa type				
quality	1	<input checked="" type="checkbox"/> dissociation	dissociation degree	0.1		
outlet point	5		quenching temp. ...	1,500		
	display		combustion eff.	0.92615		
T (°C)	1,826.85		chamber efficiency	0.81		
p (bar)	66.6846	<input type="checkbox"/> Calculate lambda	lambda	12.8		
h (kJ/kg)	2,230.71	<input checked="" type="checkbox"/> Calculate T	T (°C)	1,826.85		
quality	1	<input type="checkbox"/> Set the fuel flow rate				
		<input type="checkbox"/> set pressure			<input checked="" type="checkbox"/> by the inlet point	
		<input type="checkbox"/> set volume			<input type="checkbox"/> by the user	
		<input checked="" type="checkbox"/> set temperature				

The temperature is set, but not the evolution of the pressure and the volume. The known value is that of the total mass of fuel burnt in the engine by the intake mass unit, here 0.043 kg/kg. You must adjust λ to satisfy to 1.043 the total mass flow rate.

The heat liberated by the fuel is here also transferred in part into internal energy variation (126.6 kJ), in part into work provided to the engine crankshaft, the volume having increased at constant pressure ($W= 116.6$ kJ), and the rest (19%) into losses through the cylinder walls.

Conditions at the combustion outlet are now completely determined: pressure of 66.7 bar, and temperature of 1826.85 °C = 2100 K.

The expansion phase can be represented. It takes place between points 5 and 6, of similar composition ("prod diesel 3"). The volumetric expansion rate ρ_{56} is calculated. THERMOPTIM assumes that the volume v_6 at the bottom dead center (bdc) is known. It depends on the one hand on the geometrical characteristics of the engine, and on the other hand on the variation of the mass introduced in the cylinder. If one calls V_i and m_i the total volume of the cylinder and the mass in the cylinder at point i , one has the following relationships:

$$\rho_{56} = V_6/V_5 = (m_6 v_6)/(m_5 v_5) = v_6/v_5 \text{ since } m_6 = m_5$$

$$\text{Furthermore } \rho = V_6/V_2 = (m_6 v_6)/(m_2 v_2) = (m_5 v_6)/(m_2 v_2), \text{ and } \rho = V_1/V_2$$

$$v_6 = \rho (m_2 v_2)/m_5 = v_1 m_1/m_5$$

The screenshot shows the THERMOPTIM software interface for defining an expansion process. The process is named "expansion" and is of type "expansion". The energy type is "useful". The inlet point is 5 and the outlet point is 6. The flow rate is set to 1.04301211. The inlet conditions at point 5 are T=1,826.85 °C, p=66.6846 bar, h=2,230.71 kJ/kg, and quality=1. The outlet conditions at point 6 are T=904.61 °C, p=3.7739 bar, h=1,012.35 kJ/kg, and quality=1. The process is defined as a closed system, non-adiabatic expansion, with a polytropic efficiency of 0.9 and a polytropic exponent of 1.2526. The pressure ratio is 9.87. The expansion work is 993.37 kJ. The process is calculated.

The specific volume at the bdc is therefore equal to that of point 1 (0.9393) divided by the factor 1.043 representative of the mass variation, and is equal to 0.9. It therefore correspondingly has to be modified manually in order to take into account this phenomenon. Similarly, the flow rate of the « expansion » process must be set to 1.043.

This is "closed system" expansion with a calculated expansion ratio. The isentropic efficiency here is set equal to 0.9. The pressure at the expansion outlet is equal to 3.8 bar, the temperature to 905 °C, and the expansion work is equal to 993 kJ.

The work of the sweeping cycle can be evaluated as equal to $WB = (p_1 - p_7)(V_1 - V_2)$ that is here approximately 18 kJ.

The balance of the whole cycle can then be calculated, which gives the following results:

Balance	
efficiency	0.482704
useful energy	730.24
purchased energy	1,512.8

This balance is based on the energy transferred to the fluid, and does not take into account the 19% losses nor the sweeping cycle. To reintegrate them, multiply the indicated efficiency $(730 - 18)/1512.8$ by the thermal efficiency (0.81), which gives a value of 38 %.

You can also proceed in another way, by calculating the heat liberated by the fuel to be equal to the product of its mass flow rate by its LHV, that is approximately 1815 kJ. The indicated efficiency that one obtains is then a little bit higher.

The difference comes from the dissociation that has been taken into account: traces of CO and H₂ can be found in exhaust gases, whose composition is given below. If there had been no dissociation, the two efficiencies would have been identical.

Gas composition diesel products 3		
The first figure column from the left selects the input values from among molar and mass fractions		
component name	molar fraction	mass fraction
CO ₂	0.07966923	0.1216194
H ₂ O	0.08007063	0.05003537
O ₂	0.0760227	0.08438007
N ₂	0.7443797	0.7233079
CO	0.008852137	0.008600631
H ₂	0.002427574	0.0001697462
Ar	0.008577999	0.01188682

With the exhaust gases undertaking a final expansion in open system, assumed to be isentropic, the outlet condition for a pressure of 1.1 bar are $T_7 = 587$ °C, very close to the value that had been set for recycled gases.

The impact on the temperature of the intake mass remains very small (0.2 K).

All these results are saved in project file "diesel.prj" and diagram file "diesel.dia".

It should be noted that the automatic recalculation cannot be fully automated here. The reason is that the combustion in the motor cylinder is represented as a sequence of three closed system combustions: first constant volume, second constant pressure and third constant temperature. This corresponds to very specific parameter settings which are not taken into account by the calculation process, as for instance the setting of λ to get the right pressure or temperature or the update of v_6 .

Viewing the point state values in the diagram editor

The results obtained may be displayed on the diagram:

