Thermodynamics of energy conversion

5. PISTON ENGINES

5. PISTON ENGINES

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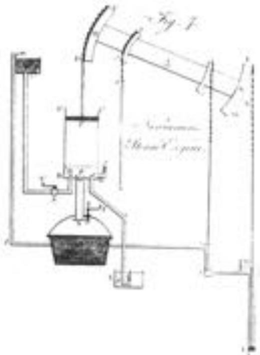
5.1. HISTORY

Thomas
NEWCOMEN



1712 first piston steam engine

François
Isaac DE
RIVAZ

1813 Hydrogen/air explosion motor

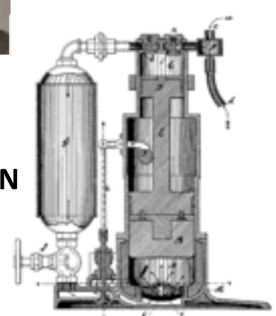
Robert
STIRLING

1843 Stirling engine

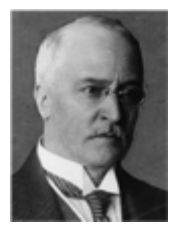
Nicolaus August
OTTO

1866 Gas Engine

George
Bailey
BRAYTON



1872 Ready Motor



Rudolf
Christian Karl
DIESEL

1892 Diesel engine

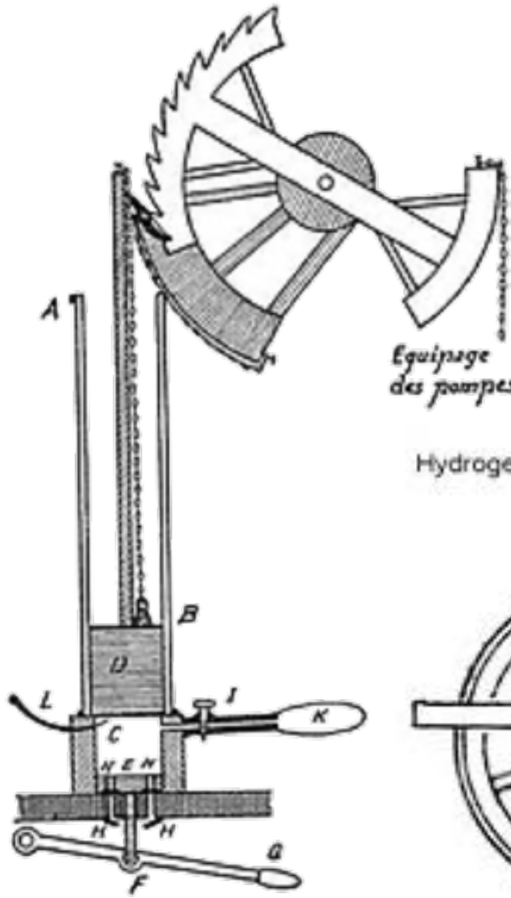
Felix Heinrich
WANKEL

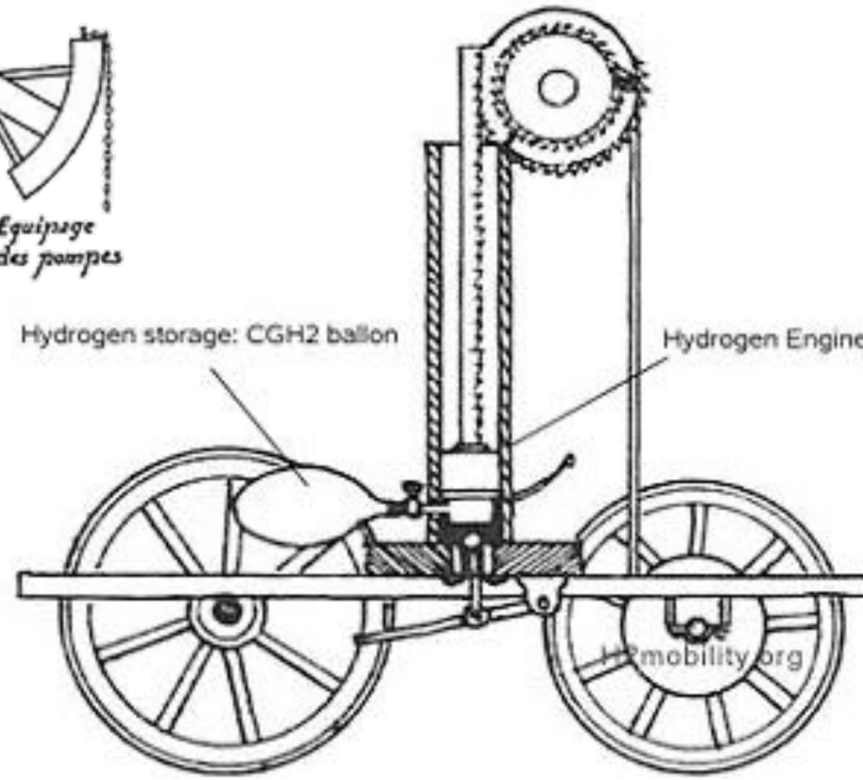
1953 Rotary piston engine

5.1.1. FIRST CAR WITH INTERNAL COMBUSTION ENGINE

François Isaac de Rivaz

(* December 19, 1752 in Paris, † July 30, 1828 in Sion, CH) was a French politician, chancellor, member of parliament and entrepreneur.

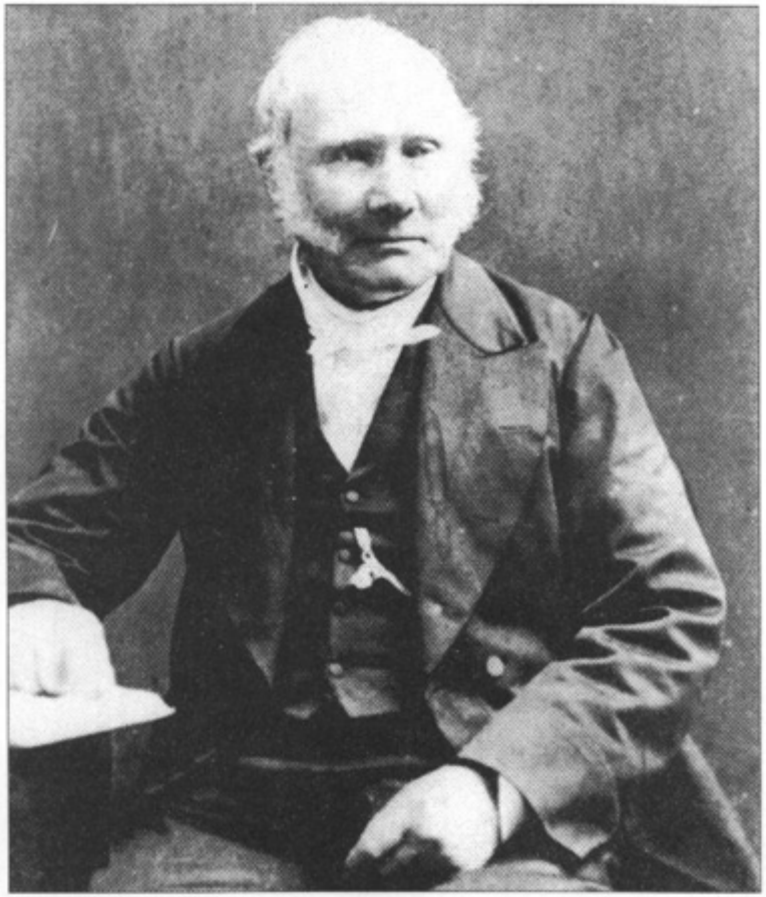




In 1813, de Rivaz attempted a large handcart powered by his engine. He was able to achieve 25 firings of H_2/air mixture in a row that had to be triggered individually by hand. The car, which was loaded with four people or a load of 700kg, was able to drive a full 26m at a speed of 3 km/h.

This trip is considered the first trip as a motor vehicle with an explosion or gas engine in the history of technology.

5.2. STIRLING ENGINE



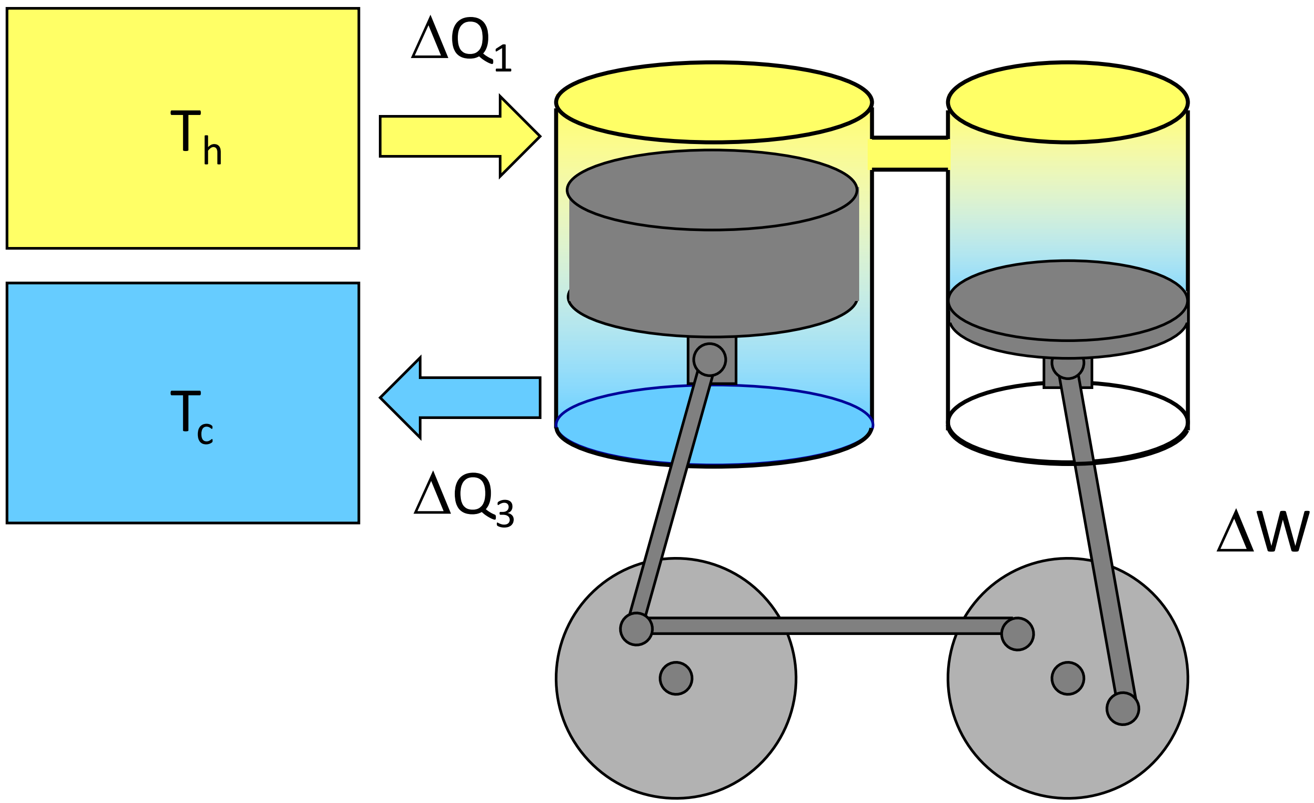
Robert Stirling D.D.

25. October 1790 in Cloag, Methvin, Scotland;
† 6. Juni 1878 in Galston, Ayrshire, Scotland),
was a British priest and engineer

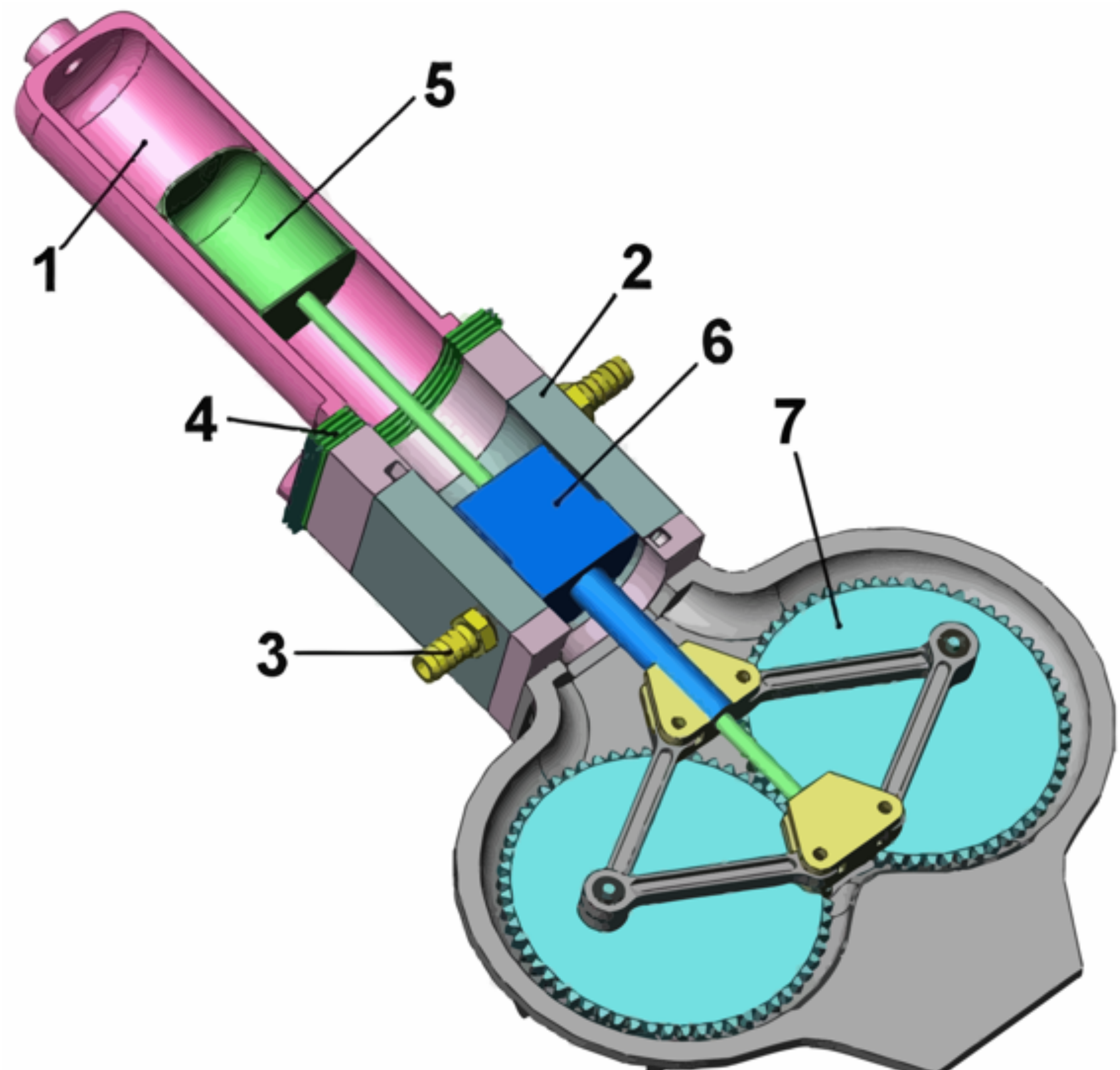
Stirling engine 1843

March 1843 to the *Dundee Foundry Company*, metal casting in Scotland.
34 kW at 28rounds/min,
Cylinder diameter: 0.4 m, hight: 1.22 m,
Efficiency of 18%

5.2.1. PRICIPLE OF THE STIRLING ENGINE



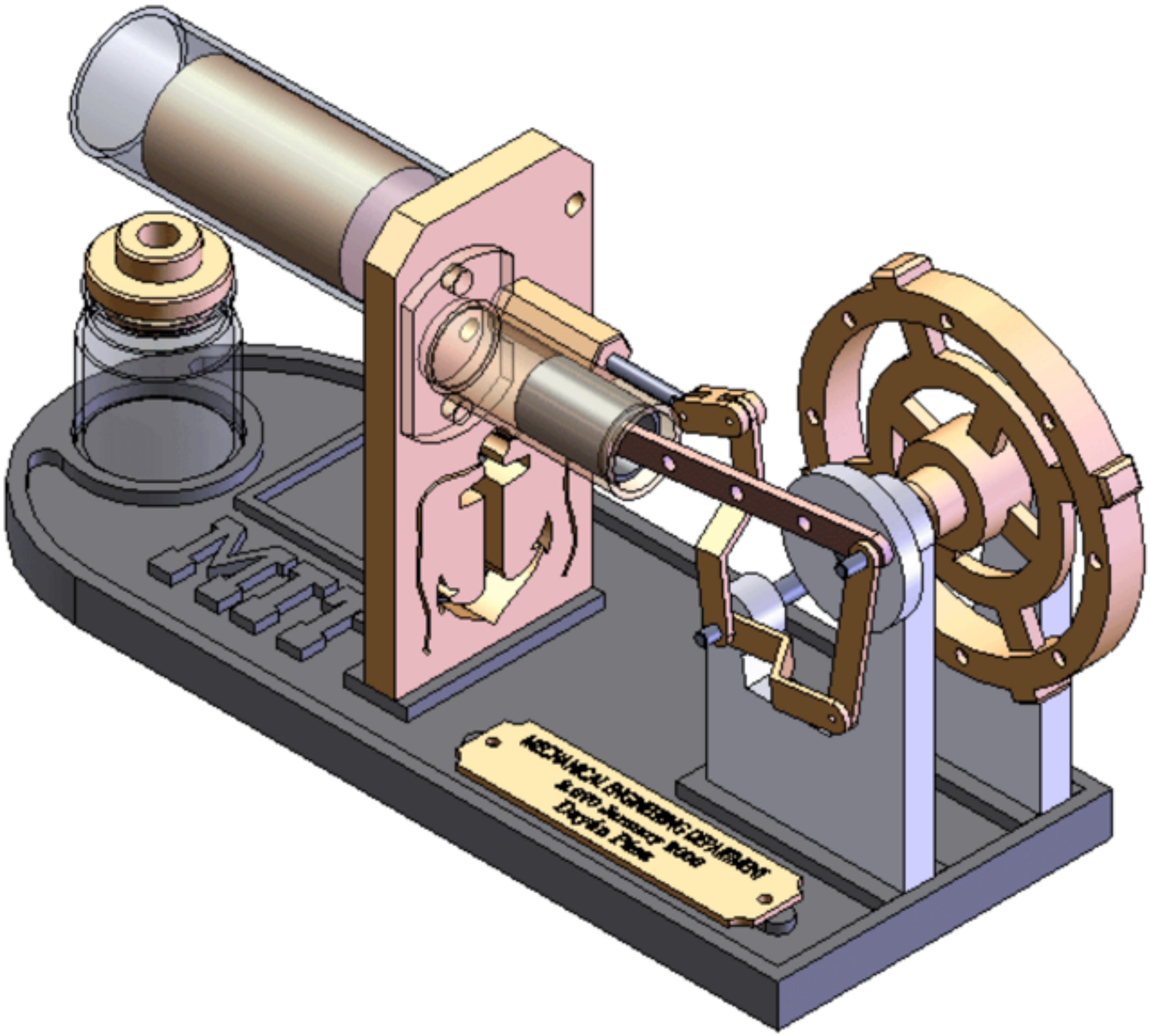
5.2.2. SINGLE CYLINDER STIRLING ENGINE



1: hot cap
2: cold wall
3: water connection
4: thermal insulation
5: displacer piston
6: working piston
7: gear

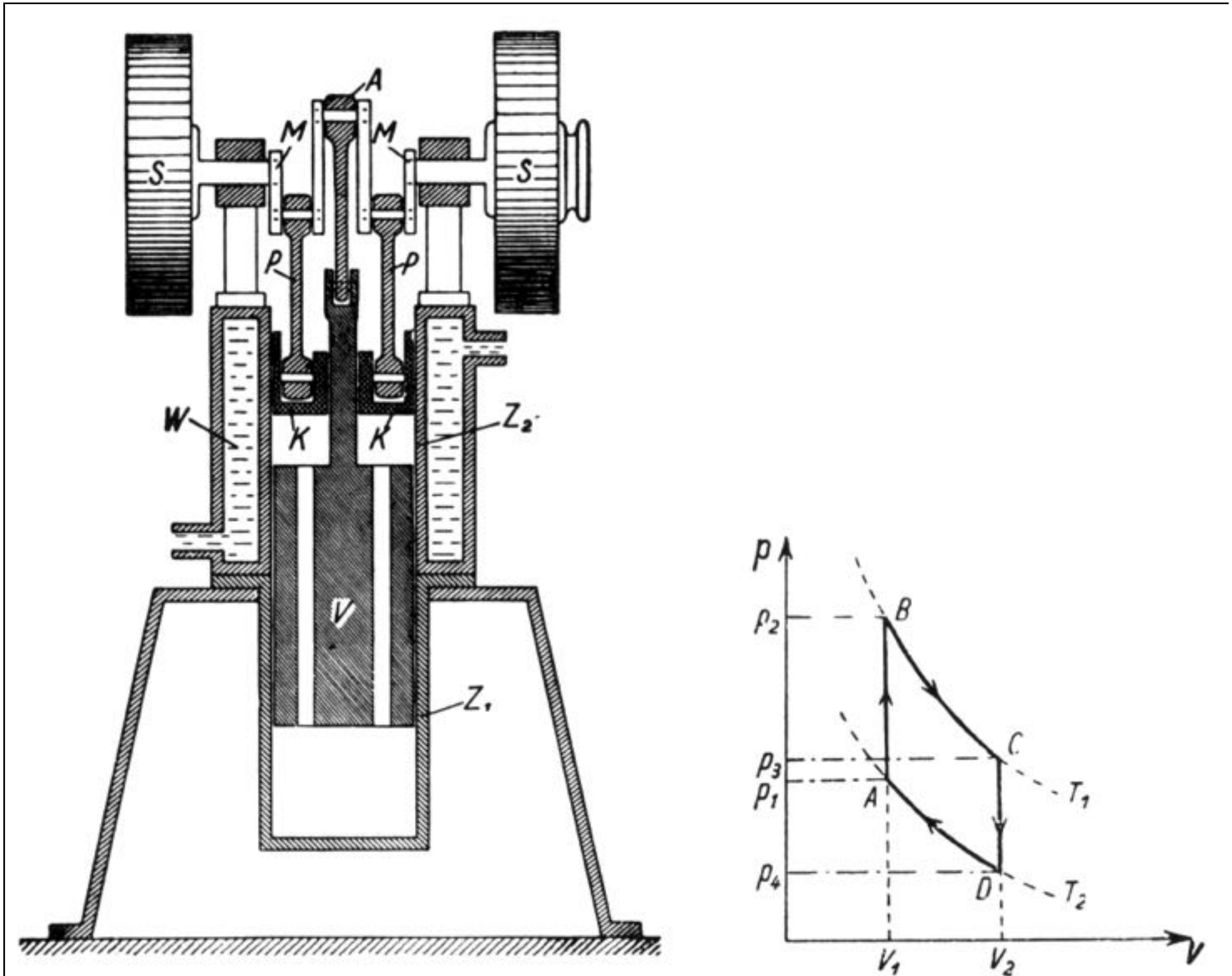
5.2.3. STIRLING ENGINE MODEL

5.2.4. MOVING STIRLING ENGINE MODEL

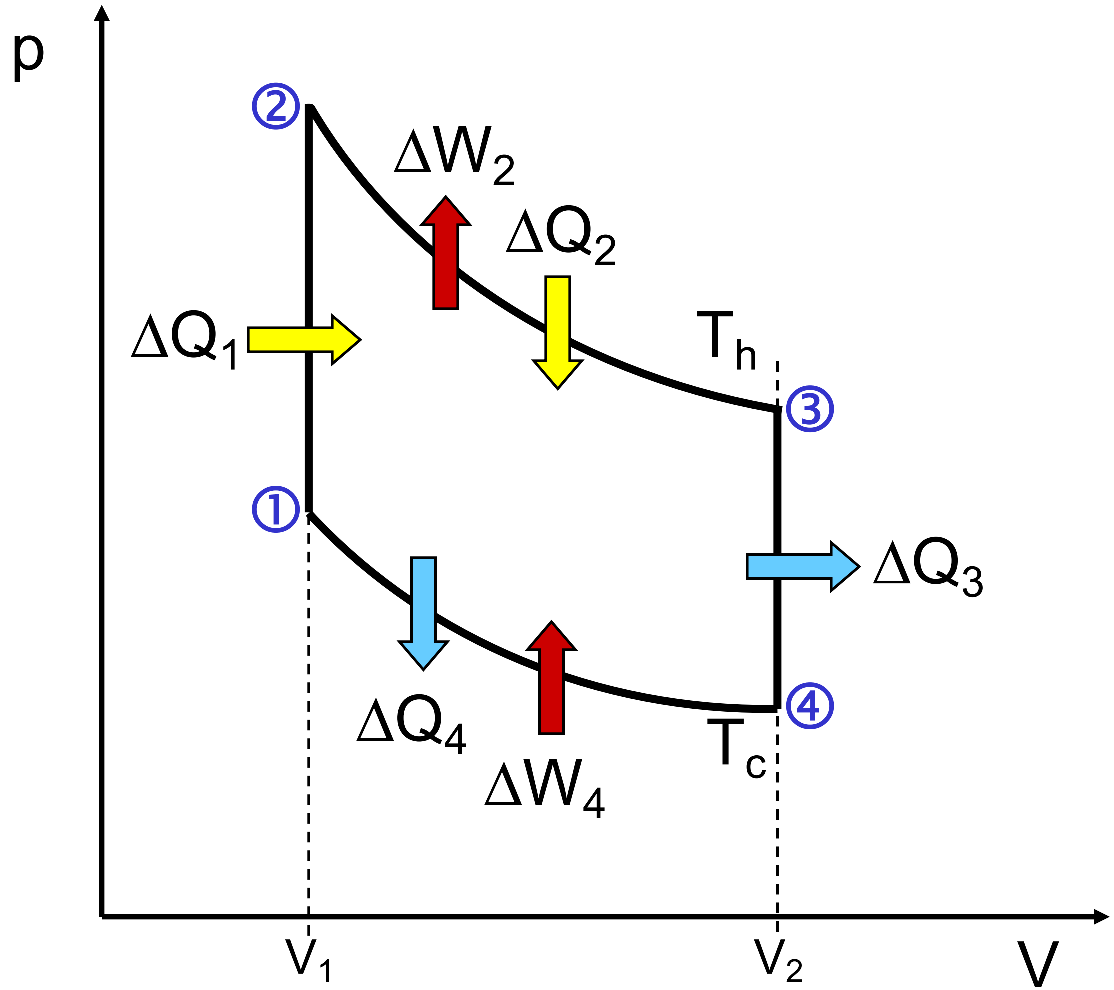


Ref.: http://giphy.com/gifs/

5.2.5. REAL STIRLING ENGINE



5.2.6. pV DIAGRAM OF THE STIRLING CYCLE



5.2.7. STIRLING CYCLE

1 → 2 isochor (V = const)

$\Delta W_1 = 0$ and $\Delta Q_1 = n\cdot c_V\cdot(T_h - T_c)$

2 → 3 isotherm ($T = T_h$ = const, $\Delta U = 0$)

$\Delta W_2 = p\cdot dV = n\cdot R\cdot T_h\cdot \ln(V_2/V_1)$ and $\Delta Q_2 = -\Delta W_2$

3 → 4 isochor (V = const)

$\Delta W_3 = 0$ and $\Delta Q_3 = n\cdot c_V\cdot(T_c - T_h)$

4 → 1 isotherm ($T = T_c$ = const, $\Delta U = 0$)

$\Delta W_4 = p\cdot dV = n\cdot R\cdot T_c\cdot \ln(V_1/V_2)$ and $\Delta Q_4 = -\Delta W_4$

Total work ΔW and heat from the hot reservoir (T_h)

$\Delta W = \Delta W_2 + \Delta W_4 = n\cdot R\cdot T_h\cdot \ln(V_2/V_1) + n\cdot R\cdot T_c\cdot \ln(V_1/V_2) = n\cdot R\cdot(T_h - T_c)\cdot \ln(V_2/V_1)$

$\Delta Q = \Delta Q_1 + \Delta Q_2 = n\cdot c_V\cdot(T_h - T_c) + n\cdot R\cdot T_h\cdot \ln(V_2/V_1)$

5.2.8. EFFICIENCY OF THE STIRLING CYCLE

Efficiency is

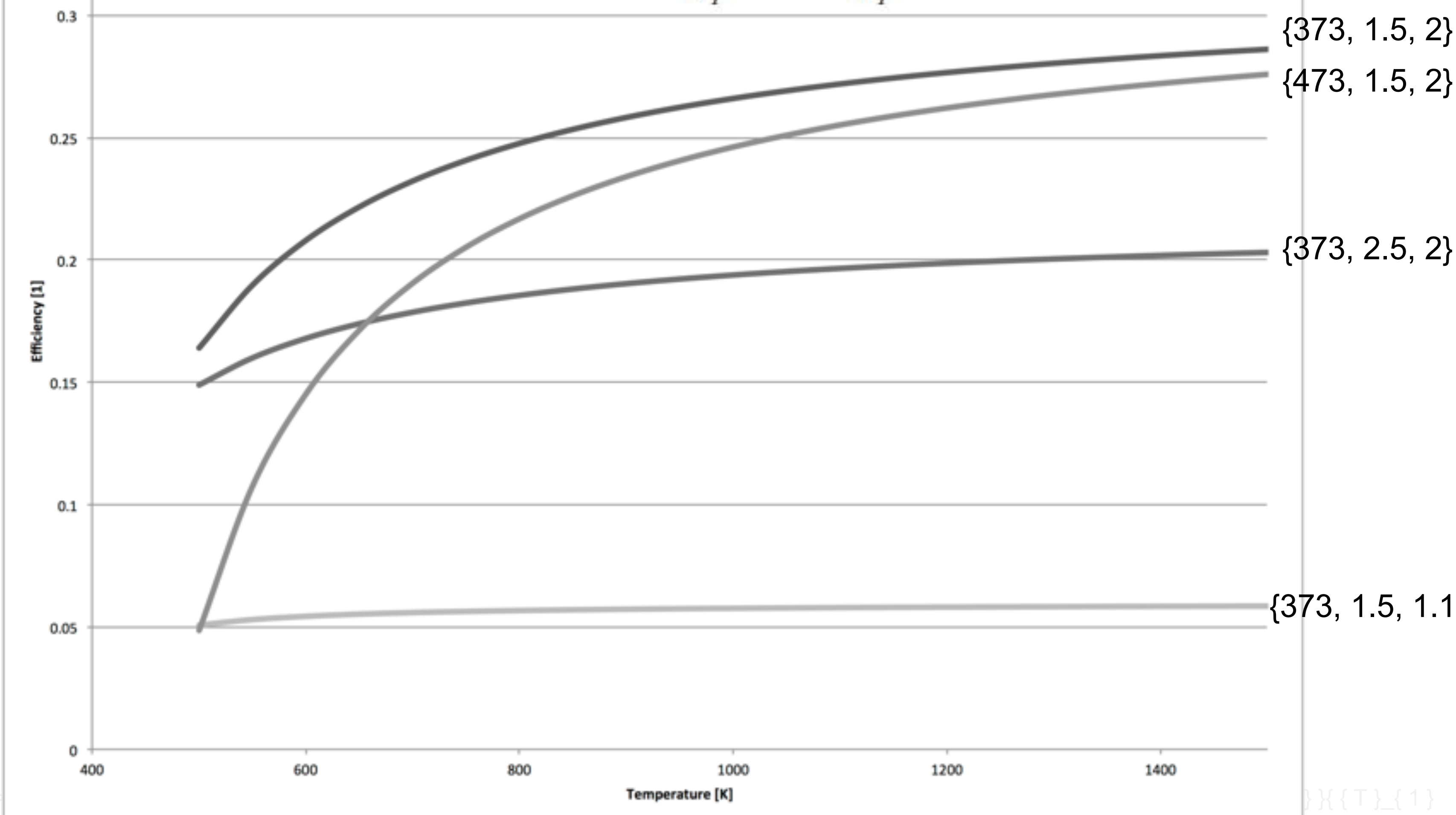
$$\frac{\Delta W}{\Delta Q} = \frac{n \cdot R \cdot (T_h - T_c) \cdot ln\left(\frac{V_2}{V_1}\right)}{n \cdot c_V \cdot (T_h - T_c) + n \cdot R \cdot T_h \cdot ln\left(\frac{V_2}{V_1}\right)} = \frac{(T_h - T_c)}{\frac{c_V \cdot (T_h - T_c)}{R \cdot ln\left(\frac{V_2}{V_1}\right)} + T_h} = \frac{1}{\frac{c_V}{R \cdot ln\left(\frac{V_2}{V_1}\right)} + \frac{T_h}{(T_h - T_c)}}$$

$$\frac{\Delta W}{\Delta Q} = \frac{1}{\frac{c_V}{R \cdot ln\left(\frac{V_2}{V_1}\right)} + \frac{1}{1 - \frac{T_c}{T_h}}}$$

5.2.9. EXAMPLES OF STIRLING CYCLE EFFICIENCY

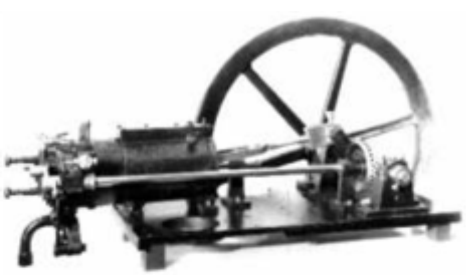
Efficiency is $$\eta = \frac{\Delta W}{\Delta Q} = \frac{1}{\frac{C_V}{R \cdot \ln \frac{V_2}{V_1}} + \frac{1}{1 - \frac{T_2}{T_1}}}$$

$\{T_c[K], c_V, V_2/V_1\}$



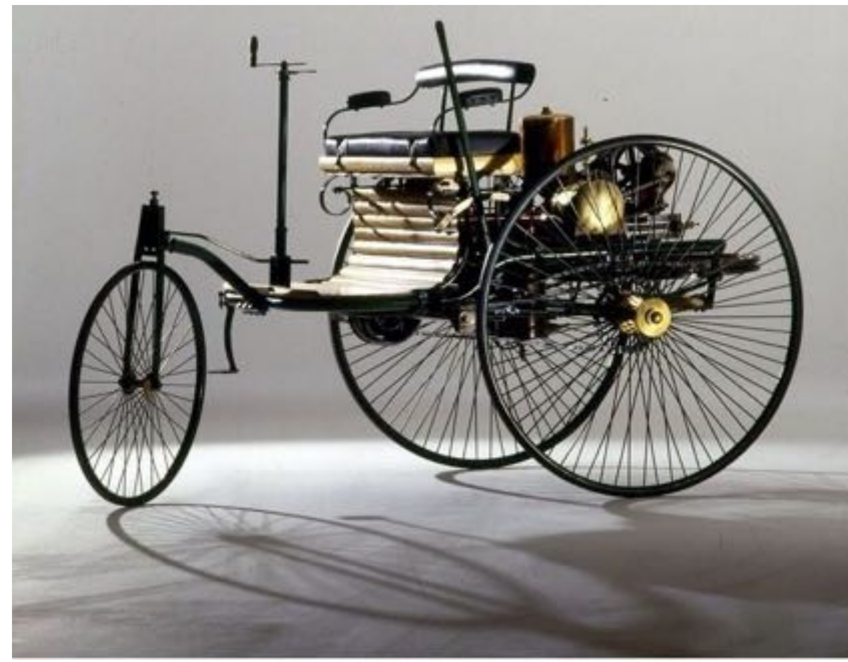
5.3. OTTO ENGINE (EXPLOSION ENGINE)

Nicolaus August OTTO
(1832 - 1891)



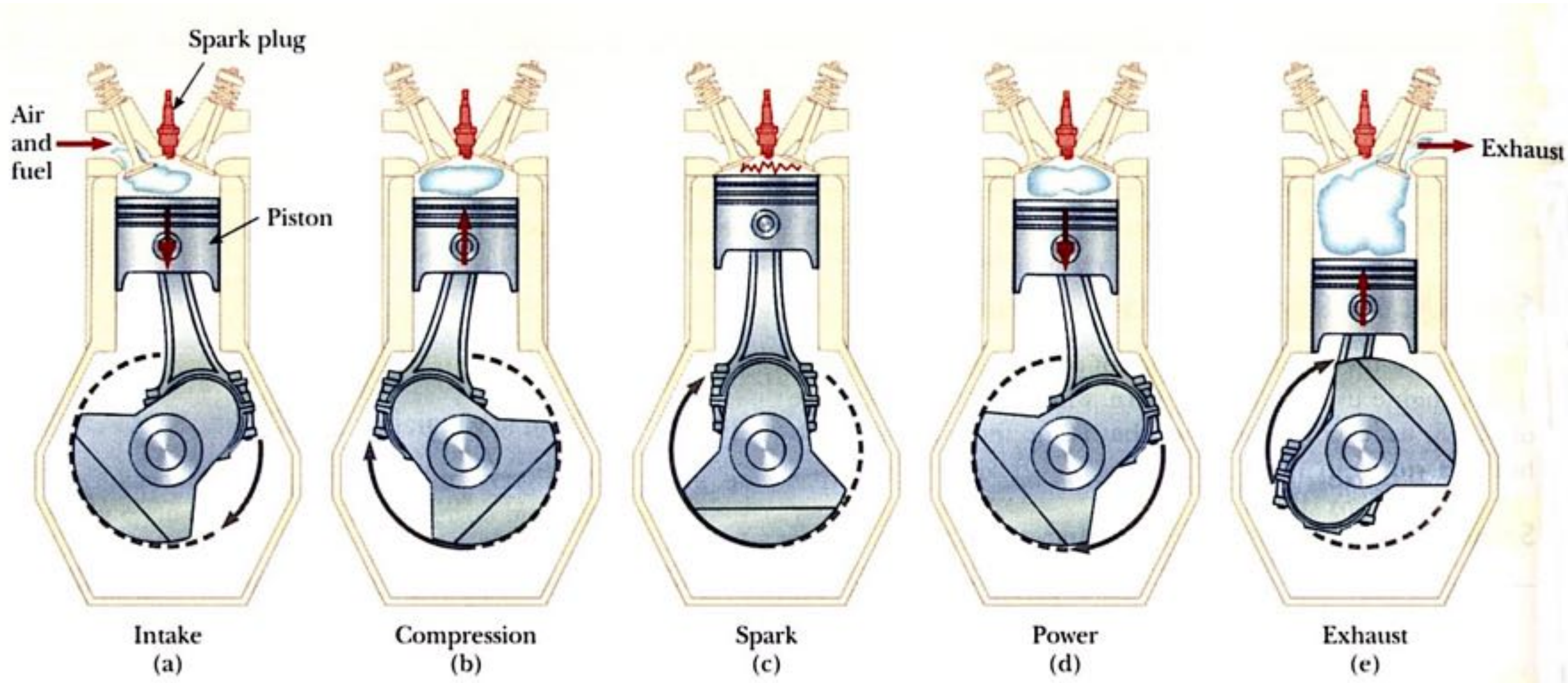
Gas Engine 1866

Carl Friedrich Benz
(* 25. November 1844 in Mühlburg
als Karl Friedrich Michael Vaillant;
† 4. April 1929 in Ladenburg



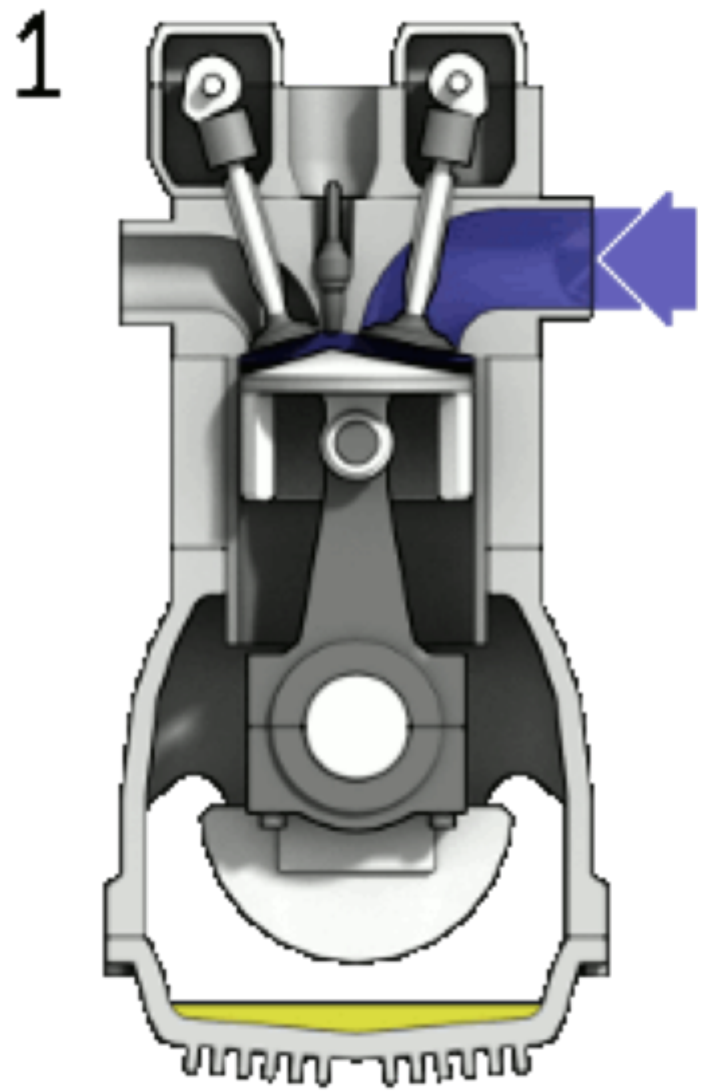
January 29, 1886 - Karl Benz received a German patent for a "Vehicle Propelled by a Gas Engine" (first functional unit of an engine with a chassis) called "Patent-Motorwagen".

5.3.1. 4-STROKE OTTO ENGINE (EXPLOSION ENGINE)

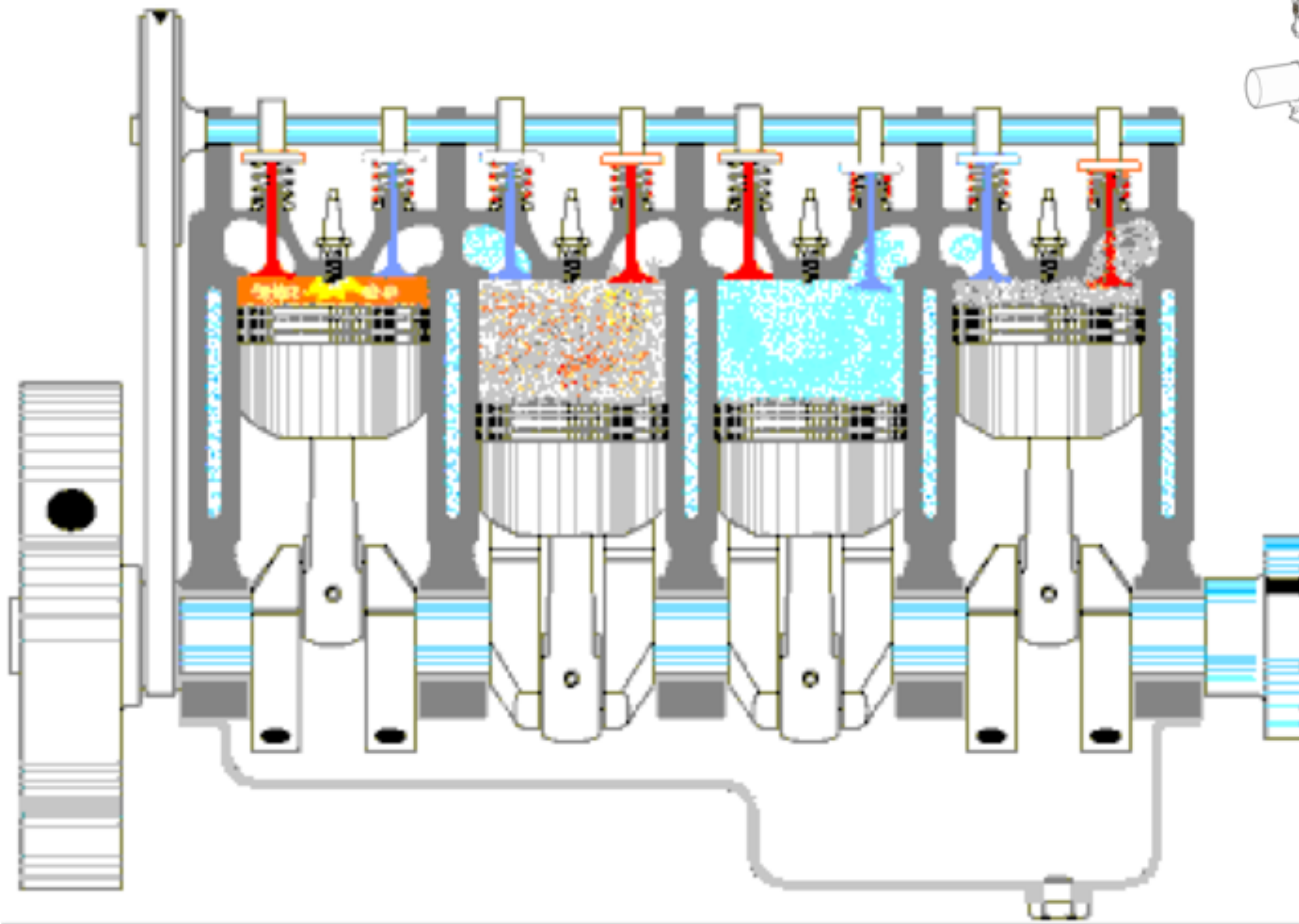


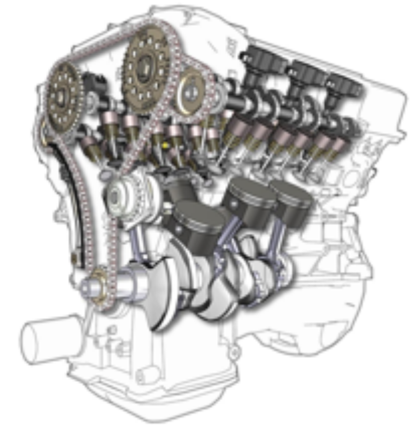
(a) The first down cycle of the piston is to suck into the cylinder a mixture of fuel and air. An inlet valve in the cylinder head opens to let in the fuel air mixture as the piston moves down within the cylinder.
(b) The inlet valve in the cylinder head closes and as the piston moves up the cylinder, the air/fuel mixture is compressed.
(c) The third cycle is the combustion cycle. When the piston reaches the top of the cylinder, the spark plug ignites the compressed air/fuel mixture.
(d) The mixture then explodes and the pressure pushing the piston down, which in turn pushes the crankshaft around.
(e) The final and fourth cycle of the Otto cycle is the exhaust cycle. After the combustion cycle, it then commences its second upstroke to push out the burnt fuel/air mixture through the exhaust valve.

5.3.2. MOVING OTTO ENGINE MODEL



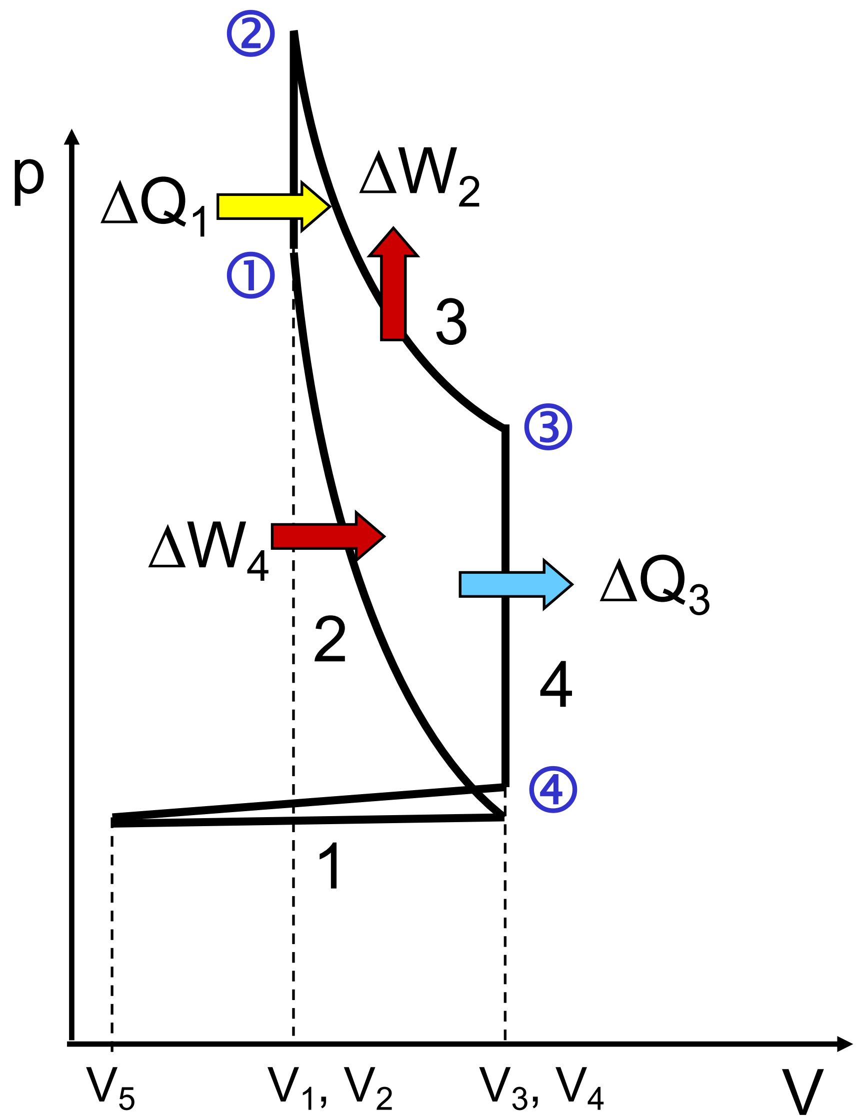
5.3.3. 4-CYLINDER OTTO ENGINE





Ref.: http://giphy.com/gifs/

5.3.4. pV- DIAGRAM OF THE OTTO CYCLE



1 → 2 Explosion (V = const)

$\Delta W_1 = 0$ and $\Delta Q_1 = n \cdot c_V \cdot (T_2 - T_1)$

2 → 3 adiabatic (ΔQ = 0)

$\Delta Q_2 = 0$ and $\Delta W_2 = n \cdot c_V \cdot (T_3 - T_2)$

3 → 4 isochor (V = const)

$\Delta W_3 = 0$ and $\Delta Q_3 = n \cdot c_V \cdot (T_4 - T_3)$

4 → 0 isobar (p = const)

$\Delta Q_5 = 0$ and $\Delta W_5 = p \cdot (V_5 - V_4)$

0 → 4 isobar (p = const)

$\Delta Q_6 = 0$ and $\Delta W_6 = p \cdot (V_4 - V_5)$

5.3.5. EFFICIENCY OTTO ENGINE

4 → 1 adiabatic ($\Delta Q = 0$)

$\Delta Q_4 = 0$ and $\Delta W_4 = n \cdot c_V \cdot (T_1 - T_4)$

Total work ΔW and heat from the hot reservoir (T_h)

$\Delta W = \Delta W_2 + \Delta W_4 = n \cdot c_V \cdot (T_3 - T_2) + n \cdot c_V \cdot (T_1 - T_4)$

$\Delta Q = \Delta Q_1 = n \cdot c_V \cdot (T_2 - T_1)$

Efficiency

$$\eta = \frac{\Delta W}{\Delta Q} = \frac{\Delta W_2 + \Delta W_4}{\Delta Q_1} = \frac{n \cdot C_V \cdot (T_3 - T_2) + n \cdot C_V \cdot (T_1 - T_4)}{n \cdot C_V \cdot (T_2 - T_1)}$$

$$\eta = \frac{\Delta W}{\Delta Q} = 1 - \frac{(T_4 - T_3)}{(T_2 - T_1)}$$

$$\eta = 1 - \frac{1}{\left(\frac{V_3}{V_1}\right)^{\kappa - 1}} \qquad \kappa = \frac{c_p}{c_V}$$

5.3.6. SELF IGNITION

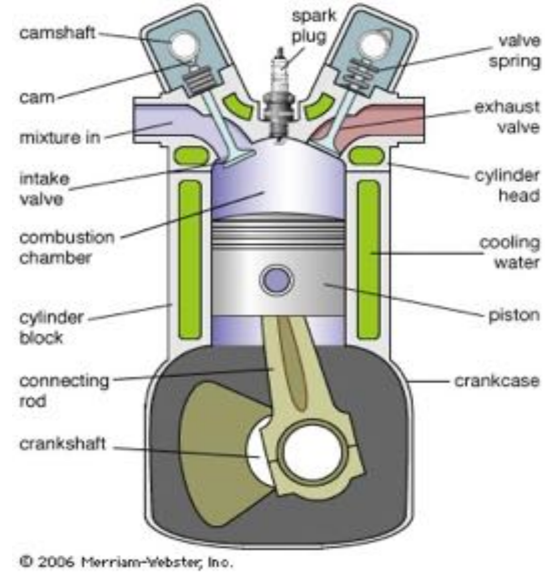
Self ignition temperature of petrol is 257°C.

Max. compression (adiabatic)

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\left(\frac{c_v}{R}+1\right)}$$

$$\frac{p_2}{p_1} = \left(\frac{530K}{293K}\right)^{\left(\frac{7}{2}\right)} = 7.9$$

5.3.7. COMBUSTION POWER



Combustion of Octane (Petrol)

$$C_8H_{18} + 12.5O_2 + 50N_2 \rightarrow 8CO_2 + 9H_2O + 50N_2$$

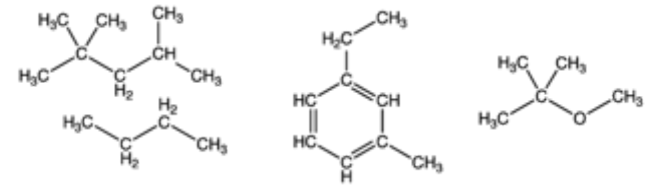
The volume of the cylinder determines the amount of molecules available for the combustion $n = p \cdot V/(R \cdot T)$.

$$\Delta H_R = \Delta H_f(CO_2) + \Delta H_f(H_2O) - \Delta H_f(C_8H_{18})$$

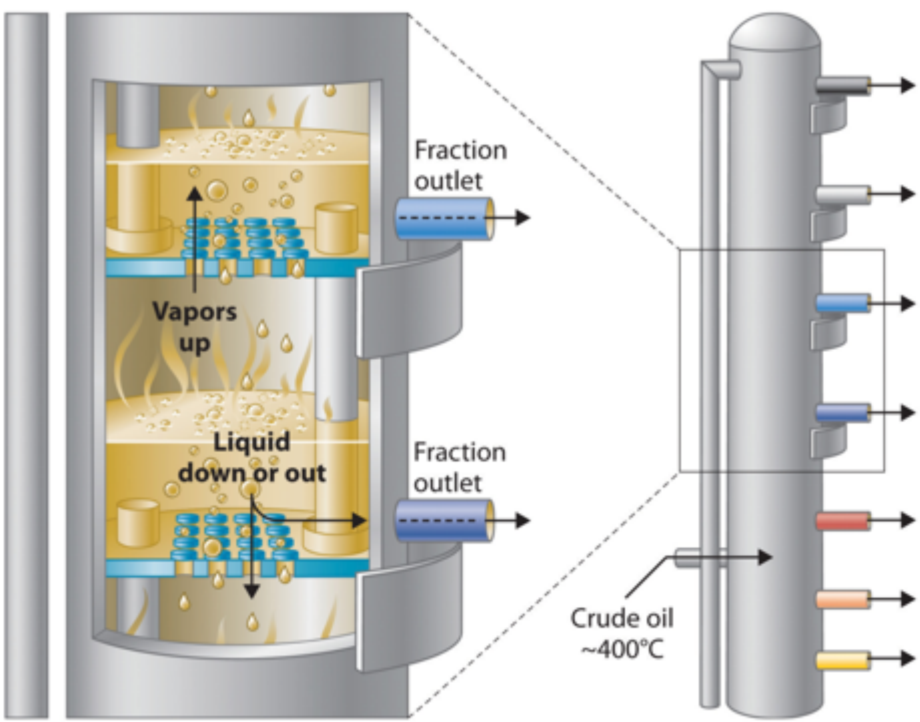
63.5 molecules produce

$\Delta H_R = -5116.5$ kJ $(H_2O)_{gas}$ and $\Delta H_R = -5512.5$ kJ $(H_2O)_{liq}$

5.3.8. PROPERTIES GASOLINE, PETROL



Main components of gasoline: isooctane, butane, 3-ethyltoluene, and the octane enhancer MTBE.
The bulk of a typical gasoline consists of hydrocarbons with between 4 and 12 carbon atoms per molecule (commonly referred to as C_4-C_{12}).[2] It is a mixture of paraffins (alkanes), cycloalkanes (naphthenes), and olefins (alkenes), where the usage of the terms paraffin and olefin is particular to the oil industry.
Gasoline contains about 42.4 MJ/kg (120 MJ/US gal, 33.3 kWh/US gal, 11.8 kWh/kg, 120,000 BTU/US gal)
Octane rating is measured relative to a mixture of 2,2,4-trimethylpentane (an isomer of octane) and n-heptane.

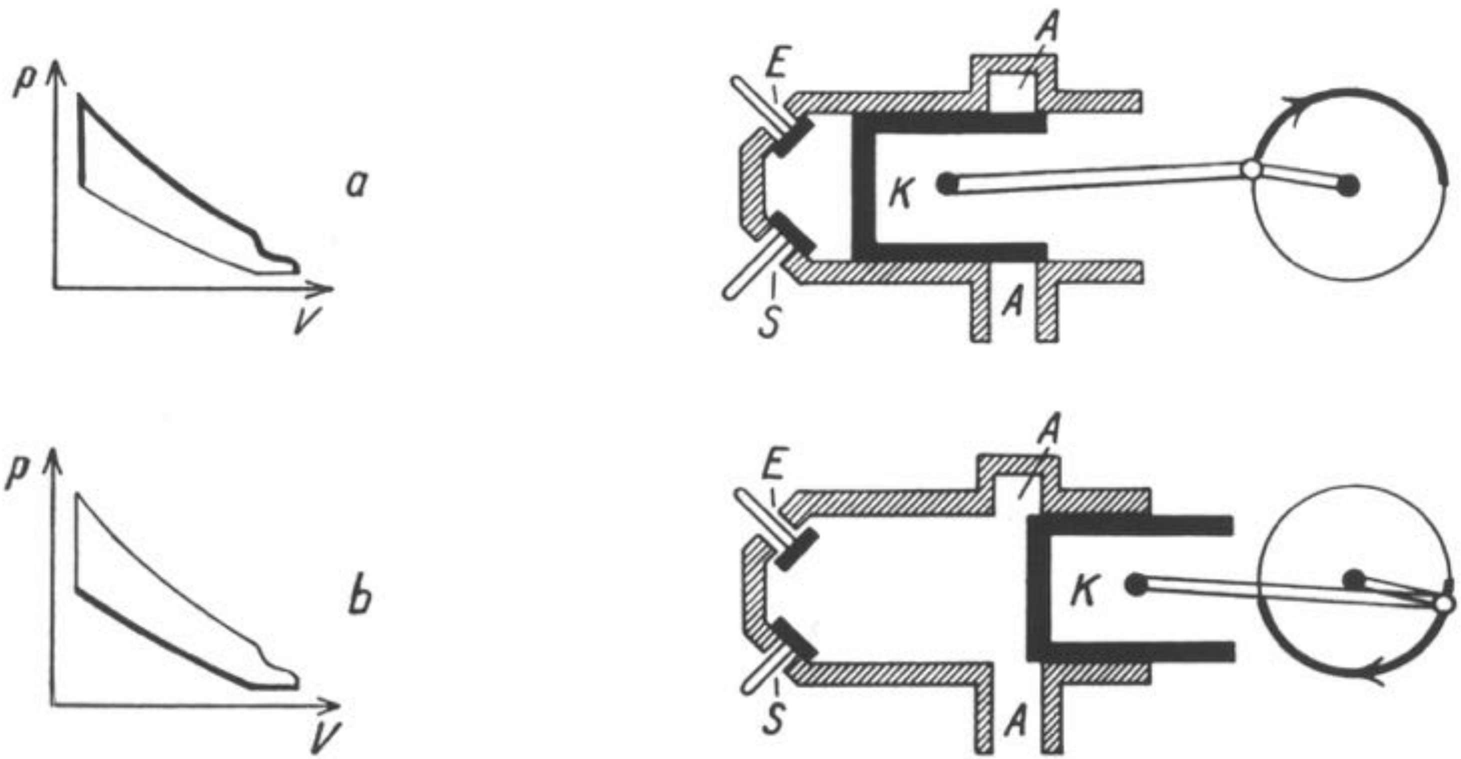


	Number of carbons	Boiling point range	Uses
Gases	1–4	0–30°C	Bottled and natural gas
Naphthas	5–10	30–180°C	Gasoline
Kerosenes	10–16	180–260°C	Kerosene for home heaters, jet fuel
Gas oils	16–60	260–350°C	Diesel fuel, feedstock for cracking
Lubricants	>60	350–575°C	Motor oil, feedstock for cracking
Fuel oil	>70	>490°C	Candles, fuel oil for ships and power stations
Asphalt	>80	>580°C	Roofing tar, road tar

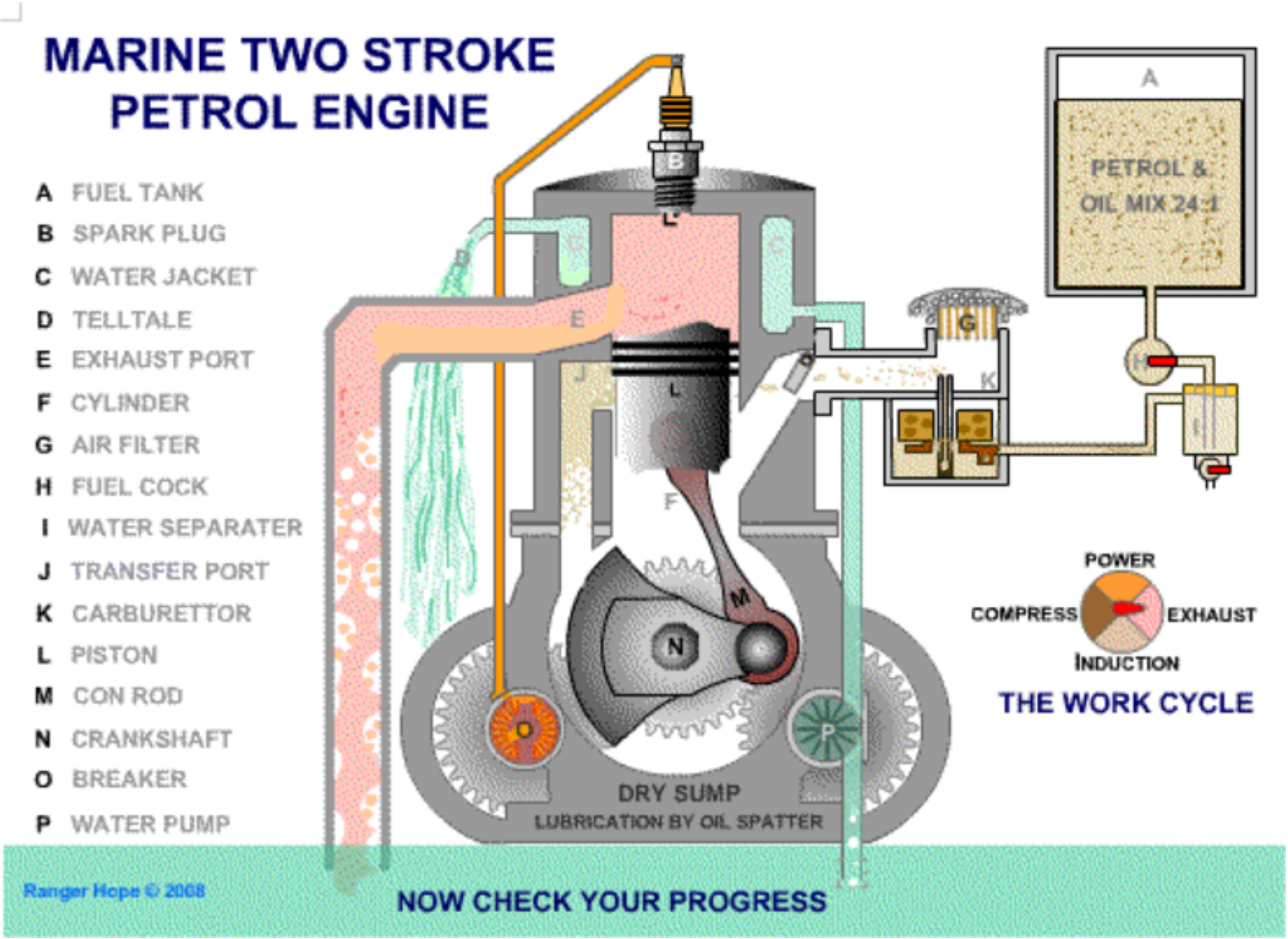
(a) Petroleum distillation tower

(b) Petroleum fractions

5.3.9. 2-STROKE OTTO ENGINE



5.3.10. MOVING 2-STROKE MARINE ENGINE



Ref.: http://giphy.com/gifs/

5.4. BRAYTON READY MOTOR

George Bailey BRAYTON
(* 3. 10. 1830 in Crompton, USA; † 17. 12. 1892 in Kingsbury, England

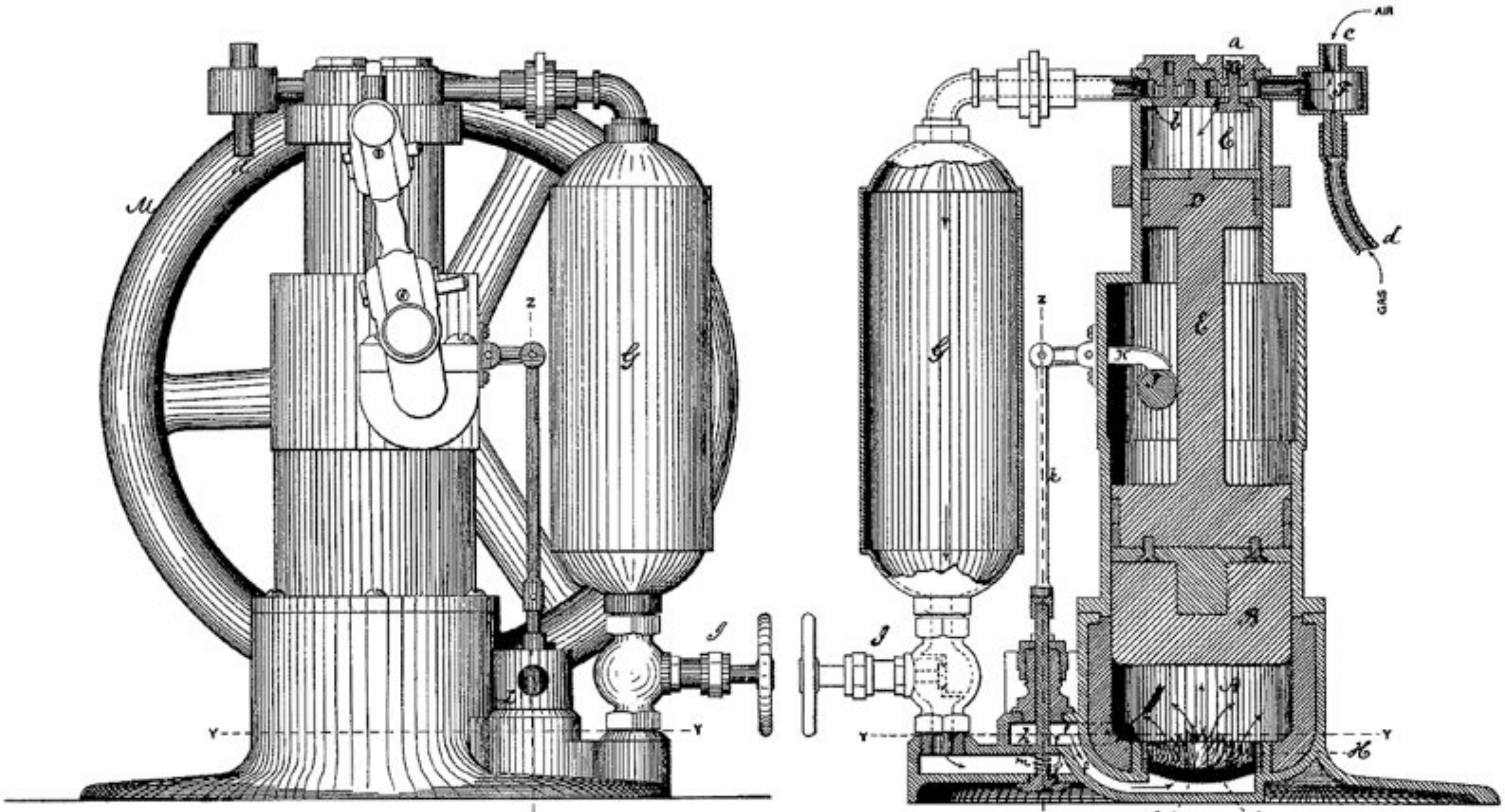
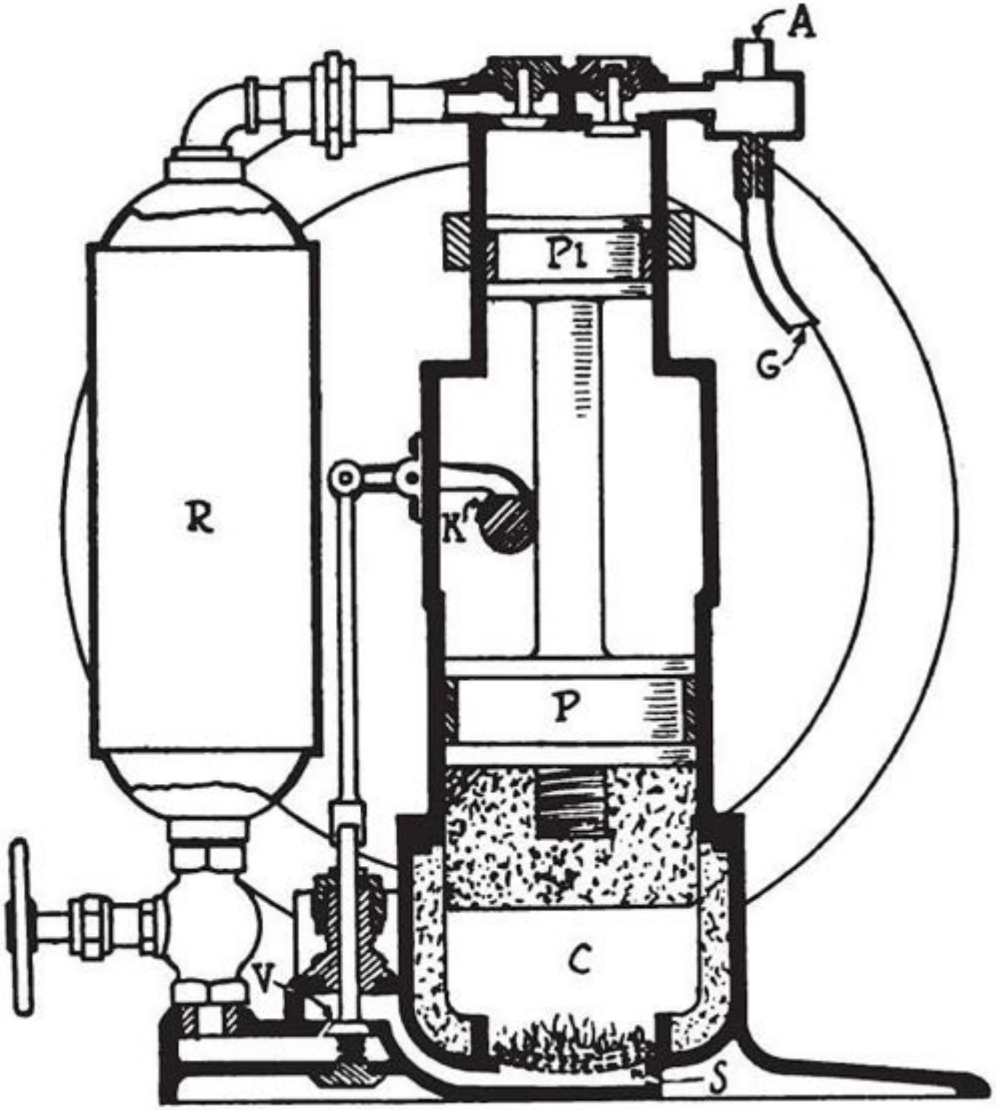
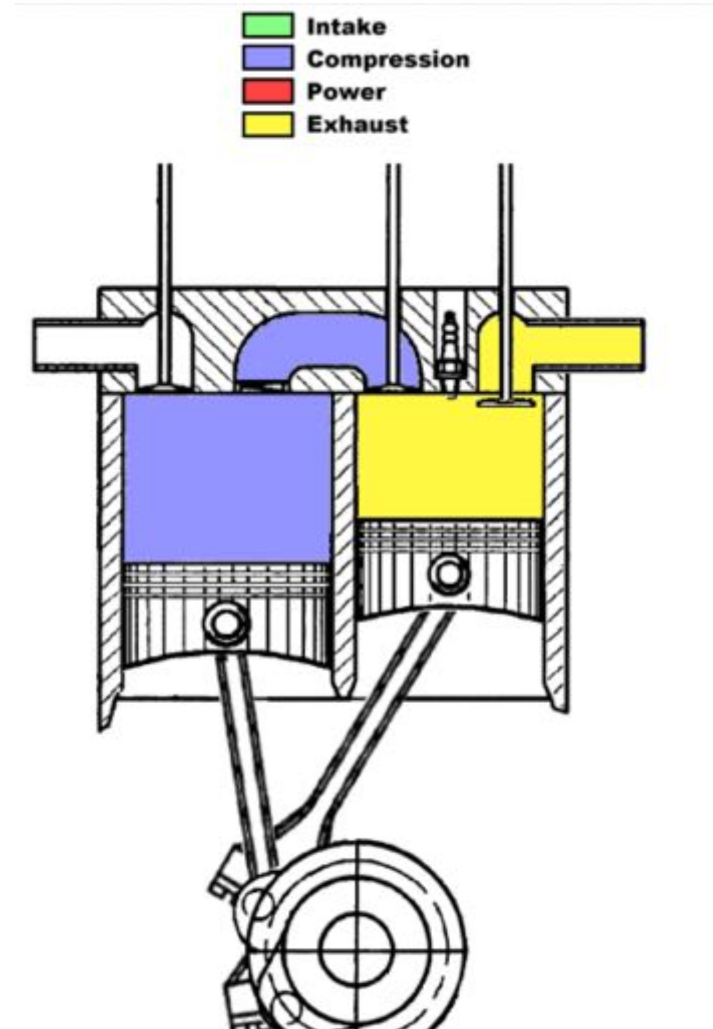


FIG.1. FIG.2.

5.4.1. PRINCIPLE OF THE BRAYTON READY MOTOR



BRAYTON'S TWO-CYCLE ENGINE 1872



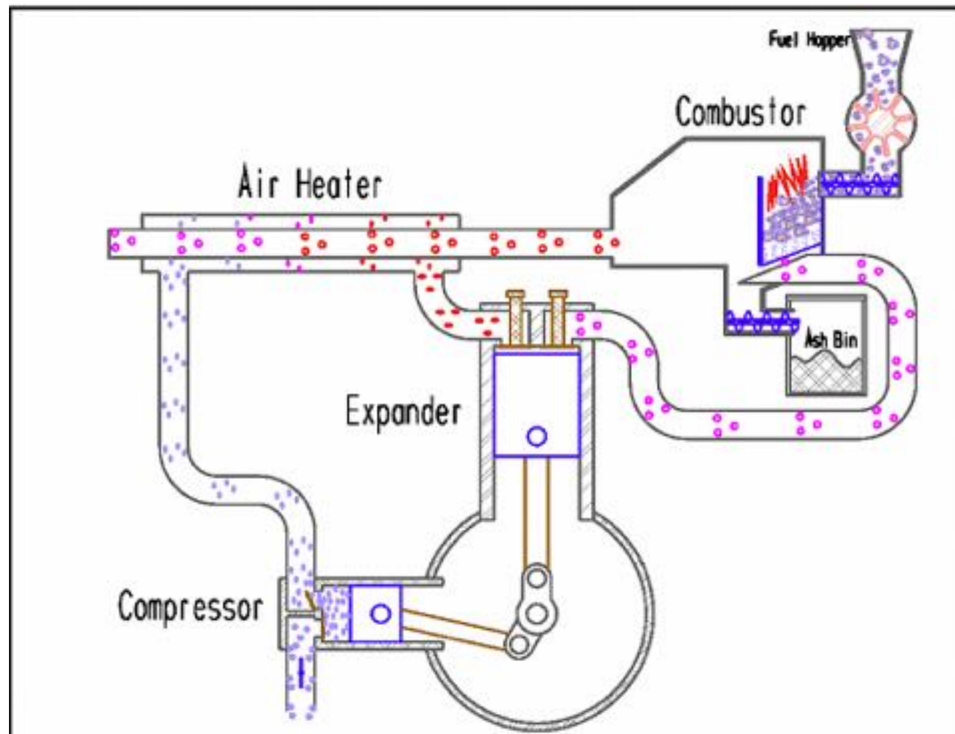
5.4.2. BRAYTON READY MOTOR CYCLE

1 → 2 Adiabatic filling: $Q_{12} = 0$, $W_{12} = n \cdot c_V \cdot (T_2 - T_1)$

2 → 3 Isobar expansion (combustion): $Q_{23} = Q_{in}$, $W_{23} = 0$

3 → 4 Adiabatic expansion $Q_{34} = 0$, $W_{34} = n \cdot c_V \cdot (T_4 - T_3)$

4 → 1 Isobar exhaust: $Q_{41} = Q_{out}$, $W_{41} = 0$

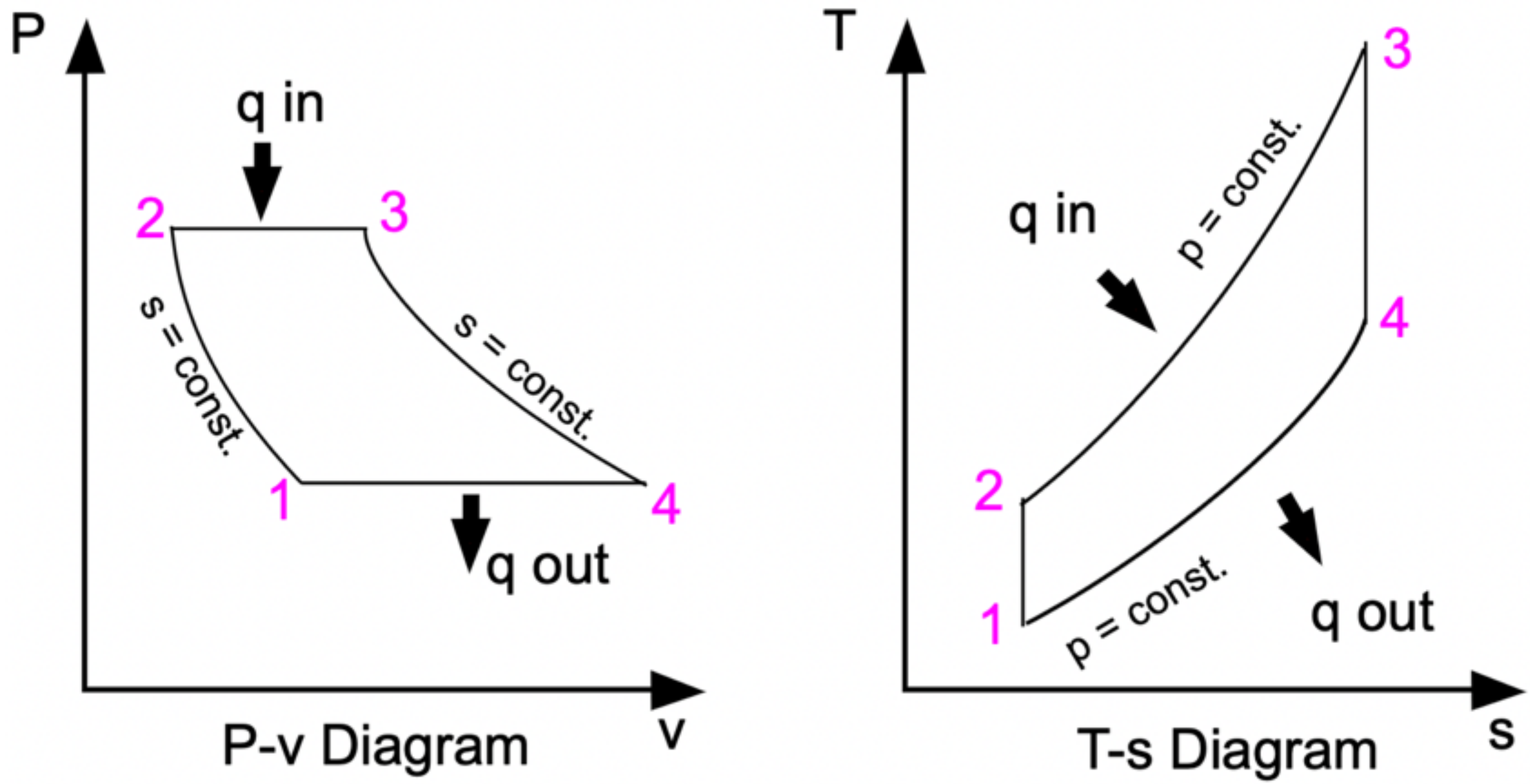


Efficiency:

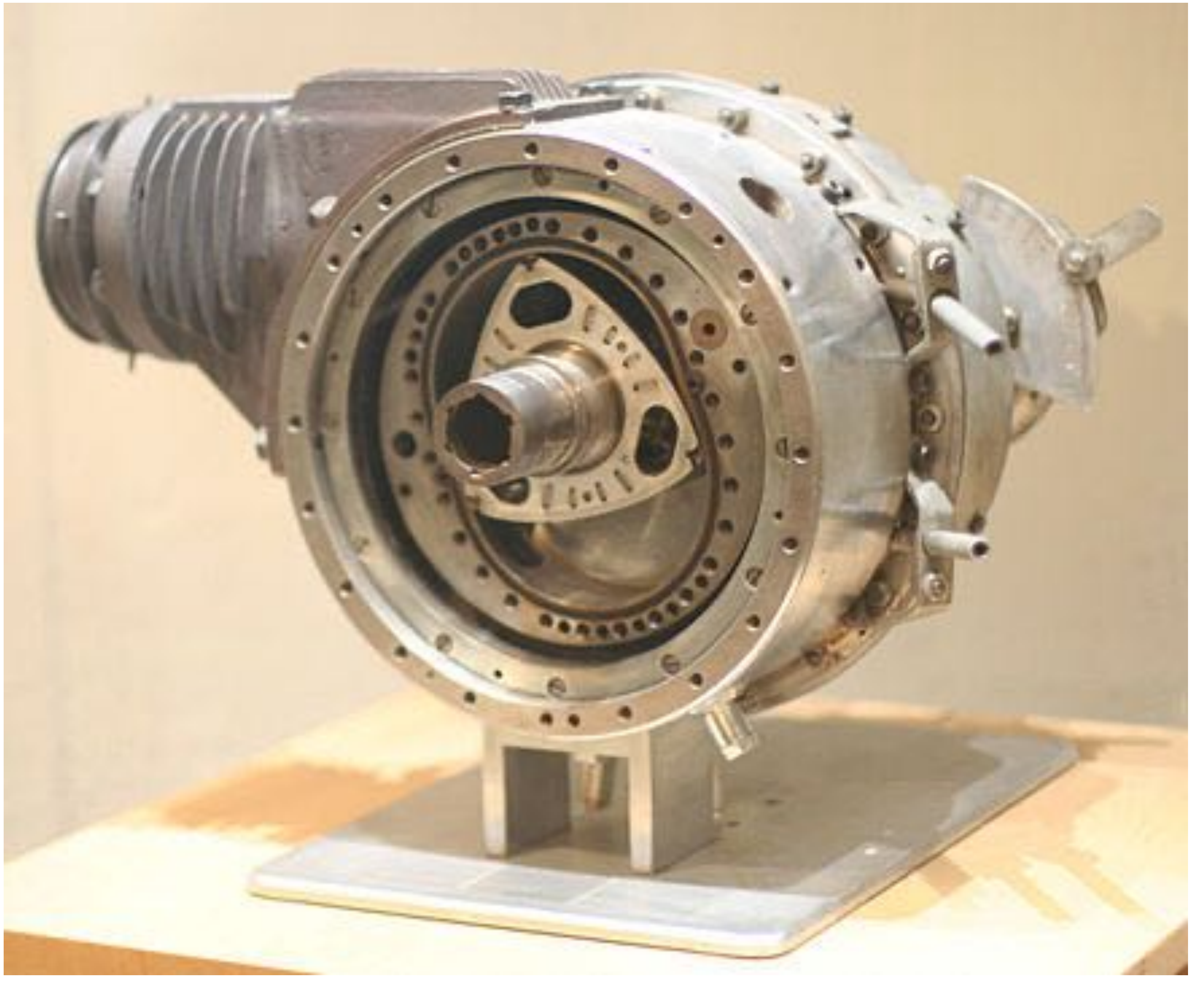
$$\eta = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}$$

$\gamma = c_p/c_V$

5.4.3. pV AND TS DIAGRAM OF THE BRAYTON READY MOTOR



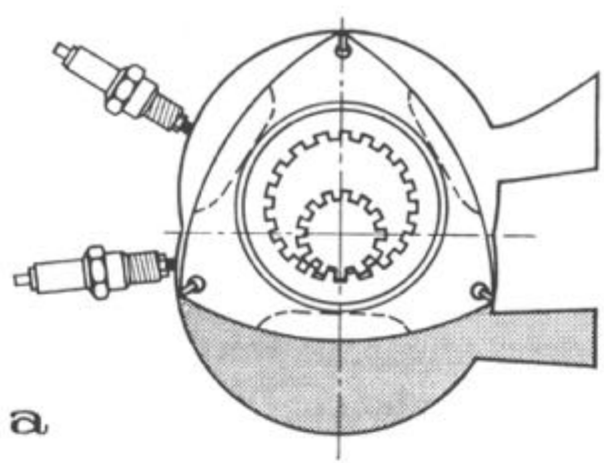
5.5. WANKEL ENGINE



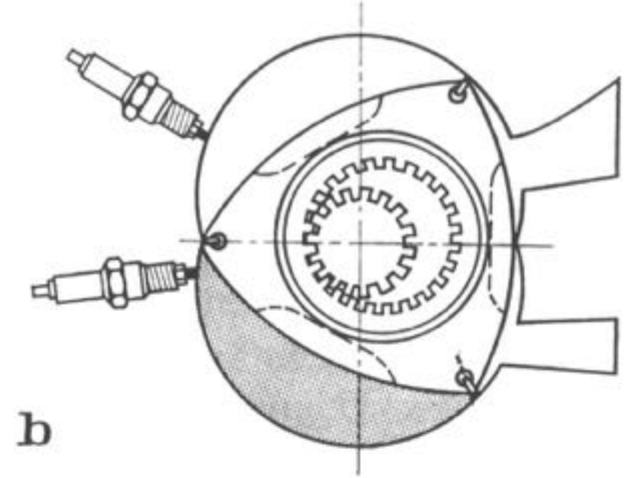
DKM 54 (DrehKolbenMotor 54) 1957

Felix Heinrich Wankel
(* 13. August 1902 in Lahr; † 9. Oktober 1988 in Heidelberg)

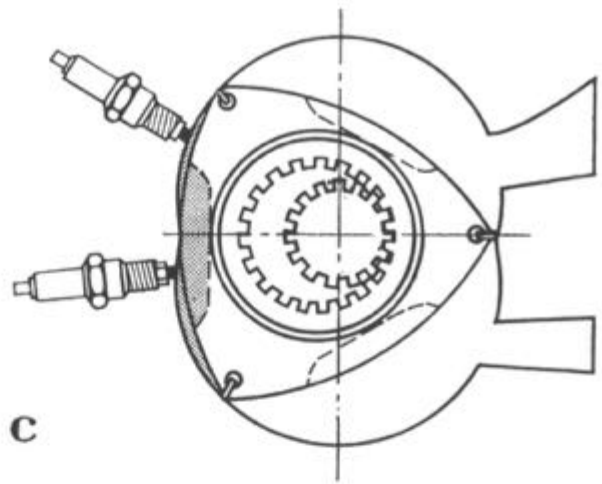
5.5.1. CYCLE OF THE WANKEL ENGINE



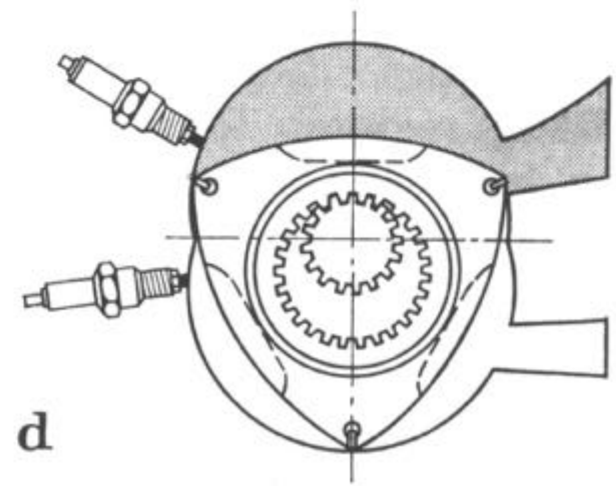
intake



compression



ignition

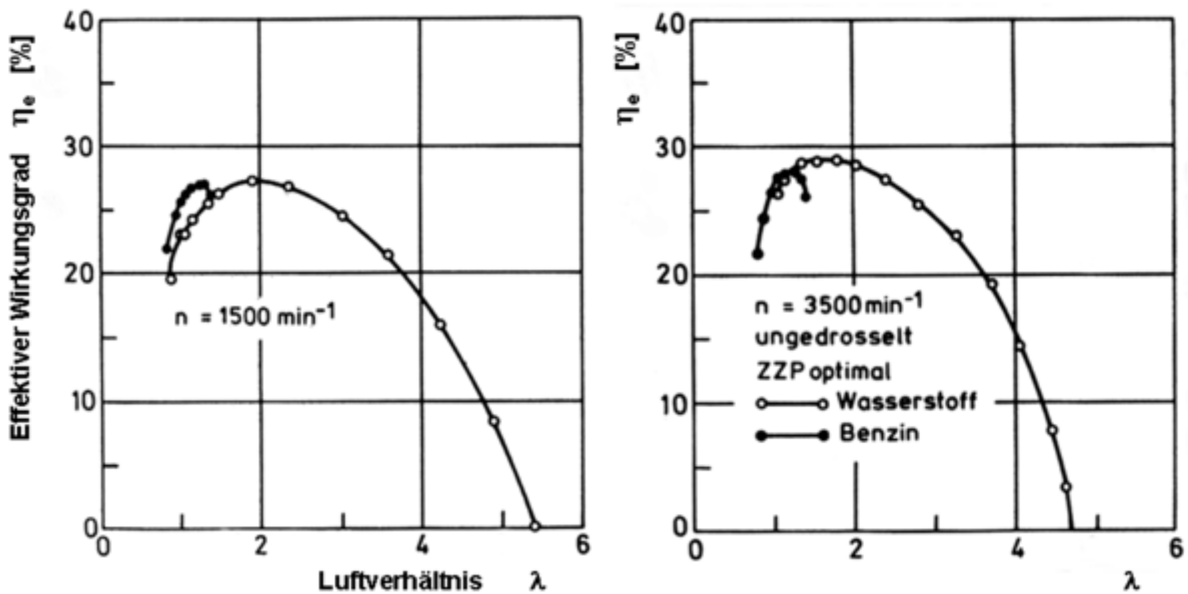


exhaust

5.5.2. EFFICIENCY OF THE WANKEL ENGINE

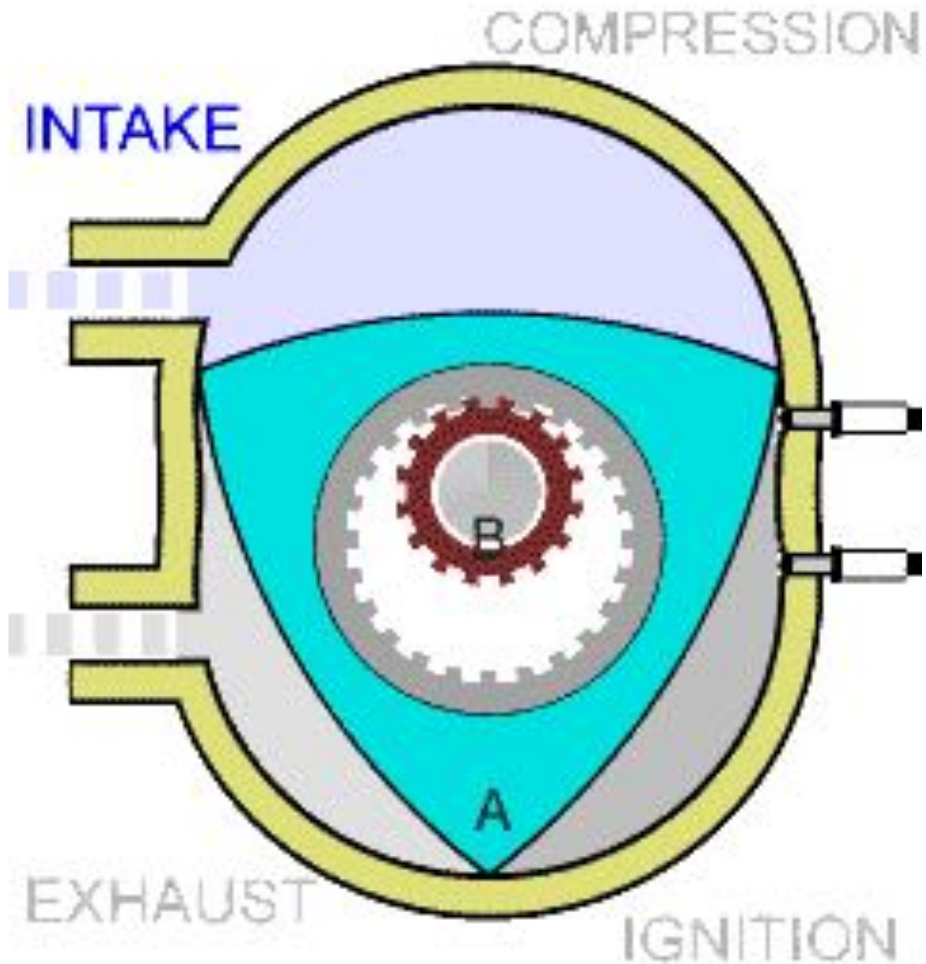
Efficiency is determined (in analogy to the Otto engine) by the compression ratio:

$$\eta = 1 - \frac{1}{\left(\frac{V_3}{V_1}\right)^{\kappa-1}} \qquad \kappa = \frac{c_p}{c_V} = 1.4$$



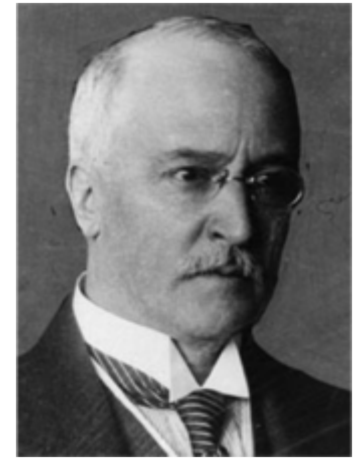
Audi NSU Wankelmotor EA 871
Stand 1977
Verdichtungsverhältnis 9,2 : 1

5.5.3. MOVING WANKEL ENGINE



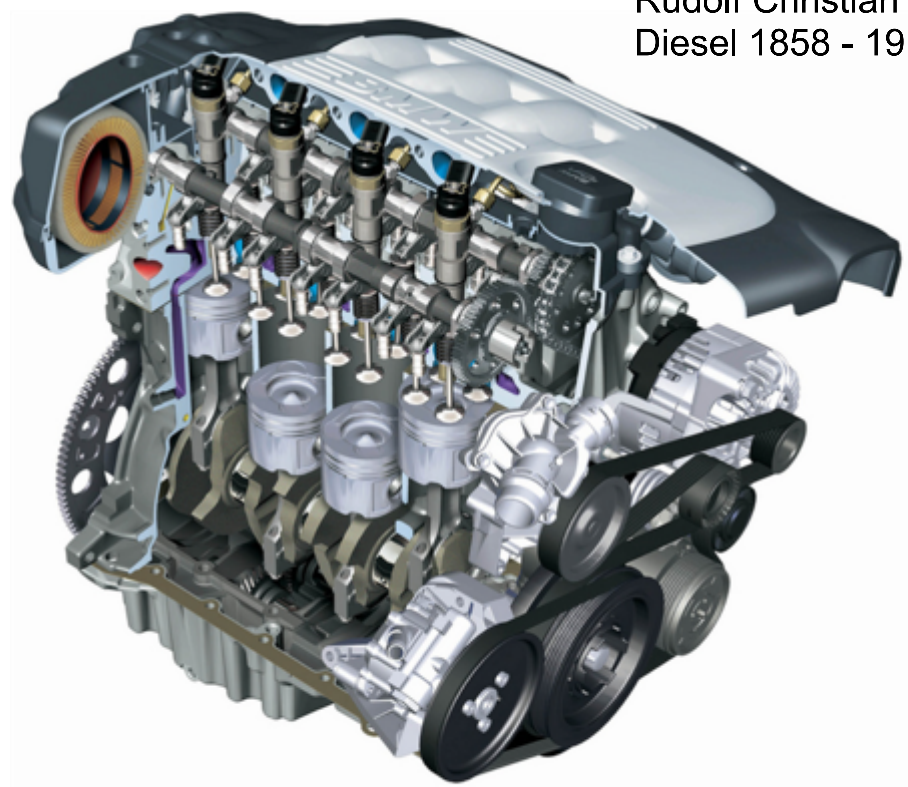
Ref.: http://giphy.com/gifs/car-works-educational-IheewDzC0n3G0

5.6. DIESEL ENGINE (COMBUSTION ENGINE)

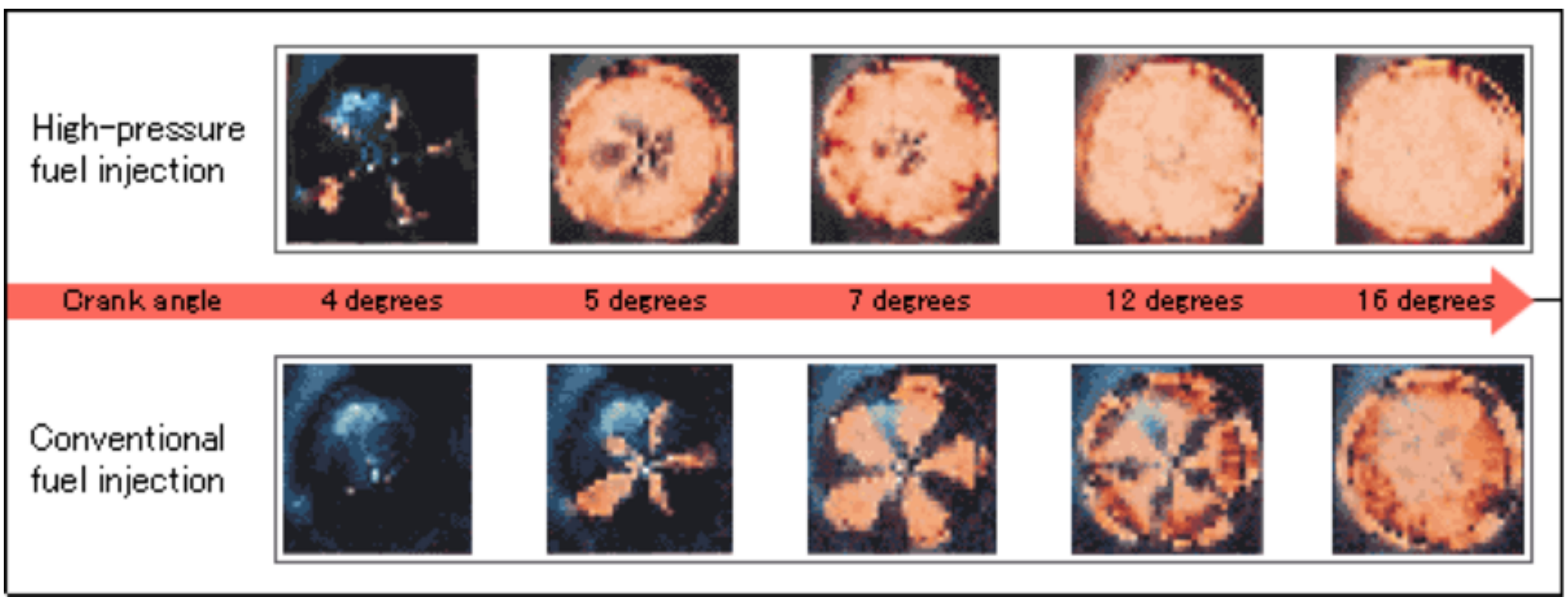


Rudolf Christian Karl Diesel 1858 - 1913

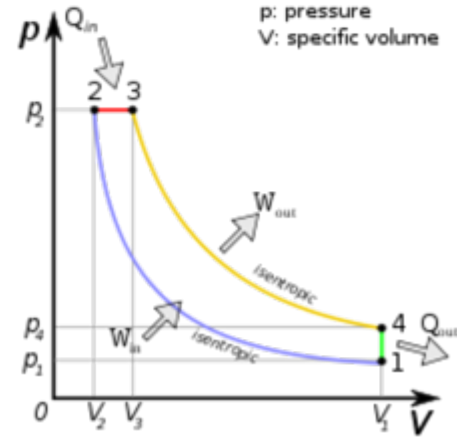
Diesel engine 1892

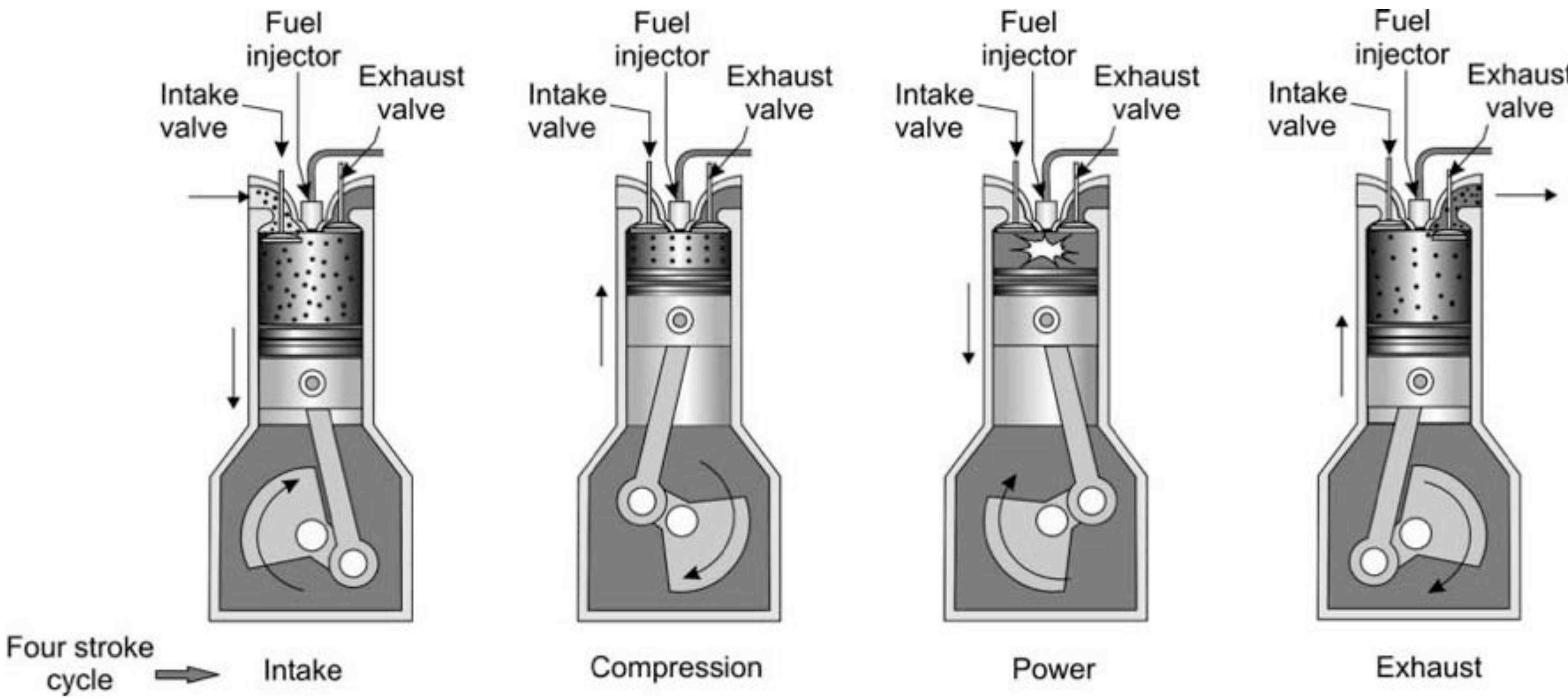


5.6.1. DIESEL COMBUSTION

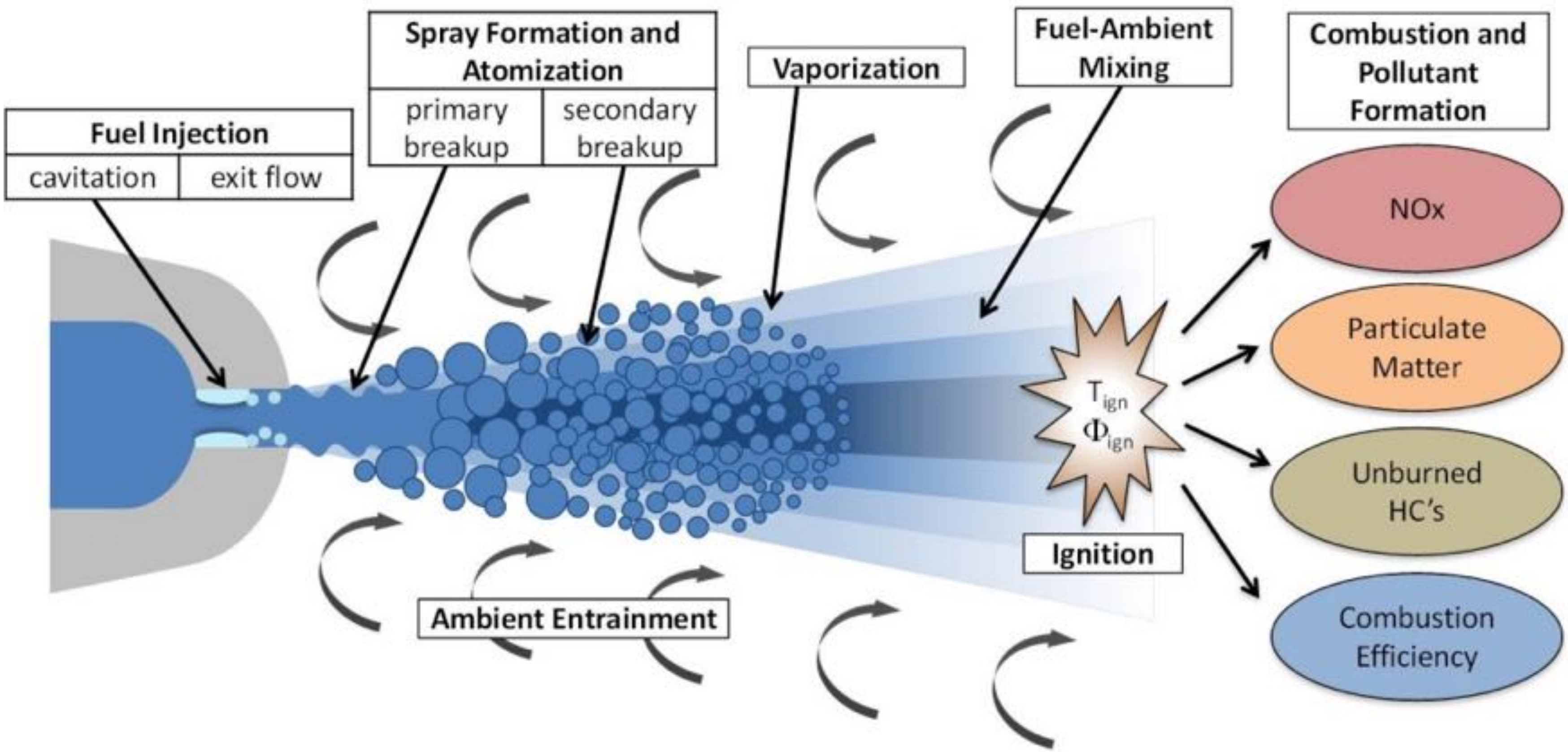


5.6.2. DIESEL ENGINE (COMBUSTION ENGINE)

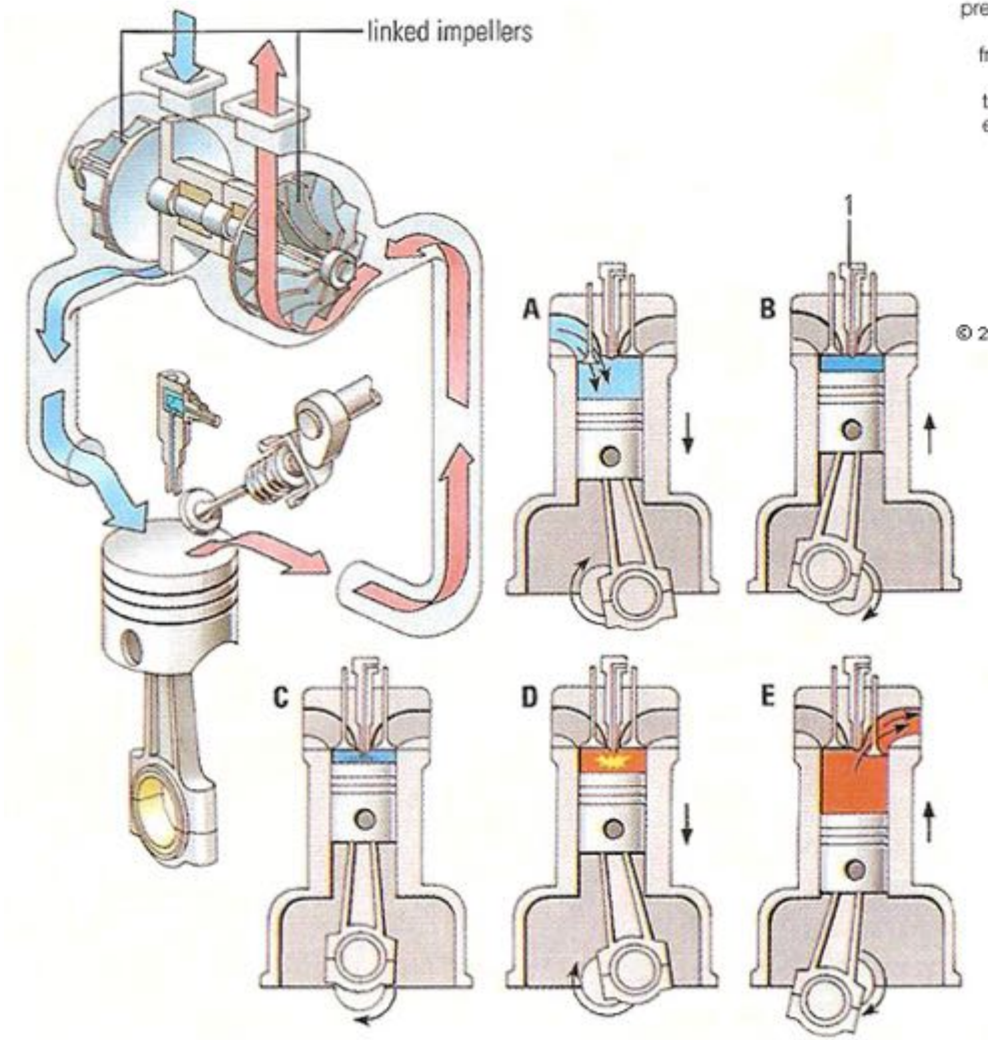


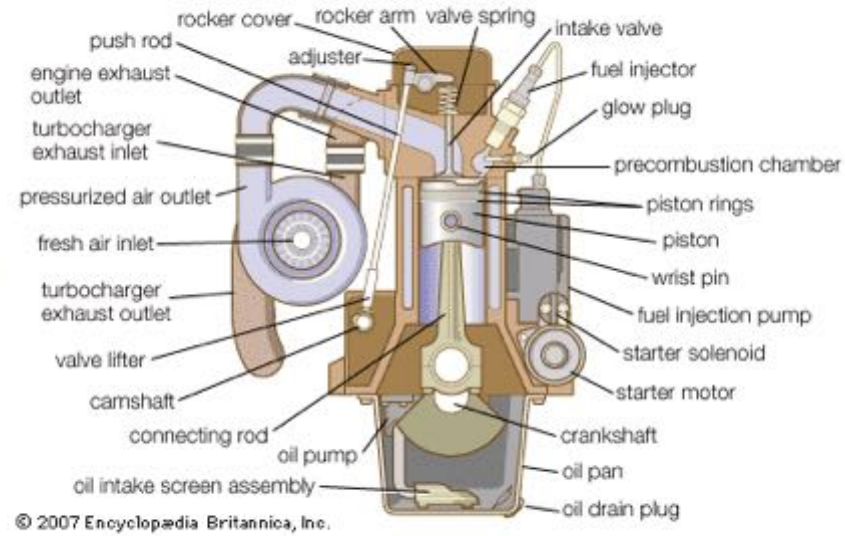


5.6.3. DIESEL DISTRIBUTION

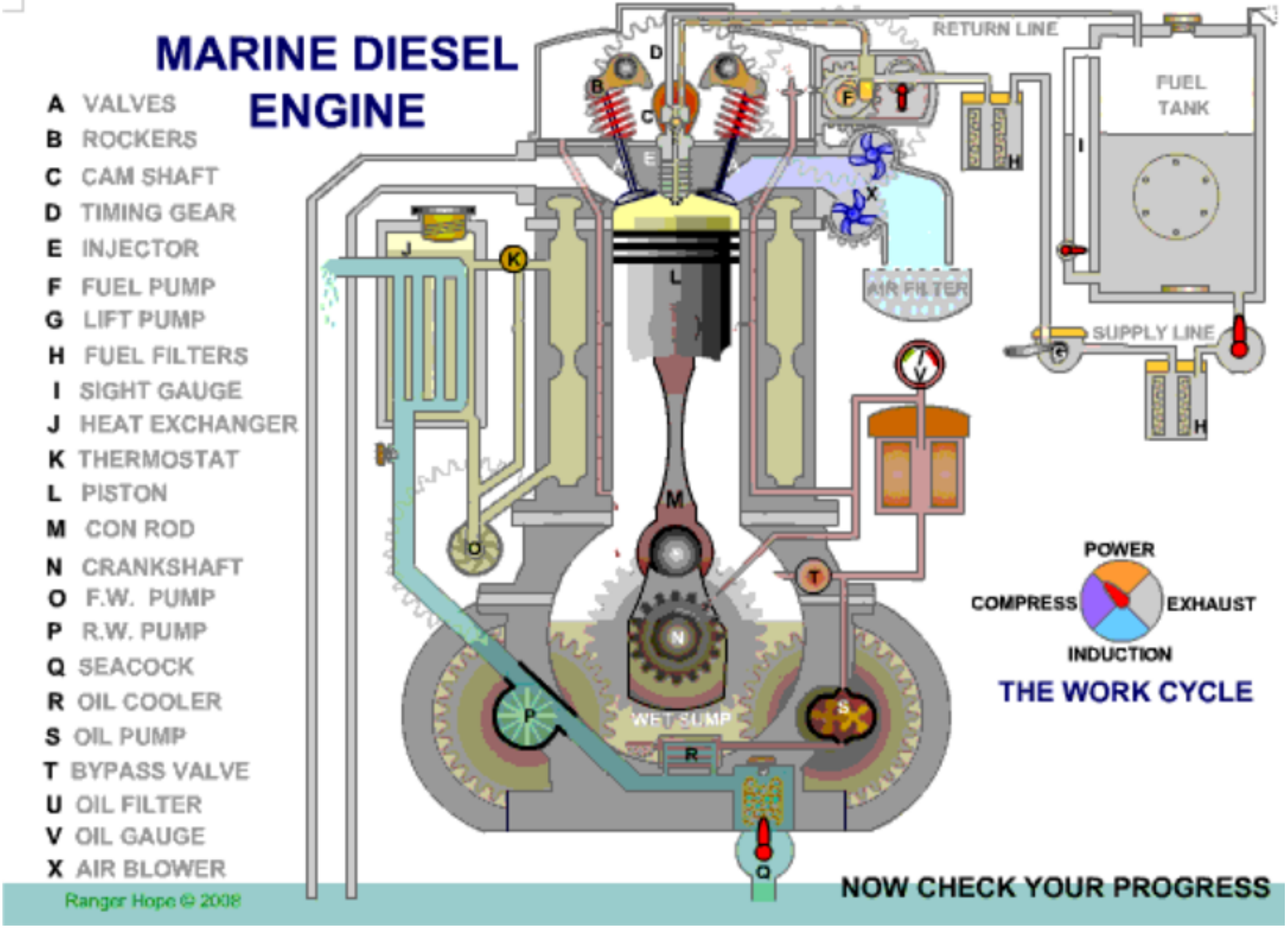


5.6.4. DIESEL ENGINE WITH TURBOLOAD



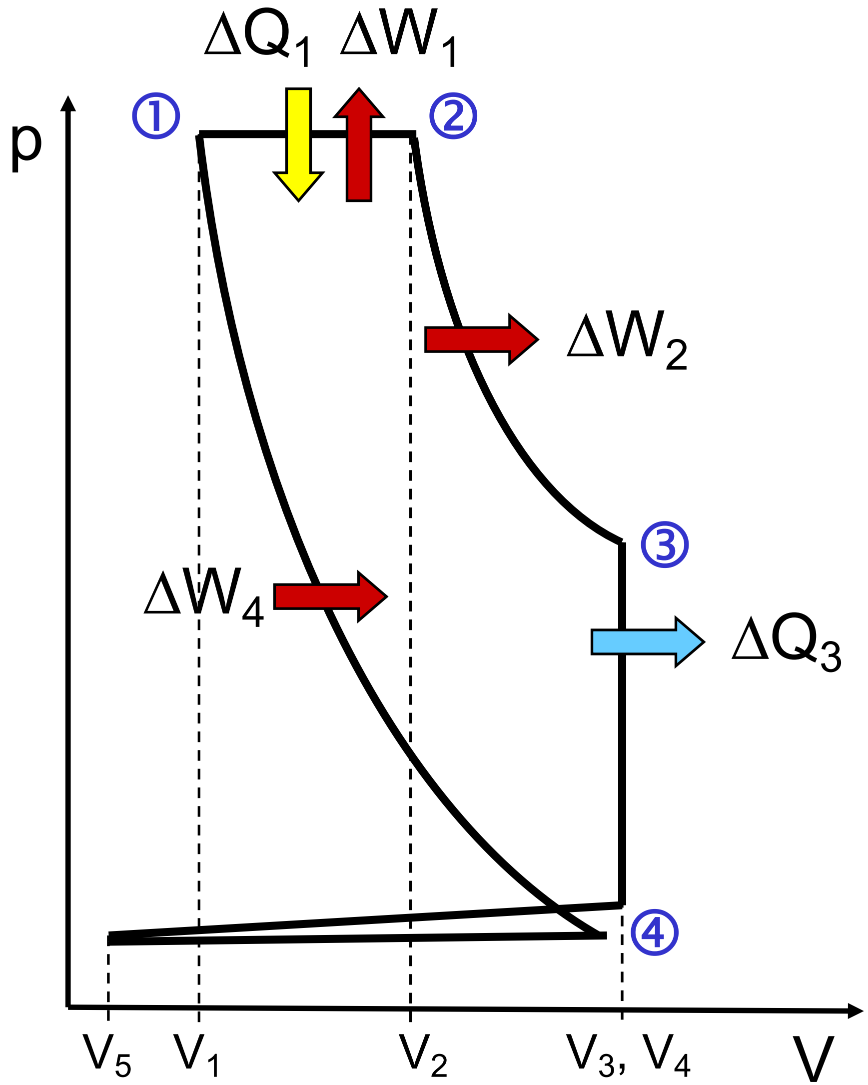


5.6.5. MARINE DIESEL ENGINE



Ref.: http://giphy.com/gifs/

5.6.6. pV-DIAGRAM OF DIESEL CYCLE



1 → 2 Injection isobar (p = const)

$\Delta W_1 = p_2 \cdot (V_2 - V_1)$ and $\Delta Q_1 = p_2 \cdot (V_2 - V_1) + n \cdot c_V \cdot (T_2 - T_1)$

2 → 3 adiabatic (ΔQ = 0)

$\Delta Q_2 = 0$ and $\Delta W_2 = n \cdot c_V \cdot (T_3 - T_2)$

3 → 4 isochor (V = const)

$\Delta W_3 = 0$ and $\Delta Q_3 = n \cdot c_V \cdot (T_4 - T_3)$

4 → 0 isobar (p = const)

$\Delta Q_5 = 0$ and $\Delta W_5 = p \cdot (V_5 - V_4)$

0 → 4 isobar (p = const)

$\Delta Q_6 = 0$ and $\Delta W_6 = p \cdot (V_4 - V_5)$

5.6.7. EFFICIENCY OF THE DIESEL CYCLE

4 → 1 adiabatic ($\Delta Q = 0$)

$\Delta Q_4 = 0$ and $\Delta W_4 = n \cdot c_V \cdot (T_1 - T_4)$

Total work ΔW and heat from the hot reservoir (T_h)

$\Delta W = \Delta W_1 + \Delta W_2 + \Delta W_4 = p_2 \cdot (V_2 - V_1) + n \cdot c_V \cdot (T_3 - T_2) + n \cdot c_V \cdot (T_1 - T_4)$

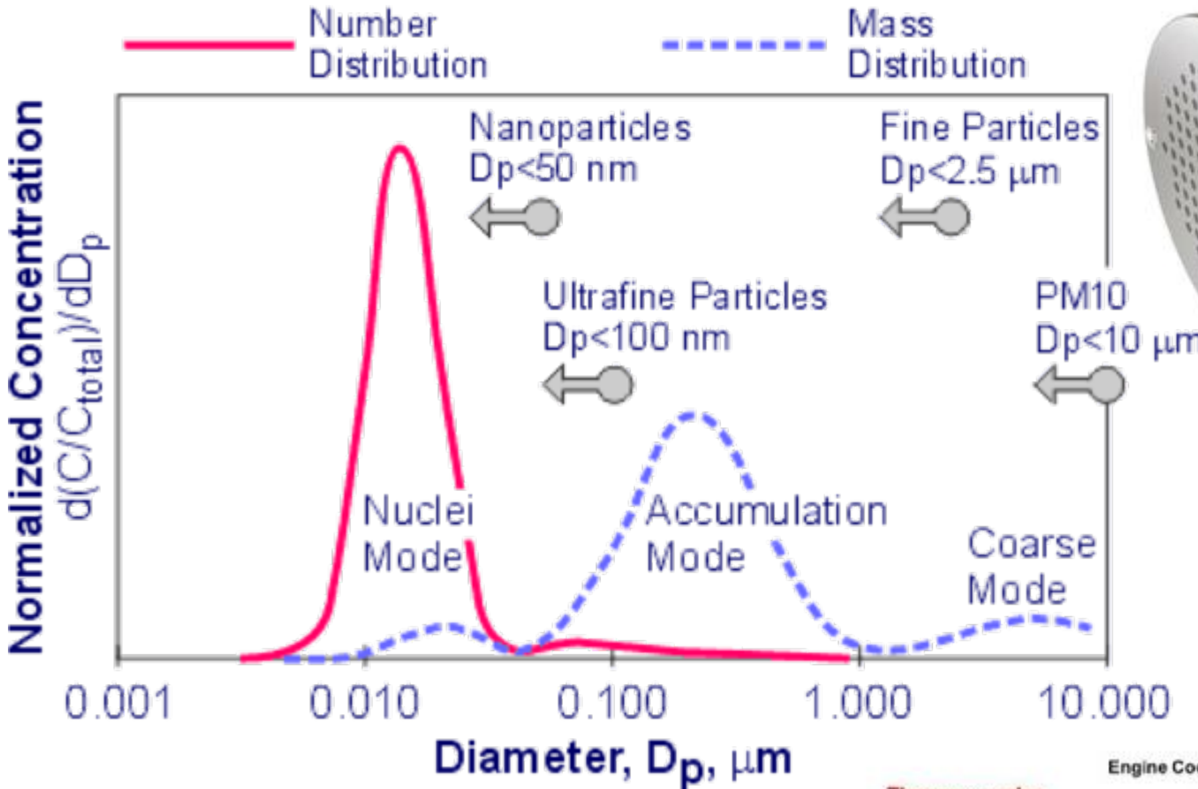
$\Delta Q = \Delta Q_1 = p_2 \cdot (V_2 - V_1) + n \cdot c_V \cdot (T_2 - T_1)$

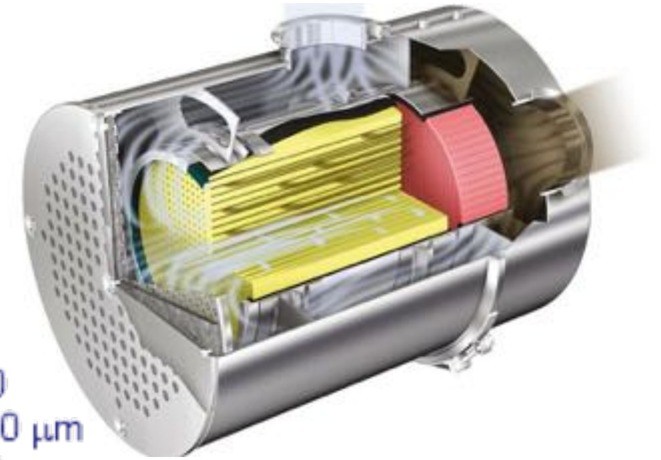
Efficiency:

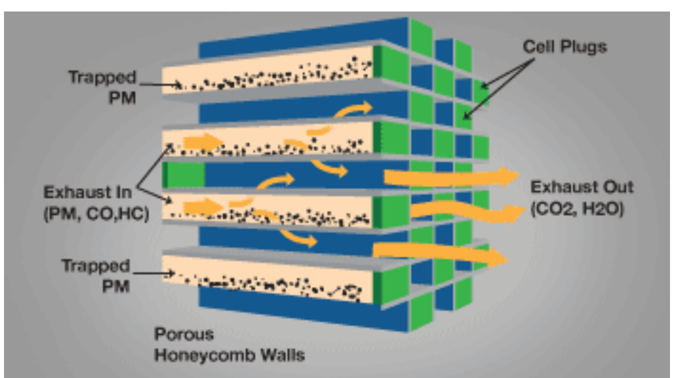
$$\eta = \frac{\Delta W}{\Delta Q} = \frac{\Delta W_1 + \Delta W_2 + \Delta W_4}{\Delta Q_1} = \frac{p_2 \cdot (V_2 - V_1) + n \cdot c_V \cdot (T_3 - T_2) + n \cdot c_V \cdot (T_1 - T_4)}{p_2 \cdot (V_2 - V_1) + n \cdot c_V \cdot (T_2 - T_1)}$$

$$\eta = \frac{\Delta W}{\Delta Q} = 1 - \frac{c_V}{c_p} \left(\frac{V_1}{V_4} \right)^{\frac{c_V}{R}} \frac{\left(\frac{V_2}{V_1} \right)^{\frac{c_V}{R}} - 1}{\frac{V_2}{V_1} - 1}$$

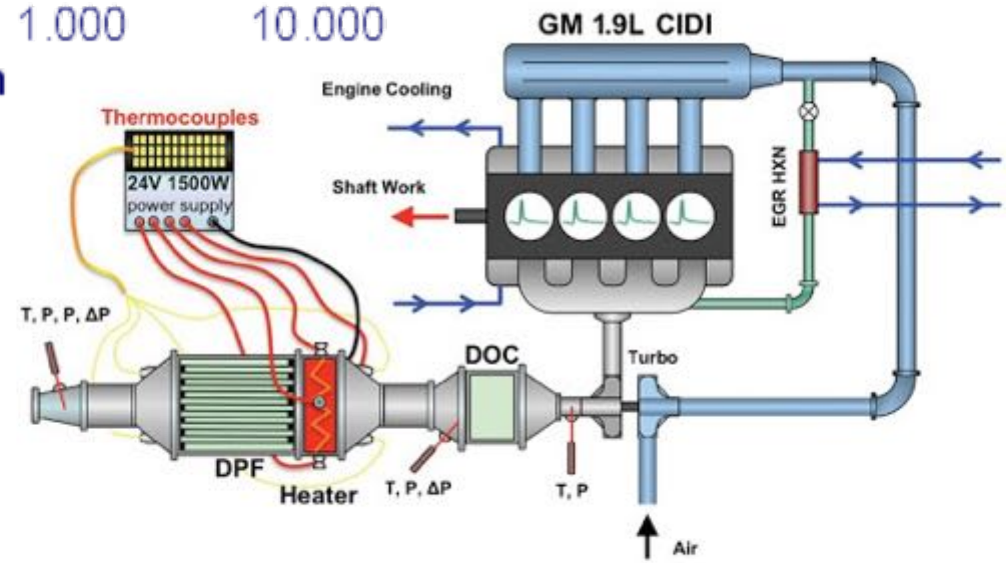
5.6.8. PARTICLE EMISSIONS AND FILTER







Structure of a typical Diesel Particulate Filter.



5.6.9. PARTICLES FROM DIESEL COMBUSTION

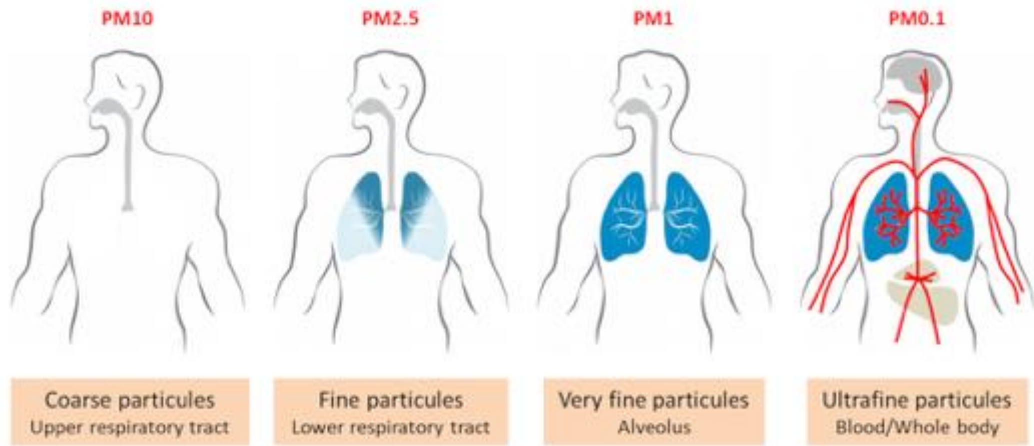
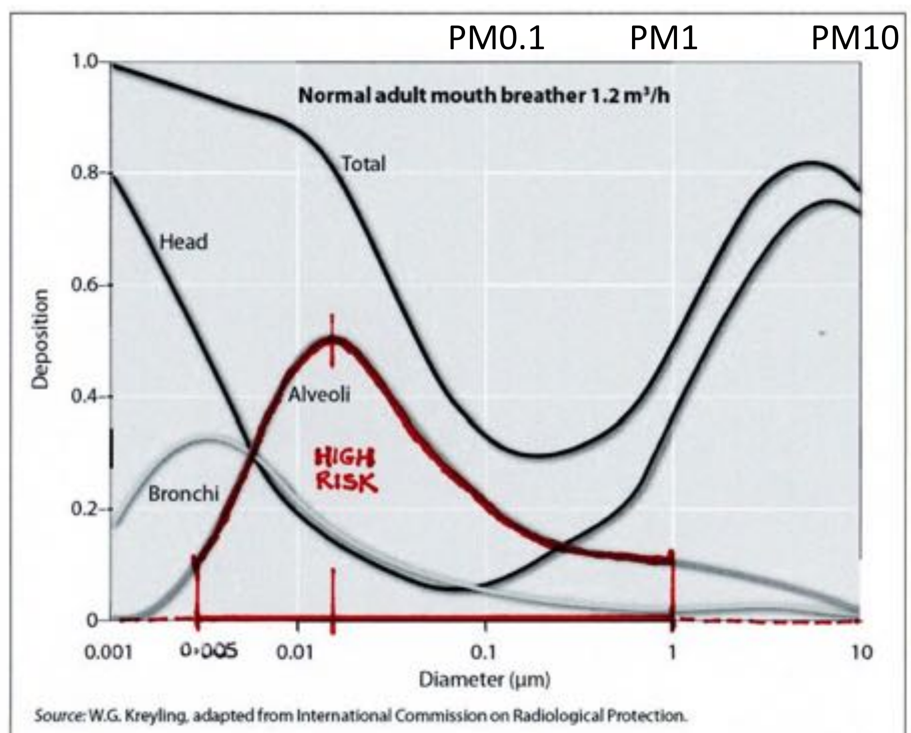


Fig. 3.
Deposition probability of inhaled particles in the respiratory tract according to particle size



5.7. PROPERTIES OF FUELS

T[°C] = (T[°F] – 32°F)*5/9

Properties of Fuels (a)

Property	Gasoline	No.2 Diesel Fuel	Methanol	Ethanol	MTBE	Propane	Compressed Natural Gas	Hydrogen	Biodiesel
Chemical Formula	C4 to C12	C8 to C25	CH3OH	C2H5OH	(CH3)3COCH3	C3H8	CH4 (83-99%), C2H6 (1-13%)	H2	C12-C22 FAME
Molecular Weight	100–105	~200	32.04	46.07	88.15	44.1	16.04	2.02	~292(q)
Composition, Weight %									
>Carbon	85–88(b)	87(g)	37.5	52.2	68.1	82	75	0	77(g)
>Hydrogen	12–15(b)	13(g)	12.6	13.1	13.7	18	25	100	12(g)
>Oxygen	0	0(g)	49.9	34.7	18.2	–	–	0	11(g)
Specific gravity, 60° F/60° F	0.72–0.78(b)	0.85(g)	0.796(h)	0.794(h)	0.744(k)	0.508(m)	0.424	0.07(o)	0.88(g)
Density, lb/gal @ 60° F	6.0–6.5(b)	7.079(g)	6.63(b)	6.61(b)	6.19(k)	4.22	1.07(n)	–	7.328(g)
Boiling temperature, °F	80–437(b)	356-644(g)	149(h)	172(h)	131(h)	-44(m)	-263.2 to -126.4(m)	-423(m)	599-662(g)
Reid vapor pressure (100° F), psi	8–15(c)	<0.2	4.6(i)	2.3(i)	7.8(l)	208	2400	–	<0.04(r)
Heating value (2)									
>Lower (Btu/gal) (d)	116,090	128,450	57,250	76,330	93,540	84,250	–	–	119,550
>Lower (Btu/lb) (d)	18,676	18,394	8,637	11,585	15,091	19,900	20,263	52,217	16,131
>Higher (Btu/gal) (d)	124,340	137,380	65,200	84,530	101,130	91,420	–	–	127,960
>Higher (Btu/lb) (d)	20,004	19,673	9,837	12,830	16,316	21,594	22,449	59,806	17,266
Octane no.(1)									
>Research octane no.	88–98(c)	–	–	–	–	112	–	130+	–
>Motor octane no.	80–88(c)	–	–	–	–	97	–	–	–
Cetane no.(1)	–	40-55(g)	–	0-54(f)	–	–	–	–	48-65(g)
Freezing point, °F	-40(e)	-40–30(4)	-143.5	-173.2	-164(h)	-305.8(m)	-296	-435(p)	26-66(g)(7)
Viscosity, mm²/s									
>@104 °F	–	1.3-4.1(g)	–	–	–	–	–	–	4.0-6.0(g)
>@68 °F	0.5-0.6(f)	2.8-5.0(f)	0.74(f)	1.50(f)	0.47(f)	–	–	–	–
>@-4 °F	0.8-1.0(f)	9.0-24.0(f)	1.345(f)	3.435(f)	0.77(f)	–	–	–	–
Flash point, closed cup, °F	-45(b)	140-176(g)	52(i)	55(i)	-14(c)	-156(m)	-300	–	212-338(g)
Autoignition temperature, °F	495(b)	~600	867(b)	793(b)	815	842(m)	900-1170(m)	932(m)	–
Water solubility, @ 70° F									–
>Fuel in water, volume %	Negligible	Negligible	100(h)	100(h)	4.8(f)	–	–	–	–
>Water in fuel, volume %	Negligible	Negligible	100(h)	100(h)	1.5(f)	–	–	–	–
Flammability limits, volume%									
>Lower	1.4(b)	1.0	7.3(i)	4.3(i)	1.6(c,e)	2.2	5.3	4.1(o)	–
>Higher	7.6(b)	6.0	36.0(i)	19.0(i)	8.4(c,e)	9.5	15	74(o)	–
Latent heat of vaporization									
>Btu/gal @ 60° F	~900(b)	~710	3,340(b)	2,378(b)	863(5)	775	–	–	–
>Btu/lb @ 60° F	~150	~100	506(b)	396(b)	138(5)	193.1	219	192.1(p)	–
Specific heat, Btu/lb °F	0.48(e)	0.43	0.60(j)	0.57(j)	0.50(j)	–	–	–	
Stoichiometric air/fuel, weight	14.7	14.7	6.45	9.00	11.7	15.7	17.2	34.3(o)	13.8(g)
Volume % fuel in vaporized stoichiometric mixture	2.0 (b)	–	12.3(b)	6.5(b)	2.7(l)	–	–	–	–

http://algaeenergy.weebly.com

5.7.1. REFERENCES TO PROPERTIES OF FUELS

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3. “Alcohols: A Technical Assessment of Their Application as Motor Fuels,” API Publication No. 4261, July 1976.
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18. ARCO Chemical Company, 1987. Biodieselion 11-20-06
19. National Biodiesel Board Notes

5.7.2. EXHAUST GAS COMPOSITION

$$C_8H_{18} + 12.5\ O_2 + 62.5N_2 \rightleftarrows 8CO_2 + 9H_2O + 62.5N_2$$

		Conventional gasoline engine	Diesel engine	Lean engine
O_2	%vol.	0.2 – 2	5 – 15	4 – 18
CO_2	%vol.	10 – 13.5	2 – 12	2 – 12
H_2O	%vol.	10 – 12	2 – 10	2 – 12
N_2	%vol.	70 – 75	70 – 75	70 – 75
CO	%vol.	0.1 – 6	0.01 – 0.1	0.04 – 0.08
HC	%vol. C_1	0.5 – 6	0.005 – 0.05	0.002 – 0.015
NO_x	%vol.	0.04 – 0.4	0.003 – 0.06	0.01 – 0.05
SO_x	Related to the content of S in the fuel			

5.7.3. EXHAUST GAS COMPOSITION VS. OXYGEN

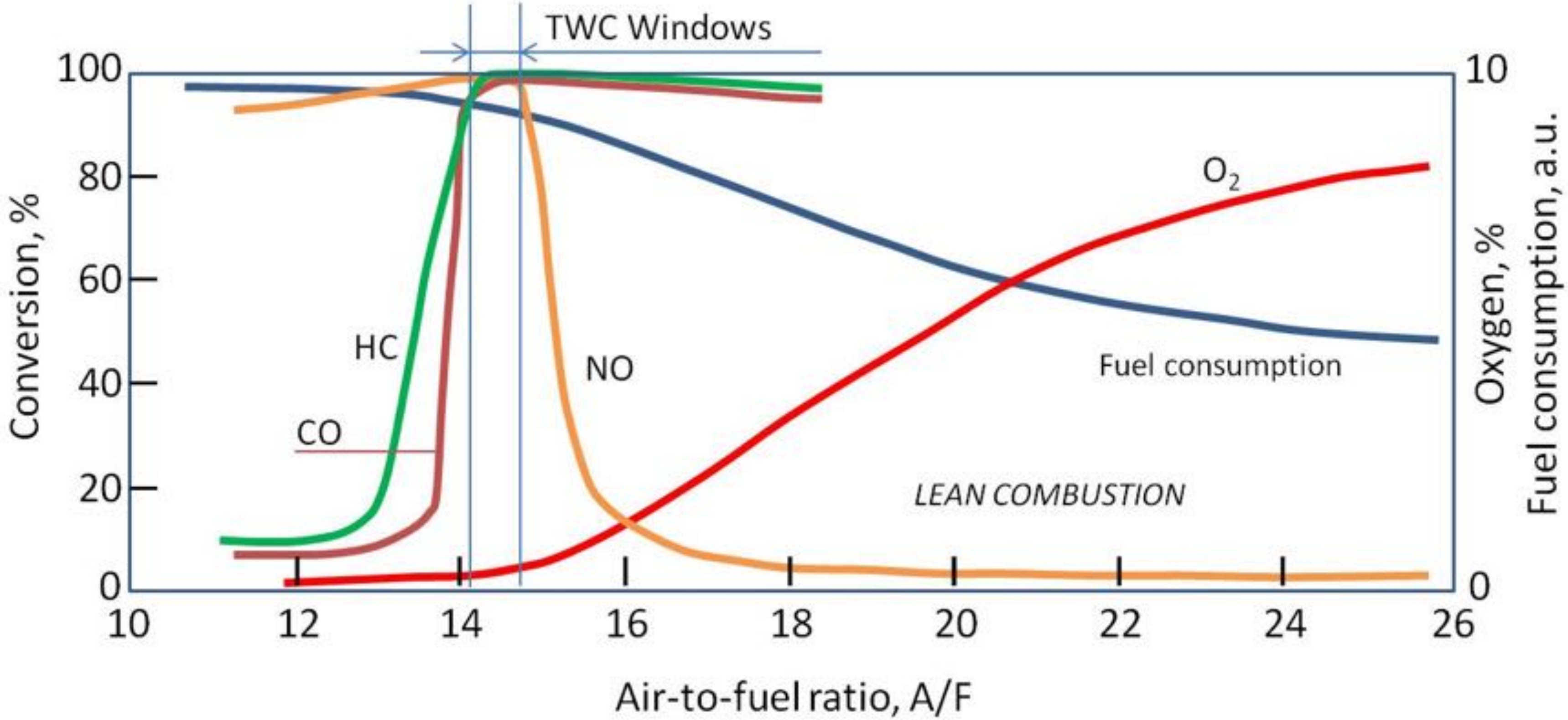
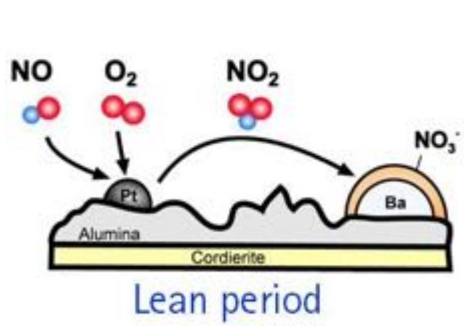


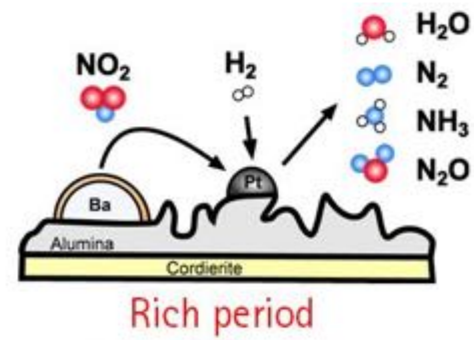
Fig. 1 shows the conversion curves for each pollutant as a function of the air/fuel ratio, for a three-way-catalyst (TWC). Around the stoichiometric point (air/fuel A/F=14.63), all the three pollutants (HC, CO and NO) are highly converted (>95 %), i.e. they are almost totally removed. However, when the environment is abundant in oxygen as in diesel engines (A/F>20), although this environment enhances the oxidation of HC and CO, the reduction of NO becomes practically inefficient, then this pollutant cannot be appropriately removed with TWC technology.

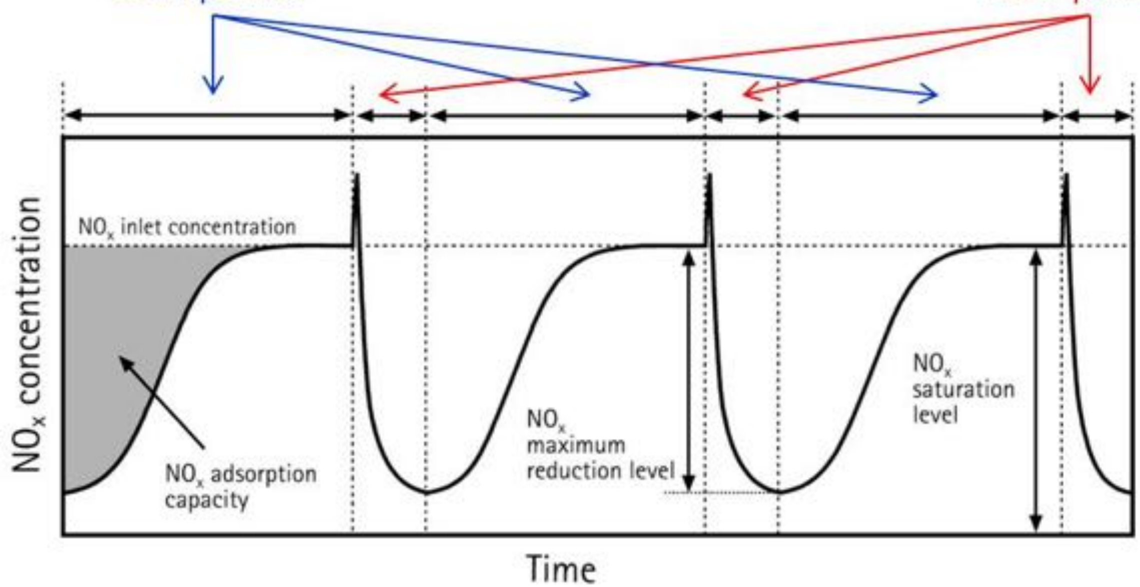
Ref.: R. M Heck, R. J Farrauto, S Gulati, Catalytic Air Pollution Control: Commercial Technology. New Yersey: John Wiley & Sons; 2009
F Basile, G Fomasari, A Grimandi, M Livi, A Vaccari, Effect of Mg, Ca and Ba on the Pt-catalyst for NOx storage reduction. Applied Catalysis B: Environmental 20066958

5.7.4. EXHAUST GAS: NO_x Storage and reduction, NSR



selective catalytic reduction (SCR) with ammonia generated by hydrolysis of urea on lorries.





The typical NO_x storage and reduction behaviour can be observed in the bottom graph of Fig. 2. At the beginning of the lean period nearly all the NO_x (NO+NO_2) entering the trap is adsorbed, afterwards the NO_x outlet concentration progressively increases due to the successive saturation of the available trapping sites. When saturation is completed, NO_x outlet concentration equals the NO_x inlet concentration. During the subsequent rich period, when H_2 is injected, the adsorbed NO_x species on the catalyst surface react with hydrogen to form N_2O, NH_3 or N_2, resulting in the regeneration of the trap which is again ready for the following lean period.

EXERCISES

1) What gas should be used and how should the Stirling engine be constructed in order to optimize the efficiency ?

2) What reduces the efficiency of a real Otto engine as compared to the calculated efficiency?

3) The efficiency of the Diesel engine depends on the ratio V_1/V_4 and the ratio V_2/V_1. Describe how the efficiency is maximized.

4) Calculate the temperature increase in the adiabatic compression of a diesel engine (1:22) and compare it with the autoignition temperature of 600 F = 315° C.

5) Calculate the maximum adiabatic temperature of the combustion of diesel ($C_{12}H_{26}$).3