Aalto University
School of Engineering

EEN-E2002 Combustion Technology

Internal Combustion Definitions and Characteristics

January 2019, Martti Larmi

Teaching personnel

Martti Larmi, Professor
Department of Mechanical Engineering
martti.larmi@aalto.fi, room: 126f/K3

Tuomas Paloposki, Senior lecturer
Department of Mechanical Engineering
tuomas.paloposki@aalto.fi, room: 205/K4

Ossi Kaario, Senior Research Fellow
Department of Mechanical Engineering
ossi.kaario@aalto.fi, room: 126/ K3

Mika Järvinen, Associate professor
Department of Mechanical Engineering
mika.jarvinen@aalto.fi, room 306/K4

Cheng Qiang, Post doc
Department of Mechanical Engineering
qiang.cheng@aalto.fi, room 150/K3

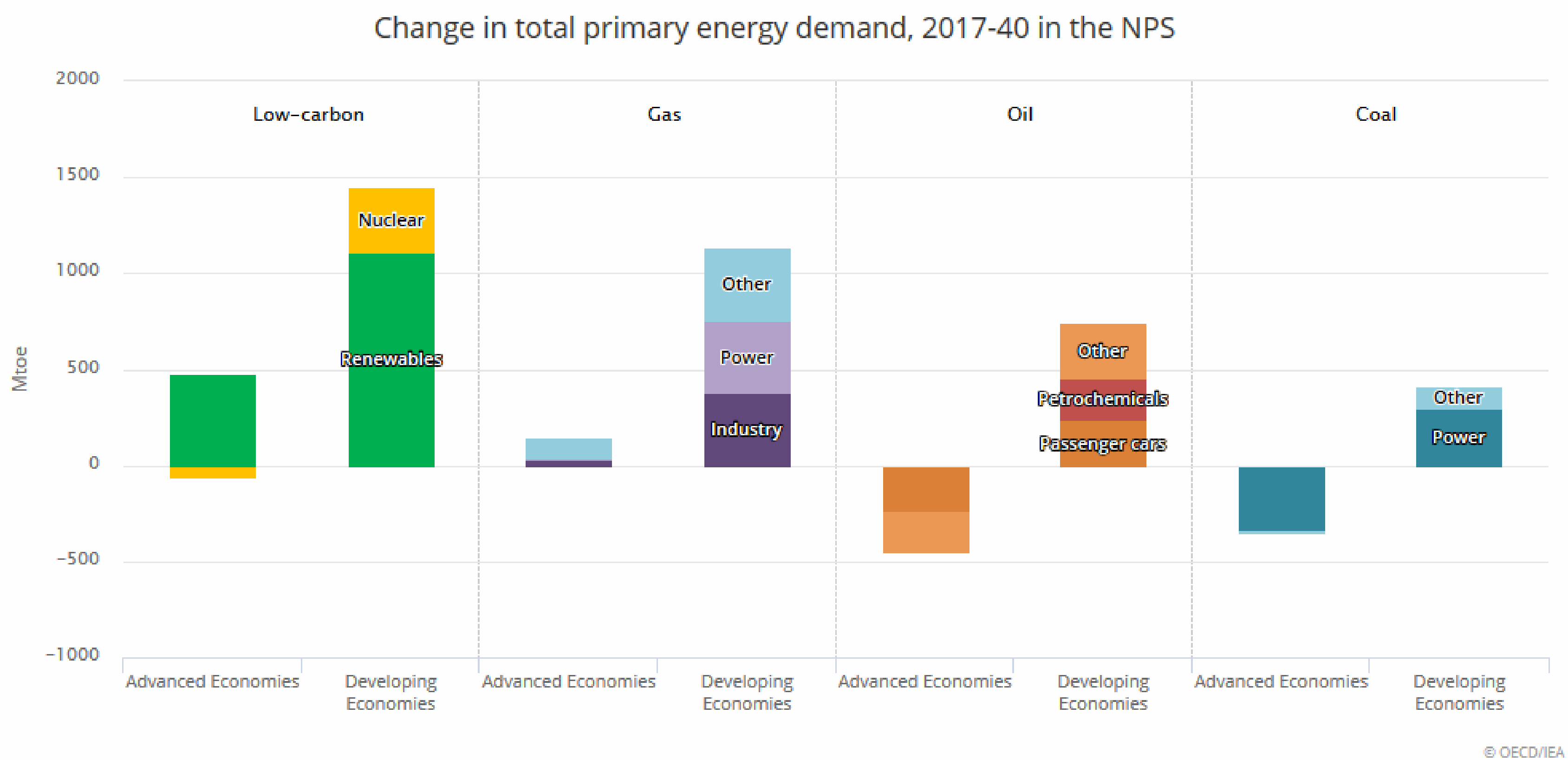
Otto Blomstedt, Laboratory manager
Department of Mechanical Engineering
otto.blomstedt@aalto.fi, room: 151/K3

Learning Outcomes / Contents

Learning Outcomes:The student should be able to understand the basics of combustion and gasification processes and to be able to recognize how they influence the design and operation of practical equipment such as boilers and engines.

Contents:Today's combustion technologies and combustion regimes in power plants and engines; design and operational considerations. Application of combustion to furnaces and boilers, spark ignition engines, diesel engines, gas engines and gas turbines. Fundamentals of gasification.

IEA World Energy Outlook 2018



Recommended further courses

AAE-E3030 - Numerical Modeling of Multiphase Flows L, periods IV-V

EEN-E3002 - Power Process Simulation, periods IV-V

Passing the course / Prerequisites

Assessment Methods and Criteria:
Six learning exercises (6 LEs) do make 100% of the grade. Alternatively 50% LEs and examination 50%. Each learning exercise is graded and at least 50% of the available points should be taken in each learning exercise. Beside the LEs, there are 2 lab exercises graded pass/ no pass.

Prerequisites: ENY-C2001 Thermodynamics and Heat Transfer or equivalent knowledge and CHEM-A1250 Principles of Chemistry or equivalent knowledge. Recommended pre-studies: EEN-E1030 Thermodynamics in Energy Technology

Week	Date		Time	Event	Location	Topic	Teacher	Exercises
EEN-E2002 Combustion Technology								
2018-2019		**Periods III-IV**			**Ver 2**	**January 8, 2019**		
						Changes still possible		
Week	**Date**		**Time**	**Event**	**Locatioı**	**Topic**	**Teacher**	**Exercises**
		Sat						
		Sun		Combustion Basics				
2	7.1.2019	Mon						
	8.1.2019	Tue						
	9.1.2019	Wed	10-12	Lecture	K3 118	Engine technology basics	Martti	
	10.1.2019	Thu	10-12	Lecture	K3 118	Combustion basics	Ossi	
	11.1.2019	Fri	8-10	Learning exercise	K3 118	Learning exercise advice session	Jonny	
	12.1.2019	Sat						
	13.1.2019	Sun		Combustion Basics + Disassembly exercise				
3	14.1.2019	Mon					Disassembly exercise	
	15.1.2019	Tue						Separate
	16.1.2019	Wed	10-12	Lecture	K3 118	Engine combustion I	Ossi	schedule
	17.1.2019	Thu						
	18.1.2019	Fri	8-10	Learning exercise	K3 118	Learning exercise advice session	Jonny	
	19.1.2019	Sat						
	20.1.2019	Sun		Engine Combustion Technology				
4	21.1.2019	Mon					Laboratory exercise	
	22.1.2019	Tue						Separate
	23.1.2019	Wed	10-12	Lecture	K3 118	Engine technology basics	Martti	schedule
	24.1.2019	Thu	10-12	Lecture	K3 118	Engine combustion II	Martti	
	25.1.2019	Fri	8-10	Learning exercise	K3 118	Learning exercise advice session	Jonny	
	26.1.2019	Sat						
	27.1.2019	Sun		Engine Combustion Technology				
5	28.1.2019	Mon					Laboratory exercise	
	29.1.2019	Tue						Separate
	30.1.2019	Wed	10-12	Lecture	K3 118	Fuel admission & air management	Martti	schedule
	31.1.2019	Thu	8-18	Excursion to Wärtsilä Turku training center			Otto	
	1.2.2019	Fri						

Textbooks on Internal Combustion

Internal combustion engine handbook : basics, components, systems, and perspectives

edited by Richard van Basshuysen and Fred Schäfer
SAE International 2004
ISBN: 0-7680-1139-6

Additional material, John B. Heywood: Internal Combustion Engine Fundamentals, McGraw-Hill 1988, ISBN:0-07-100499-8

Important Chapters

Ch 2 Definition and Classification of Reciprocating Piston Engines

Ch 3 Characteristics

Ch 10 Charge Cycle

Ch 11 Supercharging of Internal Combustion Engine

Ch 12 Mixture Formation and Related Systems

Ch 13 Ignition

Ch 14 Combustion

Ch 15 Combustion Systems

Basic definitions

Combustion engines convert the chemical energy of fuel to mechanical energy as a result of combustion

Combustion engines can be divided into internal and external combustion engines

External combustion engines

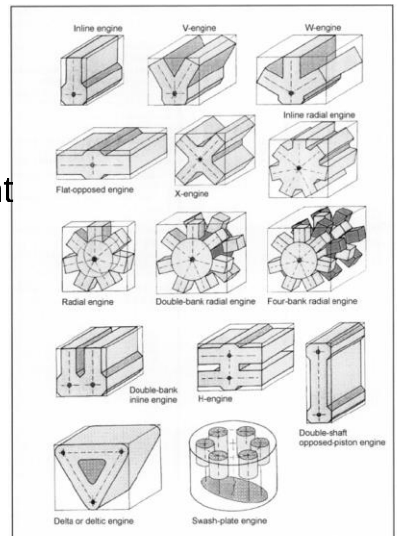
- Stirling engines
- Steam engines

Internal combustion engines

- Reciprocating piston engines
- Rotary piston engines
- Gas turbines

Classification

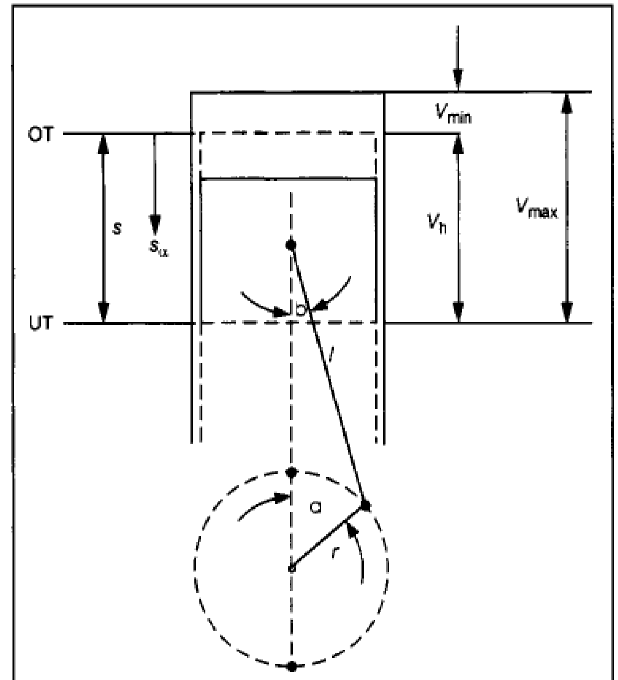
1. Combustion process
2. Fuel
3. Working cycles
4. Mixture generation
5. Gas exchange control
6. Supercharging
7. Configuration
8. Ignition
9. Cooling
10. Load adjustment
11. Application
12. Speed



<table>
<tr><td colspan="2" rowspan="5">Type of working process</td><td colspan="4">Open process</td><td colspan="2">Closed process</td></tr>
<tr><td colspan="4">Internal combustion</td><td colspan="2">External combustion</td></tr>
<tr><td colspan="4" rowspan="3">Combustion gas = working fluid</td><td colspan="2">Combustion gas ≠ working fluid</td></tr>
<tr><td colspan="2">Change of phase of the working fluid</td></tr>
<tr><td>No</td><td>Yes</td></tr>
<tr><td colspan="2">Type of combustion</td><td colspan="3">Cyclical combustion</td><td colspan="3">Continuous combustion</td></tr>
<tr><td colspan="2">Type of ignition</td><td>Auto-ignition</td><td colspan="5">Supplied ignition</td></tr>
<tr><td rowspan="2">Machine type</td><td>Engine</td><td>Diesel</td><td>Hybrid</td><td>Gasoline</td><td>Rohs[4]</td><td>Stirling[5]</td><td>Steam[6]</td></tr>
<tr><td>Turbine</td><td>—</td><td>—</td><td>—</td><td>Gas</td><td>Superheated steam</td><td>Steam</td></tr>
<tr><td colspan="2" rowspan="2">Mixture type</td><td colspan="2">Heterogeneous</td><td>Homogeneous (heterogeneous)</td><td colspan="3" rowspan="2">Heterogeneous
(in the continuous flame)</td></tr>
<tr><td colspan="3">(in the combustion chamber)</td></tr>
</table>

Basic structure of reciprocating piston engine

Cylinder
Piston
Piston pin (wrist pin, gudgeon pin)
Piston rings
Connecting rod (conrod)
Crankshaft
Valves (intake & exhaust)
Bottom dead center BDC, UT
top dead center TDC, OT



Basic dimensions

Cylinder bore [m]	D
Piston stroke [m]	S
Cylinder number	z
Stroke-bore ratio	S/D
Crank radius [m]	r
Connecting rod length [m]	l
Connecting rod ratio	$\lambda s = r/l$
Displacement vol. [m3]	$Vh = \pi D^2 / 4 * S$ (one cylinder)
Compression volume [m3]	Vc
Compression ratio	ε (or e) = (Vh +Vc)/ Vc
Crank angle [deg or rad]	φ or α

Engine size always refers to the total displacement volume of the engine (all cylinders included).

Operational characteristics

Rotational speed [r/min (rpm) or rps]	n
Mean piston speed [m/s]	$c_p = 2Sn$ (c_m)
Power [kW]	P_e
Torque [Nm]	M
Brake Mean Effective [bar or Pa]	$p_{e,}$ BMEP
Volumetric efficiency	λ_l (η_{vol})
Excess-air factor	λ (λ_{tot} ,λ_c)
Specific fuel consumption [g/kWh]	b_e
Total efficiency	η_e
Fuel net heating value [kJ/kg] (Lower calorific value)	$H_{u,}$ H_n

Excess-air factor, relative air to fuel ratio, equivalence ratio

Excess-air factor λ is the ratio of the air mass in the cylinder to the stoichiometric air mass

$$\lambda = \frac{m_L}{m_{L,St}} = \frac{m_L}{m_K L_{St}} = \frac{L}{L_{St}}$$

m_K is the fuel mass delivered in the cylinder

L_{St} is the requirement of air for stoichiometric combustion [kg/kg], so that the chemical reactions are totally finished. Typically for fuels used in internal combustion engines, such as gasoline and diesel oil, L_{St} is about 14,5 kg/kg

L is the mass of air per the mass of fuel.

The equivalence ratio Φ is the inverse of the λ. Equivalence ratio is widely used in US literature.

Rich combustion: λ < 1

Lean combustion: λ > 1

Total lambda λtot is based on total air flow trough the engines

Combustion lambda λc is based on the air trapped in the cylinder

$$\Phi = \frac{1}{\lambda}$$

Mean piston speed, compression ratio

Engine type	Max. speed [rpm] approx.	Mean piston speed [m/s] approx.
Racing engine (Formula 1)	18 000	25
Small engines (two-stroke)	20 000	19
Motorcycle engines	13 500	19
Car SI engine	7500	20
Car diesel engines	5000	15
Truck diesel engines	4200	14
Larger high-speed diesel engines	2200	13
Medium high-speed engines (diesel)	1200	10
Crosshead engines (two-stroke diesel)	200	8

Engine type	ε		Limited by
	From	To	
Two-stroke SI engine	7.5	10	Autoignition
SI engine (two-valve)	8	10	Knock, autoignition
SI engine (four-valve)	9	11	Knock, autoignition
Direct injection SI engine	11	14	Knock, autoignition
Diesel (indirect injection)	18	24	Loss of efficiency at full load, component load
Diesel (direct injection)	17	21	Loss of efficiency at full load, component load

Power, Torque, Mean Effective Pressure

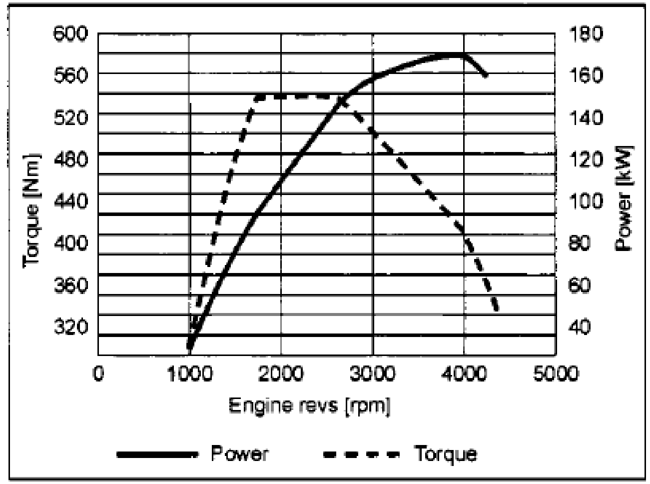
The brake power at any working point of an engine is calculated from the torque and engine rotational speed

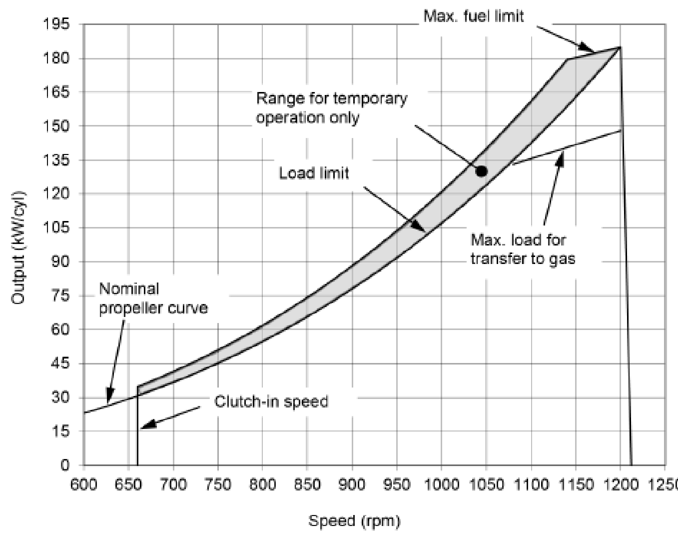
$$P_e = M_d \omega = M_d 2\pi n$$

Conclusion: increase in the power can be achieved either by increasing the torque or increasing the engine rotational speed

Brake mean effective mean pressure is a calculated valu It corresponds to a pressure level at which the gases have to work against the piston in order to get the actu work done by the engine or cylinder

$$W = p_e \frac{\pi d_k^{\,2}}{4} s$$





Brake mean effective pressure

Brake mean effective pressure describes engine load and the torque that you are able to get out of a certain displacement volume. It is not the average pressure in cylinder!

$$P_e = p_e \frac{\pi {d_k}^2}{4} Sni$$

Brake power of an engine is the effective mean pressure multiplied by the displacement volume and rotational speed.

i is the number of working cycles per revolution (0,5 for 4-stroke and 1 for 2-stroke engines)

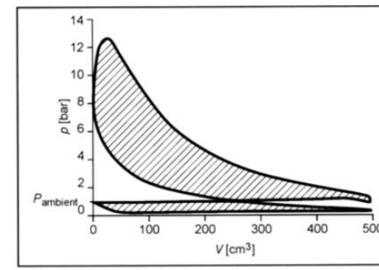
Actual brake power of an engine is also the torque multiplied by the angular velocity. So torque is proportional to the effective mean pressure and the displacement volume

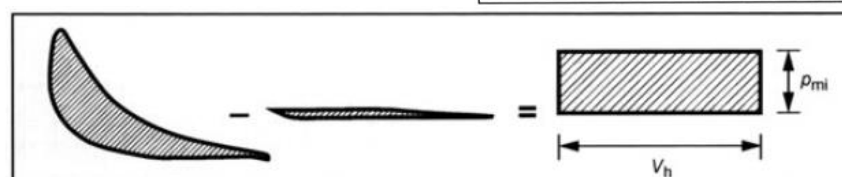
Brake mean effective pressure

Engine type	Effective mean pressure [bar]
	up to
Motorcycle engines	12
Racing engines (Formula 1)	16
Car SI engines (without turbocharger)	13
Car SI engines (with turbocharger)	17
Truck diesel engines (with turbocharger)	22
Car diesel engines (with turbocharger)	20
Larger high-speed diesel engines	30
Medium-speed diesel engines	25
Crosshead engines (two-stroke diesel)	15

$$P_e = p_e \frac{\pi d_k^{\,2}}{4} S n i = M_d \omega = M_d 2\pi n$$

$$M_d = p_e \frac{\pi d_k^{\,2}}{4} S \frac{1}{2\pi} i$$





pV-diagram

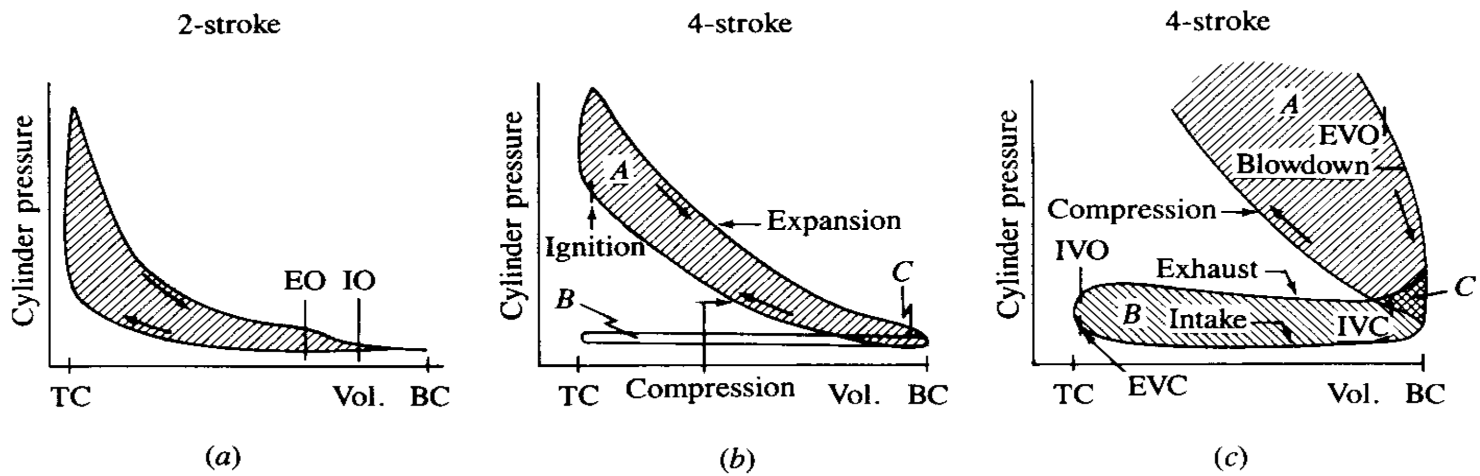
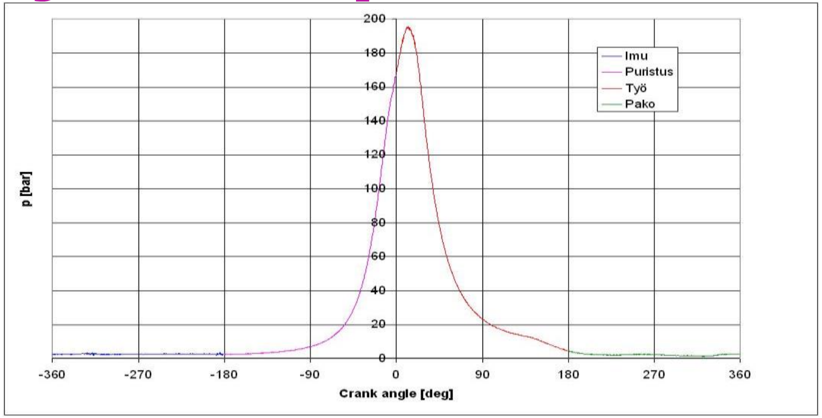
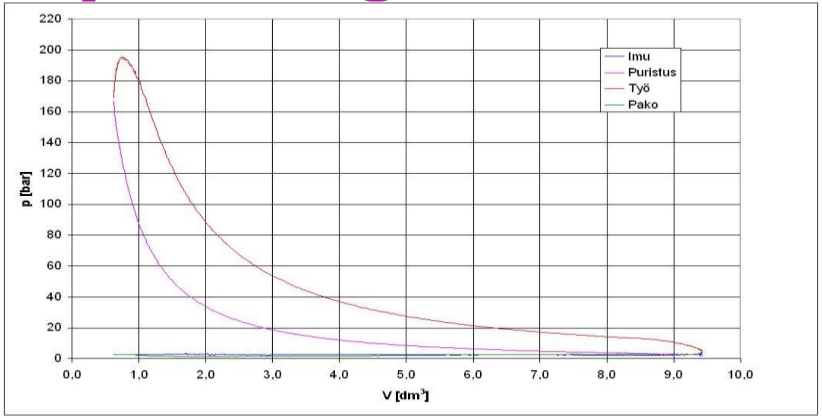


FIGURE 2-4
Examples of *p-V* diagrams for (*a*) a two-stroke cycle engine, (*b*) a four-stroke cycle engine; (*c*) a four-stroke cycle spark-ignition engine exhaust and intake strokes (pumping loop) at part load.

Cylinder pressure vs. pV-diagram





Wärtsilä 6L20 cylinder pressure and pV-diagram

The real pV-diagram differs from the theoretical diagrams

1. Combustion
2. Heat transfer
3. Exhaust blowdown
4. Gas exchange

IMEP = Indicated mean effective pressure = based on the work done by the gases

FMEP = friction mean effective pressure

BMEP = IMEP-FMEP

IMEP(720) = IMEP gross = Indicated mean effective pressure based on gas work over 720 deg CA, normally IMEP= IMEP(720)

IMEP(360) = IMEP net = Indicated mean effective pressure based on gas work over 360 deg CA

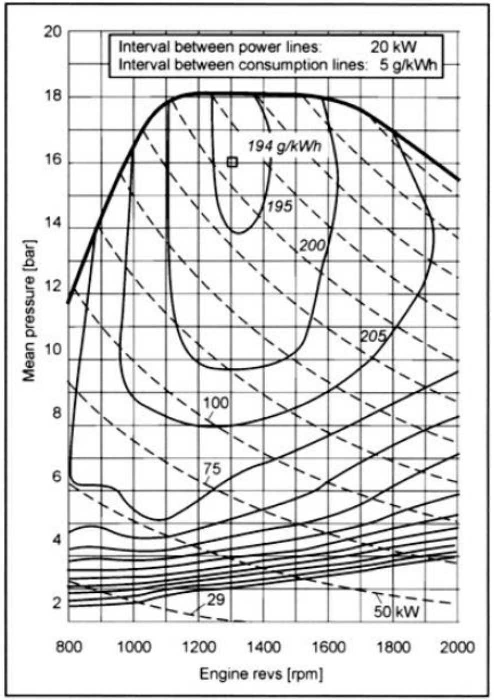
PMEP = pumping mean effective pressure = based on the work done by the gases during gas exgange

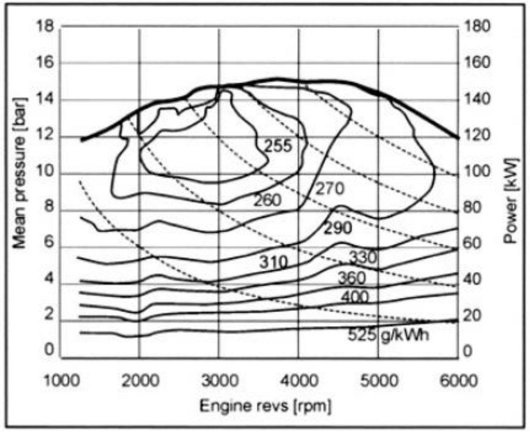
IMEP(720) = IMEP(360) + PMEP

More definitions: Heywood Chapter 13.2

Specific fuel consumption

Engine type	Specific fuel consumption [g/kWh] up to	Efficiency [%] up to
Small engines (two-stroke)	350	25
Motorcycle engines	270	32
Car SI engines	250	35
Indirect injection car diesel engines	240	35
Turbocharged DI car diesel engines	200	42
Turbocharged truck diesel engines	190	45
Crosshead engines (two-stroke diesel)	156	54





Specific power, power to weight

Engine type	Specific power output [kW/l] up to	Power-to-weight ratio [kg/kW] up to	At engine speed [rpm]
Racing engine (Formula 1)	200	0.4	($n \approx 18\,000$ rpm)
Car SI engine	70	2.0	($n \approx 6500$ rpm)
Turbocharged car SI engine	100	3.0	($n \approx 6000$ rpm)
Car diesel engine (naturally aspirated)	45	5.0	($n \approx 4500$ rpm)
Turbocharged car diesel engine	64	4.0	($n \approx 4500$ rpm)
Commercial vehicle diesel engine	30	5.5	($n \approx 3000$ rpm)
High-speed diesel engine	15.0	11.0	($n \approx 4500$ rpm)
Medium-speed diesel engine	7.5	19.0	($n \approx 500$ rpm)
Slow large diesel engine (two-stroke)	3.0	55.0	($n \approx 100$ rpm)

Volumetric efficiency

Volumetric efficiency λl (or η vol) is a measure for the charge cycle and it tells how much fresh charge has been trapped in the cylinder during charge cycle

$$\lambda_l = \frac{m_{Zges}}{\rho_{th} V_H}$$

mZges is the mass of charge air delivered to the cylinder and

VH is the total displacement volume of the engine. ρth is the density of outside air. Volumetric efficiency is a very important value for naturally aspirated SI engines. The better the volumetric efficiency, the greater the maximum torque.

Efficiency and fuel consumption

Total efficiency of an engine is the ratio of the brake power and the energy content of fuel flow

- P_e is brake power
- $\dot{m}_K$ is fuel mass flow
- H_u is fuel net heating value

$$\eta_e = \frac{P_e}{\dot{m}_K H_u}$$

Specific fuel consumption is the ratio of fuel mass flow and brake power

$$b_e = \frac{\dot{m}_K}{P_e}$$

Hence we obtain a relation between specific fuel consumption and total efficiency

$$\eta_e = \frac{1}{b_e H_u}$$

Mechanical efficiency

Mechanical efficiency is the ratio of the brake power flow to power of gases working against piston

$$\eta_{mech} = \frac{P_e}{P_i} = \frac{BMEP}{IMEP}$$

Mechanical efficiency is also the ratio of brake mean effective and indicated mean effective pressure