Internal Combustion Engines – MAK 493E

Gas Exchange Process

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Gas Exchange Process

- Introduction
- Valve mechanisms
- Induction in engines
- Scavenging in 2-stroke engines
- Parameters effecting induction and scavenging
- Volumetric efficiency

Introduction

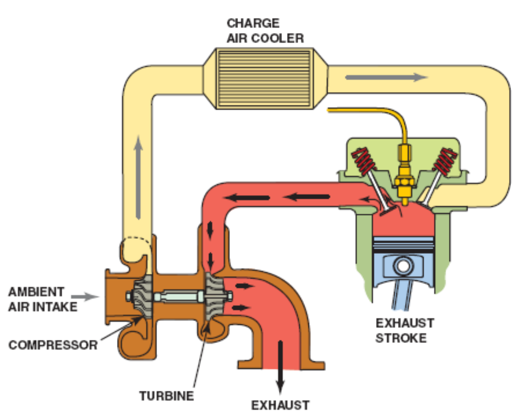
This section deals with fundamentals of gas exchange process - intake and exhaust in 4-stroke engines, and scavenging in 2-stroke engines.

The purpouse is to remove the burnt gases at the end of the power stroke and admit fresh charge for the next cycle. The power output of an engine at a given speed is proportional to the mass flow rate of air. Inducting the maximum air mass at wide-open throttle or full load is the primary goal for gas exchange process.

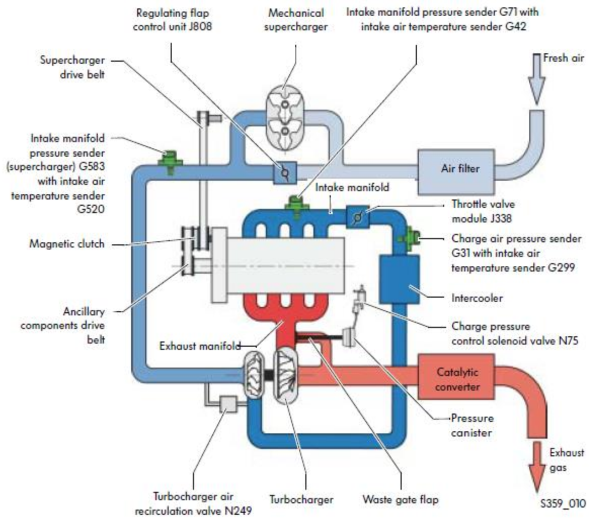
Gas exchange process is characterizzed by overall parameters like volumetric efficiency (4-stroke) and scavenging and trapping efficiency (2-stroke) - these depend on design of engine subsystems like manifolds, valves, ports, as well as engine operating conditions.

Supercharging and turbocharging are used to increase air flow through engines and hence power density.

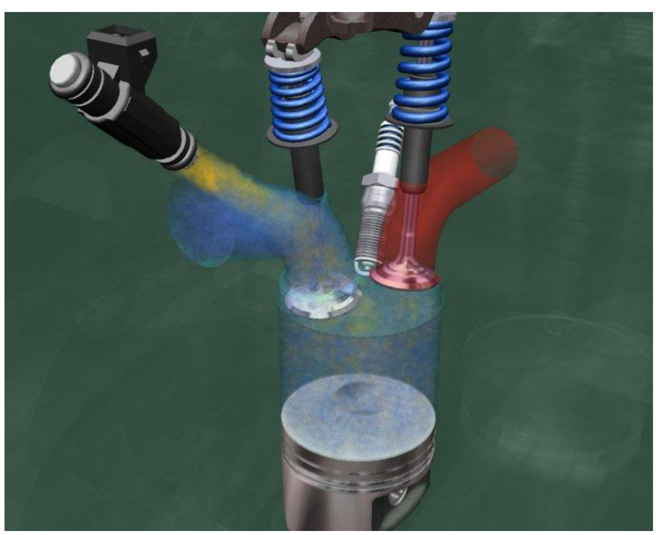
Gas Exchange in a Turbocharged Engine



Gas Exchange

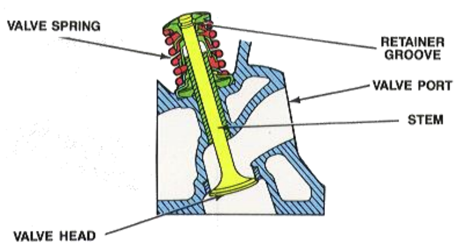


Introduction



Introduction

VALVE



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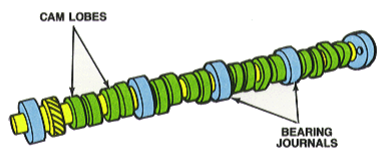
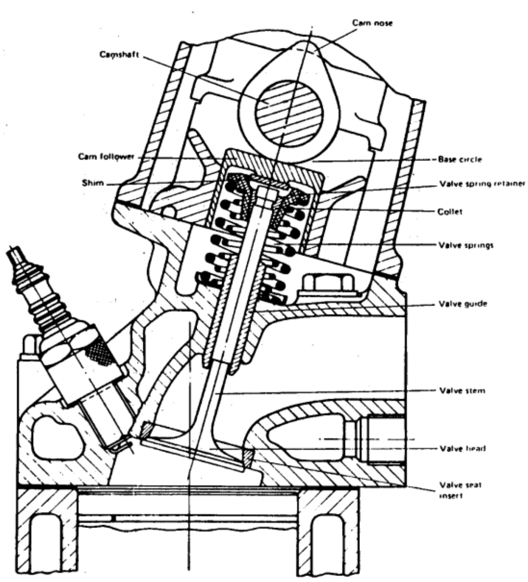


Introduction



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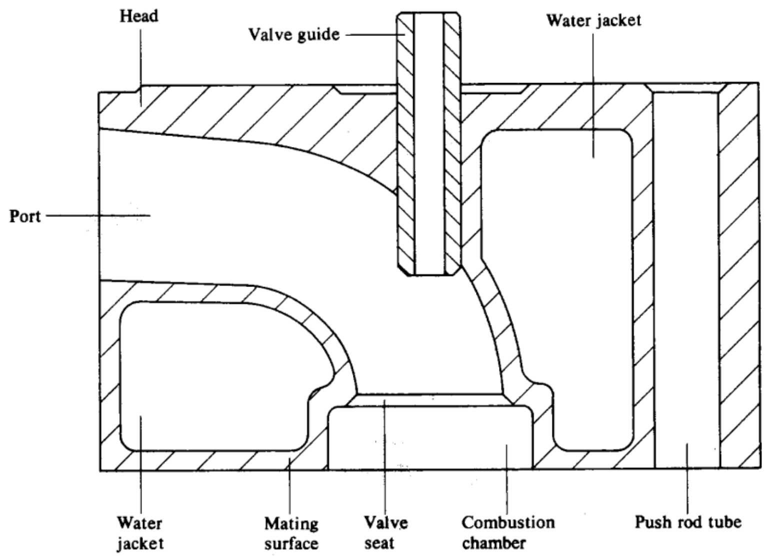
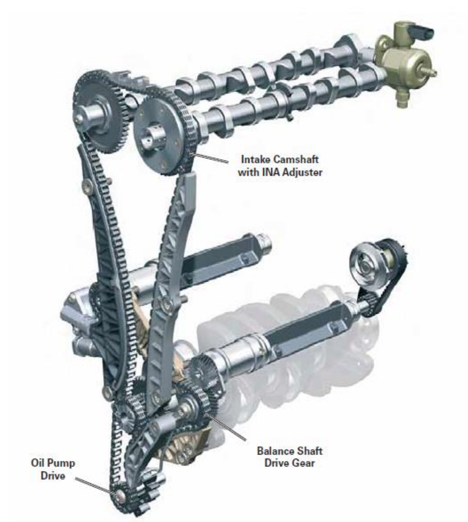
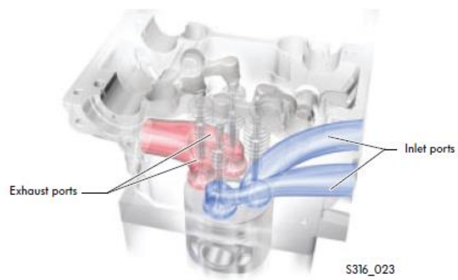
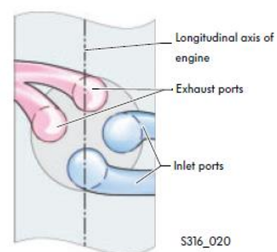


Valve Mechanism

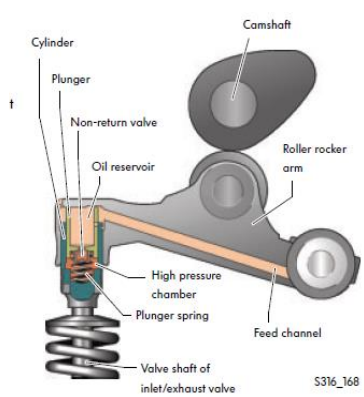


Valve Mechanism





Valve Mechanism



Valve Mechanism

Rocker arm

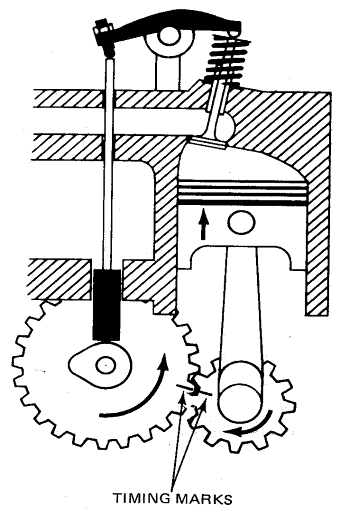
Push rod

Cam follower

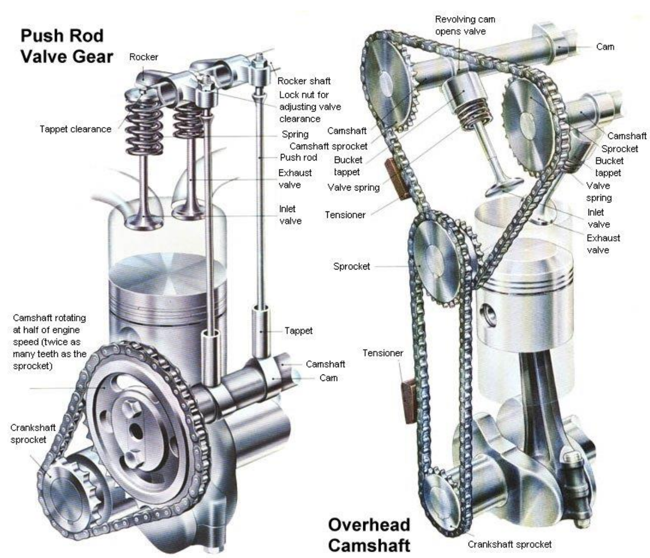
Camshaft

Inlet valve

Exhaust valve



Valve Mechanism



Valve Mechanism

Valve-operating Systems

In engines with overhead poppet valves, the camshaft is either mounted in the cylinder block or in the cylinder head (overhead camshaft - OHC).

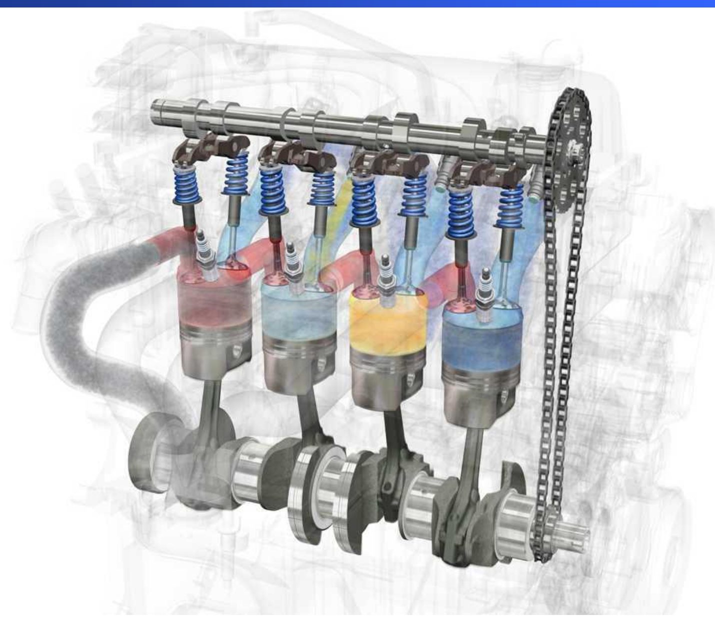
In OHC engines, camshaft can be mounted directly over the valve stems, or it can be offset - offset valves are operated by rockers and valve clearences can be adjusted by altering pivot height.

The drive is by chain or toothed belt.

Valve seat inserts are used, especially for engines with alluminium alloy cylinder head to ensure minimum wear - poppet valves rotate to even out any wear and to maintain good seating.

Engines with inlet and exhaust valves not placed in line, can use various push rod mechanisms or double overhead camshafts (DOHC) - one for inlet valves and other for exhaust valves.

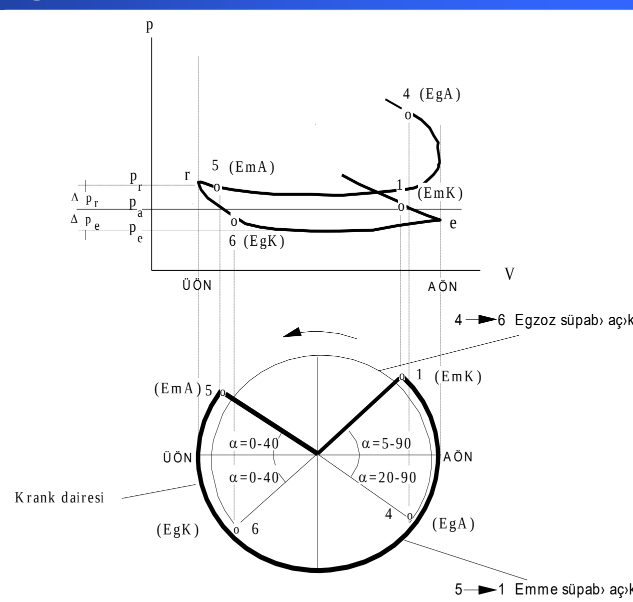
Valve-operating Systems



Valve Timing

4-stroke engines

valve timing and
p ~ V diagram
for gas exchange
process



Induction

IVO   inlet valve opening   0 - 40 (10 - 25) ^{o}CA BTDC

when intake valve is closed, the p behind the valve is the sum of static and dynamic pressures. When the valve is opened, the pressure p_r is greater than cylinder pressure and gases flow into the cylinder.

This early opening depends on the gas velocities and the geometry of the intake manifold (cross section area etc)

To be able to use the pressure wave action, IV can be opened up to 5 - 10 ^{o}CA ATDC in some engines.

With the movement of the piston from TDC to BDC, p in cylinder drops and generally is lower than the reference pressure, p_O - gas flow is obtained by this pressure difference, Δp_e

Induction

IVC   inlet valve closing   5 - 90 (40 - 60) ^{o}CA ABDC

the kinetic energy of the gases provide the gas flow into cylinder - according to the level of the KE, intake valve is kept open to allow max amount of gases into cylinder.

This depends on the engine speed (r.p.m.) - as the engine speed, n increases, this delay is increased.

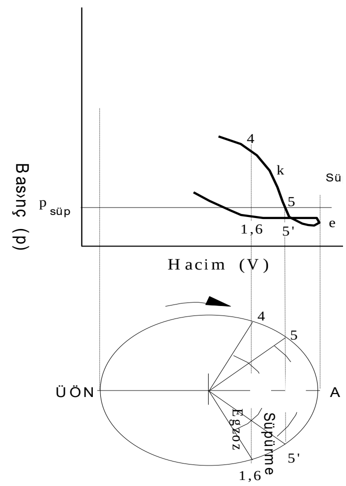
Usually valve opening and closing is set at engine design, according to the specifications of the engine (low speed, medium speed, high speed etc).

Some modern engines have mechanisms to adjust valve timing during engine operation to set the best valve opening duration, for best volumetric efficiency - Honda VTEC for example.

Scavenging in 2-stroke Engines

2-stroke engines

scavenging takes place at BDC,
and ports are used instead of valves.



Scavenging

Flow of gases is done by a scavenging pump which provides scavenging pressure above atm.

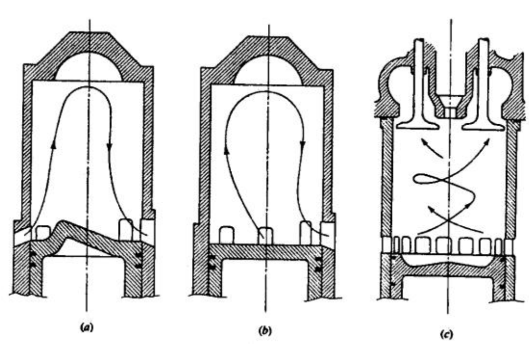
p_{scav} = 0.11 - 0.13 MPa

This pressure increase can be provided by various pump configurations.

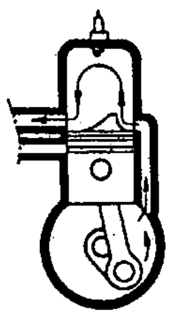
A) Cross scavenged

B) Loop scavenged

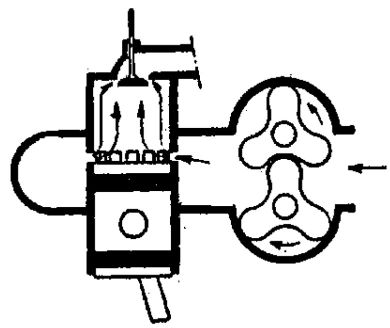
C) Uniflow scavenged



Scavenging



A) Crankcase compression



B) Roots blower

Parameters Effecting Intake and Scavenging

Intake and scavenging gas pressure

Intake and scavenging gas temperature

Residual gas fraction

Parameters Effecting Intake and Scavenging

Intake and scavenging gas pressure

Pressure of gases in cylinder at BDC is specified as p_e, intake gas pressure or scavenging gas pressure - this depends on engine speed, losses at intake manifold.

$$p_e = p_o - \Delta p_e$$

Where p_o is pressure infront of intake valve and Δp_e is the pressure drop during induction.

p_e = (0.80 - 0.90) p_O

Pressure Drop at Induction

Bernoulli equation,

$$p_o + \frac{1}{2}\rho_o v_o^2 = p_e + \frac{1}{2}\rho_e v_e^2 + \frac{1}{2}\rho_e \zeta v_e^2$$

here	v_o	gas velocity at inlet position of the valve, [m/s]
	v_e	gas velocity at exit position of the valve, [m/s]
	ζ	coefficient indicating pressure drop at the valve
	ρ_o	density of gases entering the cylinder, [kg/m^3]
	ρ_e	density of gases in the cylinder, [kg/m^3]

assuming, v_o = 10 - 20 m/s and v_e = 100 - 150 m/s

incompressible gases, $\rho_o = \rho_e$

Pressure Drop at Induction

In comparison to v_e^2, v_o^2 is negligable , so $v_o^2 = 0$

Bernoulli eqn becomes,

$$\Delta p_e = \frac{1}{2} \rho_e v_e^2 (1 + \zeta)$$

indicating that the pressure drop is proportional to gas velocity squared at the valve, and the coefficient of KE loss.

Average velocity at the valve can be given by,

$$v_e \approx c_m \frac{A}{a} = c_m \left(\frac{\mathrm{D}}{\mathrm{d}} \right)^2$$

$$A = \pi \frac{D^2}{4} \qquad c_m = \frac{Sn}{30}$$

Pressure Drop at Induction

The pressure drop will then be,

$$\Delta p_e \approx \frac{1}{2} \rho_e (1 + \zeta) c_m^2 \left(\frac{D}{d} \right)^4 = \frac{1}{2} \rho_e (1 + \zeta) S^2 n^2 \frac{D^4}{900\, d^4}$$

here	A	piston surface area, [m^2]
	a	valve opening, [m^2]
	c_m	mean piston speed, [m/s]
	D	cylinder diameter, [m]
	d	valve diameter, [m]
	S	stroke, [m]
	n	engine speed, [r.p.m.]

Pressure Drop at Induction

The **pressure drop** is **directly proportional to n^2** and **inversly proportional to d^4**

$d = (0.45 - 0.50)\ D$ for intake valve - single valve / cylinder

$d = 0.4\ D$ double intake valve / cylinder increases the total flow area by 1.25

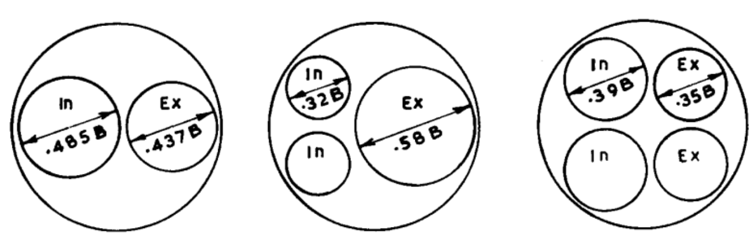
double intake valve,

valve mass is reduced, **dynamic effects are reduced** - allows operation at higher engine speeds, valve acceleration is reduced with low valve lift obtaining the same flow area - eliminate valve jumping

$h_{max} = (0.25 - 0.35)\ d$ **maximum valve lift**

Multiple Valves

Considerable gain in geometric valve area can be obtained by adopting multiple valve configurations. For a flat cylinder engine with fixed limitations on gaps between valve and cylinder bore, two, three and four valve layouts are shown in the figure.



Multiple Valves

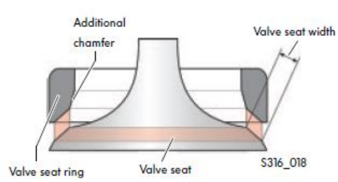
With equal lift for intake and exhaust valves, geometric exhaust valve area is 80% of intake.

3-valve layout gives inconveniently large exhaust valve.

4-valve layout is preferable, providing space at center for fuel injector or spark plug. For same actual valve lift 4-valve head gives 61% increase of geometric area over 2-valve design.

5-valve layout Ferrari engine

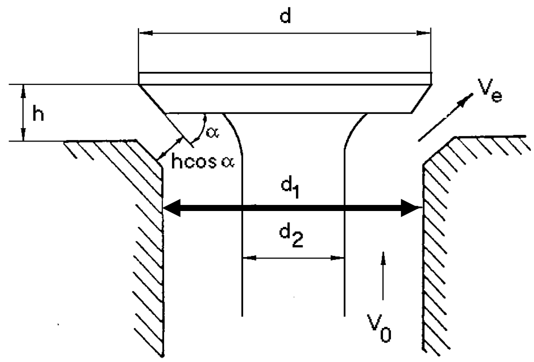
Valve Seat



Valve Geometry

d	head diameter
d_1	inner seat diameter
d_2	stem diameter
α	seat angle
h	lift

$$a = \pi d_1 h \cos \alpha$$



With increasing α , **flow area decreases.**

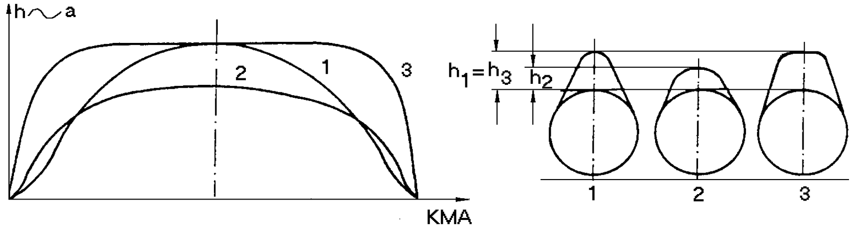
Generally it is 45° (can be reduced to 30°)

Increasing seat angle : increases seating pressure,

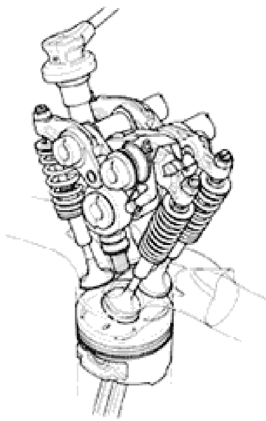
decreasing : reduces centering accuracy and produces sealing problems

Valve Lift Curve

Valve lift curve for different cam profiles



Variable Valve Timing



DOHC VTEC ENGINE

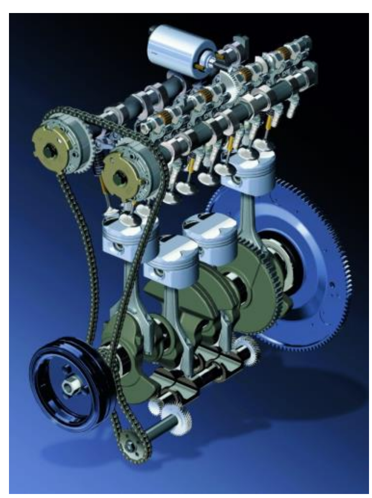
Variable Valve Timing

BMW VANOS : Variable Cam Timing combined hydraulic and mechanical camshaft control device managed by electronic engine management system

Adjustment mechanism that can modify the position of the intake camshaft versus the crankshaft - the timing of the intake cam is changed at two distinct rpm points

Double-VANOS adjustment of both intake *and* outlet camshafts - continuously variable throughout the majority of the rpm range

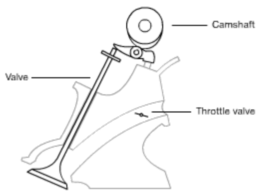
internal exhaust gas re-circulation, quick warming up



Variable Valve Timing

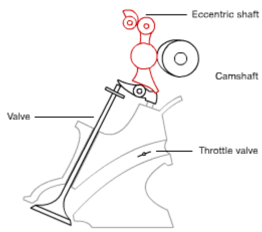
Intake valve with throttle plate.

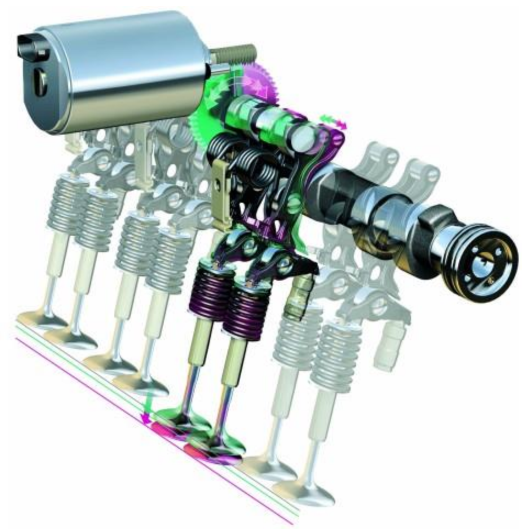
The supply of the fuel/air mixture is controlled by the throttle plate. Valve lift is unchanged.



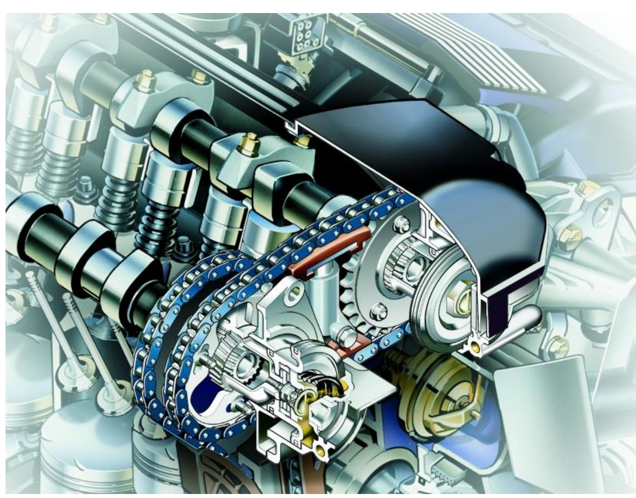
Intake valve with VALVETRONIC.

The fuel/air mixture is controlled by a variable valve lift, without a throttle plate.



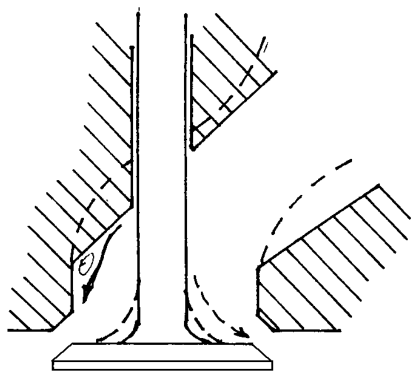


Variable Valve Timing

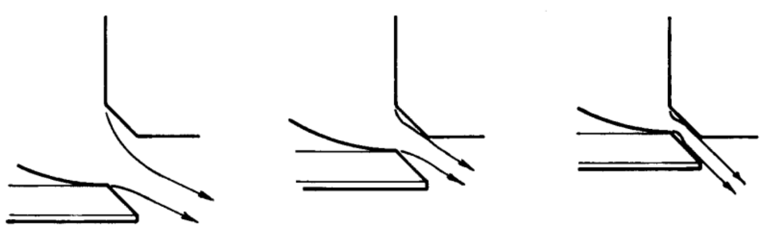


Flow Characteristics at Inlet Valve

Discharge coefficient



Flow Characteristics at Inlet Valve



Scavenging Pressure - two-stroke engines

Pressure of cylinder charge at BDC,

$$p_e = \frac{p_s + p_{exhaust}}{2}$$

at high speed engines, p_e = 0.085 - 0.105 MPa

Scavenging pressure,

for low speed engines p_s = 0.11 - 0.125 MPa

for high speed engines p_s = 0.12 - 0.14 MPa

Parameters Effecting Intake and Scavenging

Intake and scavenging gas temperature

Temperature at the end of induction can be obtained from heat balance,

$$c_p m_o (T_o + \Delta T) + \varphi c_p m_r T_r = c_p (m_o + m_r) T_e$$

intake gas temperature will be, $$T_e = \frac{m_o (T_o + \Delta T) + \varphi\, m_r T_r}{m_o + m_r}$$

where indices show,

- e inlet gas,
- o reference,
- r residual gas conditions

Parameters Effecting Intake and Scavenging

Scavenging gas temperature will depend on the compression provided by the scavenging pump,

$$T_s = T_o \left(\frac{p_s}{p_o} \right)^{\frac{n-1}{n}}$$

where n is the polytropic coefficient (1.5 - 2.0)

$$T_e = \frac{m_o \left(T_{compressor} + \Delta T \right) + m_r T_r}{m_o + m_r}$$

T_e = 320 - 400 K 2-stroke engines

T_e = 310 - 350 K 4-stroke engines

Parameters Effecting Intake and Scavenging

Residual gas fraction

$$\gamma_r = \frac{m_r}{m_o}$$

defines the ratio of

mass of residuals to the **mass of cylinder charge** at reference conditions

Mass of residuals is effected by **temperature** and **pressure of residual gases**, and the **compression volume**, V_c

Increase of compression ratio (with other parameters being constant) reduces the amount of residual gases

Residual Gas Fraction

4-stroke engines

CI engines γ = 0.03 - 0.06

SI engines γ = 0.06 - 0.10

2-stroke engines

uniflow scavenged engines γ = 0.03 - 0. 05

cross scavenged engines γ = 0.06 - 0.12

crankcase scavenged engines γ = 0.20 - 0.30

Volumetric Efficiency

Volumetric efficiency is an overall measure of the effectiveness of an IC engine and its intake and exhaust system.

It is **defined as the ratio of the mass of intake charge to the mass of the same charge at reference conditions**.

$$\eta_v = \frac{m_g}{m_o}$$

4-stroke engines

at point r , beginning of induction

$$m_r = \frac{V_c p_r}{R_r T_r}$$

Volumetric Efficiency

at point e , end of induction

$$m_e = \frac{V_e p_e}{R_e T_e}$$

mass of charge entered the cylinder $\quad m_g = m_e - m_r$

$$\eta_v m_o = m_g = m_e - m_r$$

$$\eta_v = \frac{273}{\varepsilon - 1}\left(\frac{p_e}{T_e} - \frac{p_r}{T_r}\right)$$

with T_o = 273 K and p_o = 1 bar

volumetric efficiency is effected by pressure and temperature at the end of induction, residual gas pressure and temperature, and compression ratio.

SI engines $\eta_v = 0.75 - 0.85$

CI engines low speed $\eta_v = 0.8 - 0.9$ high speed $\eta_v = 0.75 - 0.9$

Volumetric Efficiency

2-stroke engines

at the beginning of compression, at point 1 total gas mass is,

$$m_1 = m_g + m_r$$

$$\eta_v = \frac{m_g}{m_o} = \frac{m_1 - m_r}{m_o} \qquad \eta_v = \frac{\left(\frac{p_1 V_1}{T_1} - \frac{p_r V_c}{T_r}\right)}{\frac{V_h p_o}{T_o}}$$

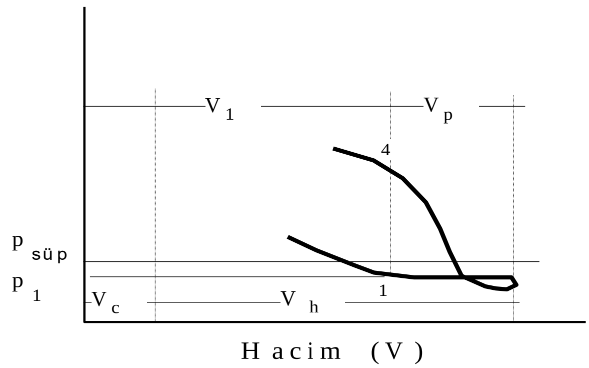
useful volume is (V_1, V_p, V_c from figure) $\quad V_1 = V_h + V_c - V_p$

$$V_1 = V_c + V_h(1 - S') \qquad S' = \frac{a}{S} = \frac{V_p}{V_h}$$

a is exhaust port height

S is stroke

Volumetric Efficiency



$$\eta_v = \frac{T_o}{p_o}\left[\frac{p_1}{T_1} - \frac{p_r}{T_r}\right]\left(\frac{1-S'}{\varepsilon - 1}\right)$$

$$\eta_{v-2stroke} = \eta_{v-4stroke}(1-S')$$

Volumetric Efficiency

In 2-stroke engines, $p_1 > p_o$ therefore volumetric efficiency can be greater than 1.0

uniflow scavenged engines	η_v = 0.97 - 1.05
cross scavenged engines	η_v = 0.80 - 0.85
crankcase scavenged engines	η_v = 0.50 - 0.70

Volumetric Efficiency

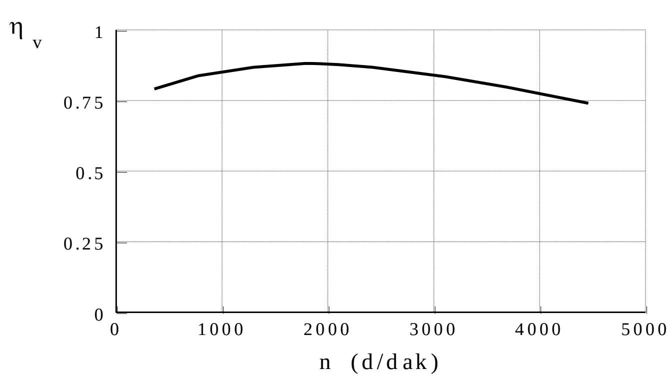
Volumetric efficiency is affected by the **fuel**, **engine design** and **engine operating variables**,

- Fuel type, F/A ratio, fraction of fuel vaporized in intake system and fuel heat of vaporization
- Mixture T as influenced by heat transfer
- Ratio of exhaust to inlet manifold pressure
- Compression ratio
- Engine speed
- Intake and exhaust manifold and port design
- Intake and exhaust valve geometry, size, lift and timing

Volumetric Efficiency

Inlet manifold pressure

Is effected by the design of intake manifold and the intake valve. This p is effected by the engine speed - decreases proportionally with n^2 .

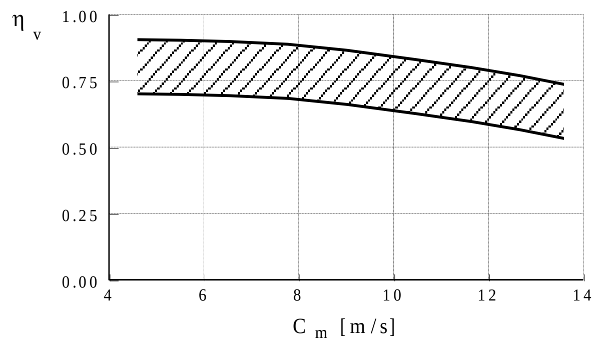


Volumetric Efficiency

At low speeds, dynamic pressure of the incoming gases is low - so volumetric efficiency is reduced.

At high speeds, pressure loss is increasing with the square of engine speed (crank shaft revolution)

Mean piston speed can also be used to indicate the change



Volumetric Efficiency

Intake gas temperature

Increasing the heat transfer to the incoming gases reduces volumetric efficiency.

All parameters that effect gas T, effects volumetric eff.

This is more dominant with Diesel engines - **increase in engine load** or change in λ changes volumetric eff.

In SI volumetric eff is reduced with a **throttle valve** intensionally for part load operations.

Volumetric Efficiency

Residual gas pressure and temperature

Inc the residual gas pressure and temperature reduces volumetric efficiency.

Inc in aerodynamic losses, inc the amount of residuals (combustion products from the previous cycle) and their pressure. This reduces the amount of fresh charge entering the cylinder, vol eff. is reduced.

Exhaust valves are smaller in diameter than inlet valves - exhaust system cross section area should be 0.6 to 0.7 of the inlet system.

Volumetric Efficiency

Compression ratio

When CR is increased with all other parameters being kept constant, volumetric efficiency should be reduced theoratically.

In practice, increasing CR **increases temperatures** - reduces vol eff, and **decreases the mass of residual gases** - increases vol eff.

So in some engines these two effects cancel out each other - there is no apparent effect of CR on volumetric efficiency.

Volumetric Efficiency

Scavenging system

In two-stroke engines, volumetric eff is influenced by the scavenging pump.

Effective scavenging can even increase the volumetric eff to a value greater than 1.0