INTERNAL COMBUSTION ENGINES

Kashif Liaqat

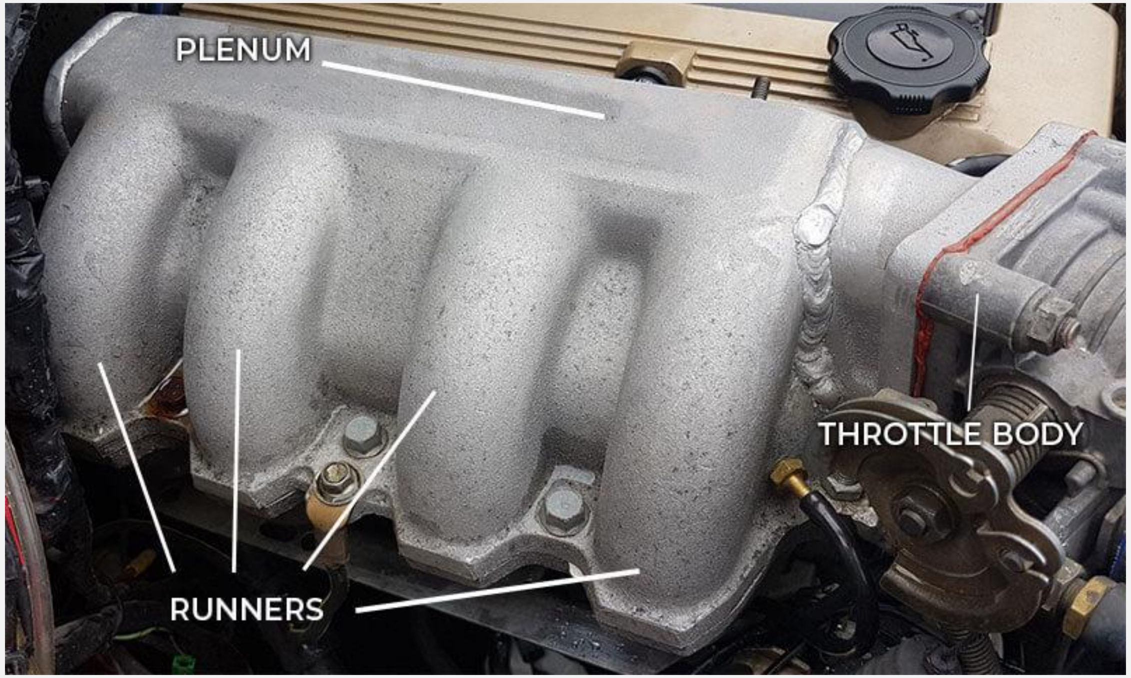
Department of Mechanical Engineering, BUITEMS, Quetta, Pakistan

Spring 2021

Lecture # 8 (Air and Fuel Induction)

I INTAKE MANIFOLD

- The intake manifold is a system designed to deliver air to the engine through pipes to each cylinder, called runners.



2. VOLUMETRIC EFFICIENCY OF SI ENGINES

It is desirable to have maximum volumetric efficiency in the intake of any engine. This will vary with engine speed, as shown in Fig. 1, which represents the efficiency curve of reciprocating engines. There will be a certain engine speed at which volumetric efficiency will be maximum, decreasing at both higher and lower speeds. There are many physical and operating variables that shape this curve. These will be examined.

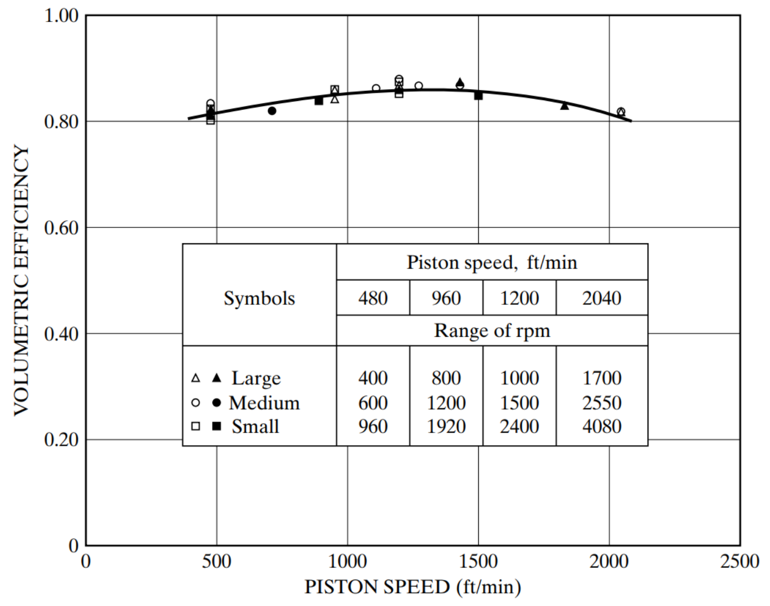


FIGURE 1

Volumetric Efficiency of three reciprocating internal combustion engines as a function of piston speed or engine speed. Reprinted with permission from *The Internal Combustion Engine in Theory and Practice* by C. F. Taylor, © MIT Press, [120].

2. VOLUMETRIC EFFICIENCY OF SI ENGINES

FUEL

- In a naturally aspirated engine, volumetric efficiency will always be less than 100%
- Because fuel is also being added and the volume of fuel vapor will displace some incoming air.
- The type of fuel, as well as how and when it is added, will determine how much the volumetric efficiency is affected.
- Systems with carburetors or throttle body injection add fuel early in the intake flow and generally have lower overall volumetric efficiency.
- This is because the fuel will immediately start to evaporate and fuel vapor will displace incoming air.

2. VOLUMETRIC EFFICIENCY OF SI ENGINES

Heat Transfer—High Temperature

- All intake systems are hotter than the surrounding air temperature and will consequently heat the incoming air.
- This lowers the density of the air, which reduces volumetric efficiency.
- At lower engine speeds, the air flow rate is slower, and the air remains in the intake system for a longer time.
- It thus gets heated to higher temperatures at low speeds, which lowers the volumetric efficiency curve in Fig. 1 at the low-speed end.

2. VOLUMETRIC EFFICIENCY OF SI ENGINES

Valve Overlap

- At TDC at the end of the exhaust stroke and the beginning of the intake stroke, both intake and exhaust valves are open simultaneously for a brief moment.
- When this happens, some exhaust gas can get pushed through the open intake valve back into the intake system.
- The exhaust then gets carried back into the cylinder with the intake air–fuel charge, displacing some of the incoming air and lowering volumetric efficiency.

2. VOLUMETRIC EFFICIENCY OF SI ENGINES

Fluid Friction Losses

- Air moving through any flow passage or past any flow restriction undergoes a pressure drop.
- For this reason, the pressure of the air entering the cylinders is less than the surrounding atmospheric air pressure, and the amount of air entering the cylinder is subsequently reduced.
- The viscous flow friction that affects the air as it passes through the air filter, carburetor, throttle plate, intake manifold, and intake valve reduces the volumetric efficiency of the engine intake system.

2. VOLUMETRIC EFFICIENCY OF SI ENGINES

Choked Flow

- The extreme case of flow restriction is when choked flow occurs at some location in the intake system.
- As air flow is increased to higher velocities, it eventually reaches sonic velocity at some point in the system.
- This choked flow condition is the maximum flow rate that can be produced in the intake system regardless of how controlling conditions are changed.
- The result of this is a lowering of the efficiency curve on the high-speed end in Fig. 1.
- Choked flow occurs in the most restricted passage of the system, usually at the intake valve or in the carburetor throat on those engines with carburetors.

2. VOLUMETRIC EFFICIENCY OF SI ENGINES

Closing Intake Valve After BDC

- The ideal time for the intake valve to close is when this pressure equalization occurs between the air inside the cylinder and the air in the manifold.
- If it closes before this point, air that was still entering the cylinder is stopped and a loss of volumetric efficiency is experienced.
- If the valve is closed after this point, air being compressed by the piston will force some air back out of the cylinder, again with a loss in volumetric efficiency.

2. VOLUMETRIC EFFICIENCY OF SI ENGINES

Exhaust Residual

- During the exhaust stroke, not all of the exhaust gases get pushed out of the cylinder by the piston, a small residual being trapped in the clearance volume.
- The amount of this residual depends on the compression ratio, and somewhat on the location of the valves and valve overlap.
- In addition to displacing some incoming air, this exhaust gas residual interacts with the air in two other ways.
  - When the very hot gas mixes with the incoming air, it heats the air, lowers the air density, and decreases volumetric efficiency.

2. VOLUMETRIC EFFICIENCY OF SI ENGINES

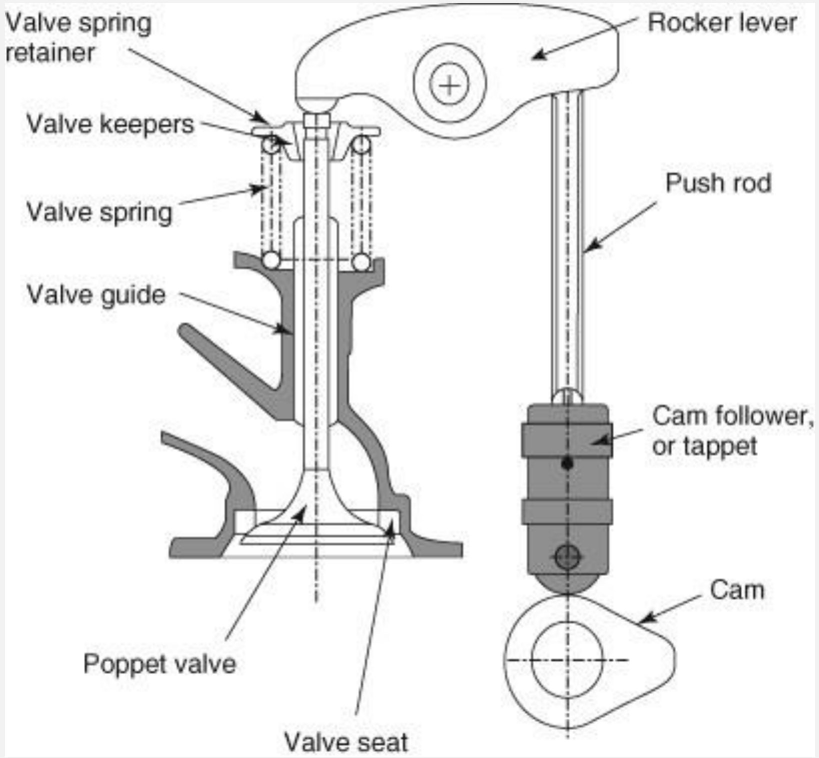
Exhaust Gas Recirculation (EGR)

- In all modern automobile engines and in many other engines, some exhaust gas is recycled (EGR) into the intake system to dilute the incoming air.
- This reduces combustion temperatures in the engine, which results in less nitrogen oxides in the exhaust.
- Up about 20% of exhaust gases will be diverted back into the intake manifold, depend on how the engine is being operated.
- Not only does this exhaust gas displace some coming air, but it also heats the incoming air and lowers its density. Both of these in actions lower the volumetric efficiency of the engine.

- An emission reduction method/technique.

3. INTAKE VALVES

- Intake valves of most IC engines are poppet valves that are spring loaded closed and pushed open at the proper cycle time by the engine camshaft.
- Much rarer are rotary valves or sleeve valves, found on some engines.
- They are connected by hydromechanical or mechanical linkage to the camshaft.



3. INTAKE VALVES

The distance that a valve opens (dimension 1 in Fig. 2) is called **valve lift** and is generally on the order of a few millimeters to more than a centimeter, depending on the engine size. The valve lift is usually about 5 to 10 mm for automobile engines. Generally,

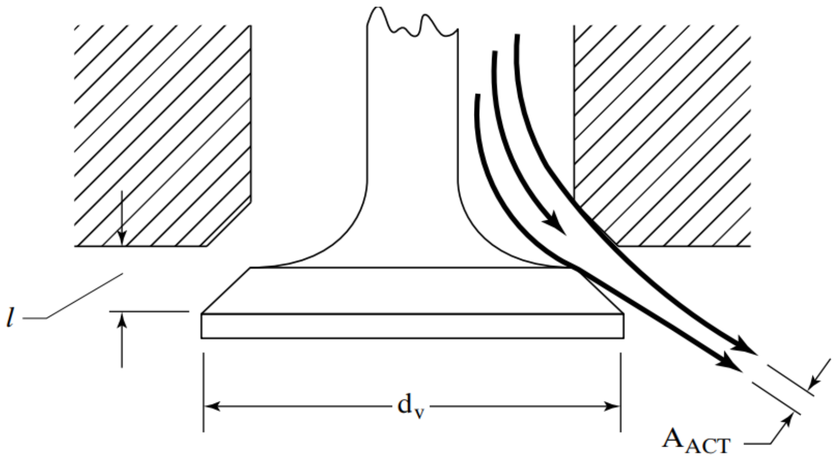
$$l_{max} < d_v/4 \tag{1}$$

where

l_{max} = valve lift when valve is fully open
d_v = diameter of valve

FIGURE 2

Flow through a poppet valve. When flow separates from the surface at the corners, the actual flow area is less than the geometric passage area of the valve. The ratio of these areas is called the discharge coefficient. Valve diameter is d_v and valve lift is 1.



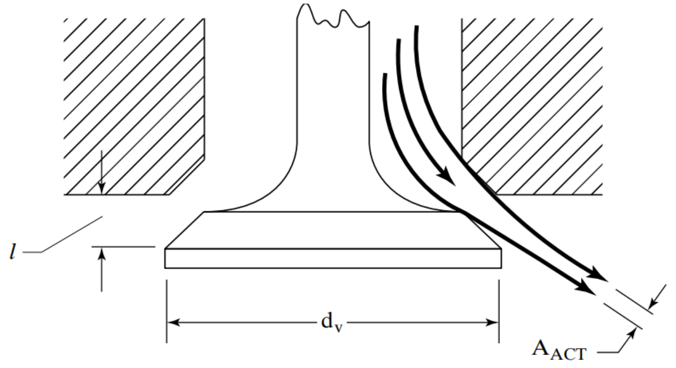
3. INTAKE VALVES

The angle of the valve surface at the interface with the valve seat is generally designed to give minimum flow restriction. As air flows around corners, the streamlines separate from the surface, and the actual cross-sectional area of flow is less than the flow passage area, as shown in Fig. 2. The ratio of the actual flow area to the flow passage area is called the *valve discharge coefficient*:

$$C_{Dv} = A_{act}/A_{pass} \tag{2}$$

The passage area of flow is

$$A_{pass} = \pi d_v l \tag{3}$$



3. INTAKE VALVES

Intake valves offer the greatest restriction to incoming air in most engines. This is especially true at higher engine speeds. Various empirical formulas can be found in technical engine literature for sizing intake valves. Equations giving the minimum valve intake area necessary for a modern engine can be given [40] in the form

$$A_i = CB^2[(\bar{U}_p)_{max}/c_i] = (\pi/4)d_v^2 \tag{4}$$

where

C = constant having a value of about 1.3

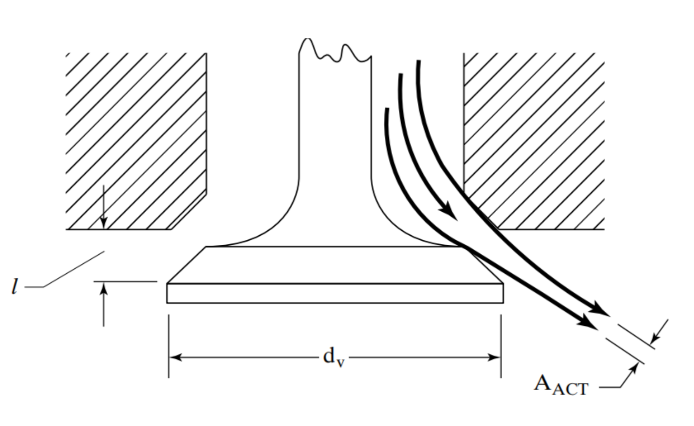
B = bore

$(\bar{U}_p)_{max}$ = average piston speed at maximum engine speed

c_i = speed of sound at inlet conditions

d_v = diameter of valve

A_i is the total inlet valve area for one cylinder, whether it has one, two, or three intake valves.



3. INTAKE VALVES

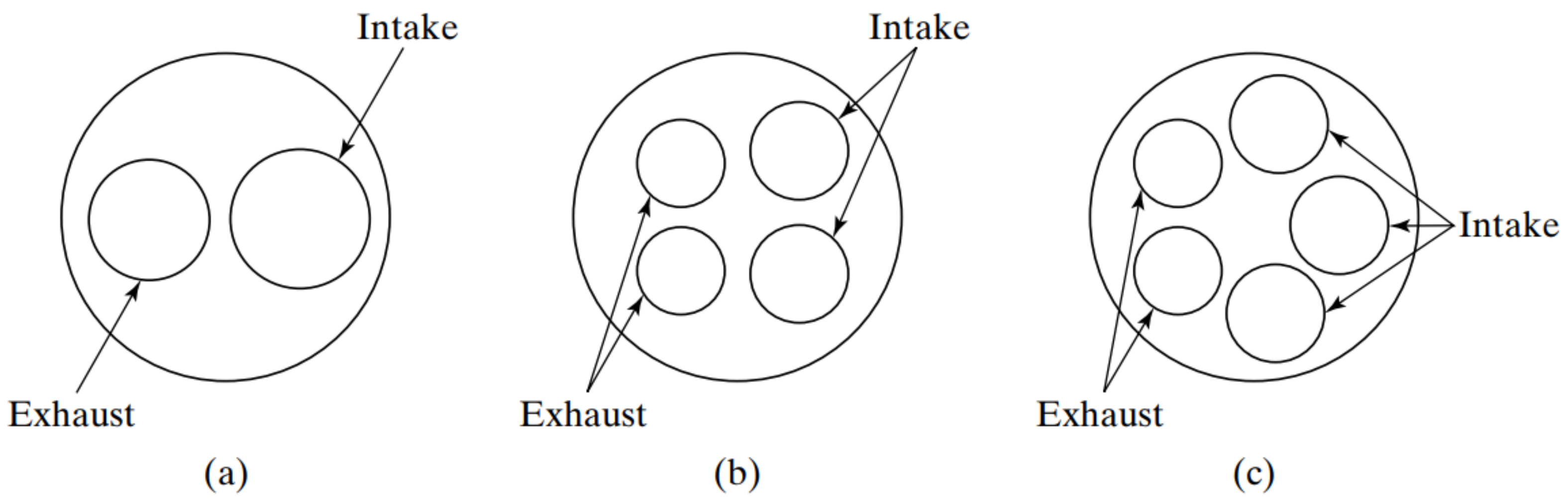


FIGURE 3

Possible valve arrangements for a modern overhead valve engine. For a given combustion chamber size, two or three smaller intake valves will give greater flow area than one larger valve. For each cylinder, the flow area of the intake valve(s) is generally about 10 percent greater than the flow area of the exhaust valve(s). (**a**) Most early overhead valve engines (1950s–1980s) and a few modern engines. (**b**) Most present-day automobile engines. (**c**) Some modern high-performance automobile engines.

3. INTAKE VALVES

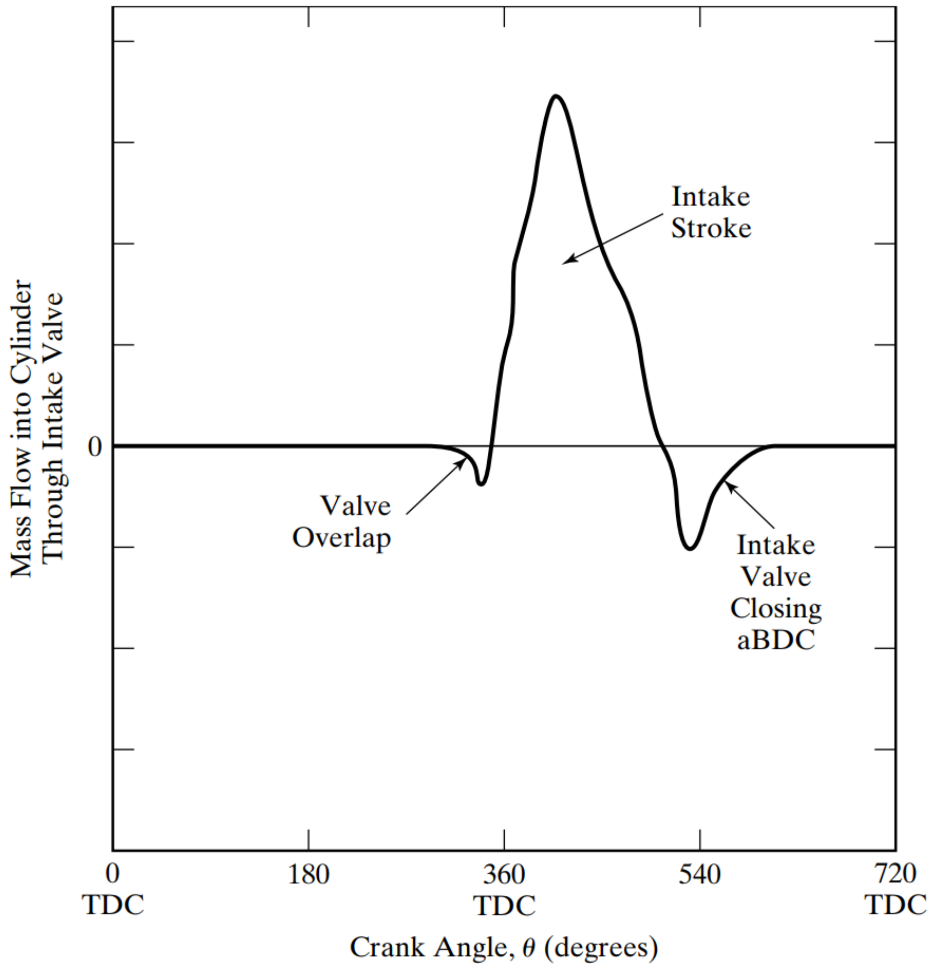


FIGURE 4

Flow of air–fuel mixture through the intake valve(s) into an engine cylinder. Possible backflow can occur during valve overlap and when the intake valve closes after BDC. Adapted from [28].

PRESENTATION TOPICS

The following topics from the chapter are part of student presentations

4. Variable Valve Control

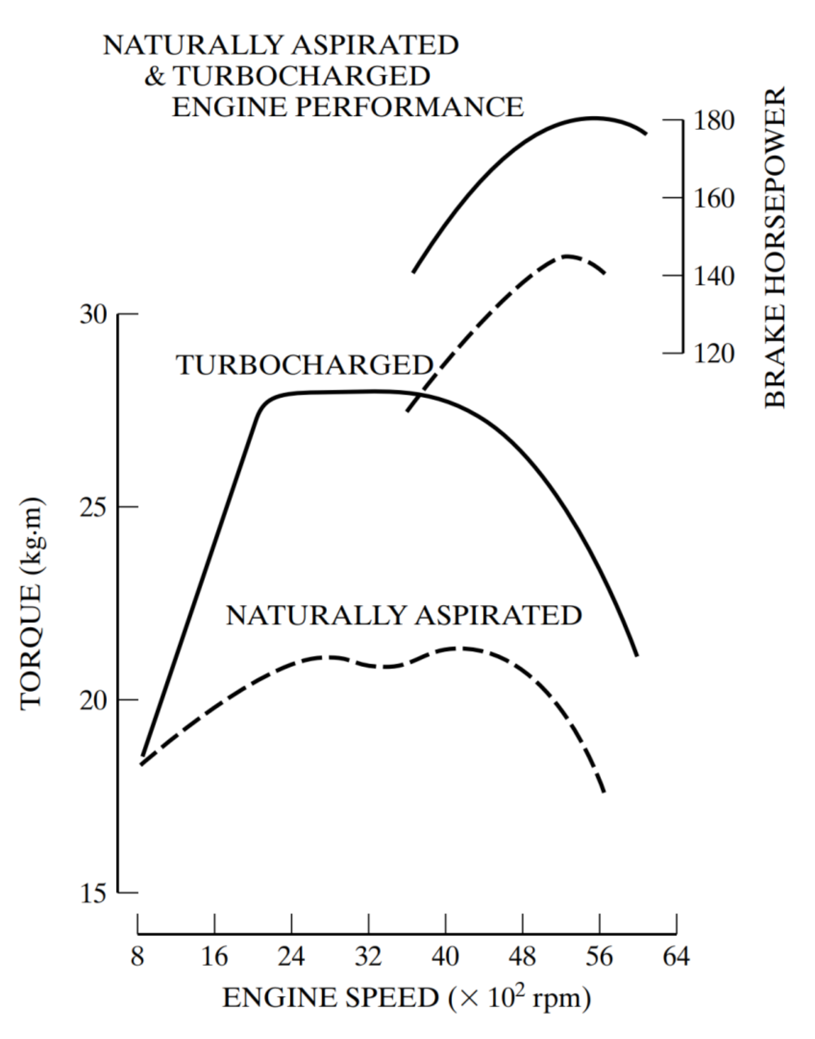
5. Fuel Injection

6. Carburetors

7. SUPERCHARGING AND TURBOCHARGING

- Superchargers and turbochargers are compressors mounted in the intake system and used to raise the pressure of the incoming air.
- This results in more air and fuel entering each cylinder during each cycle.
- This added air and fuel creates more power during combustion, and the net power output of the engine is increased

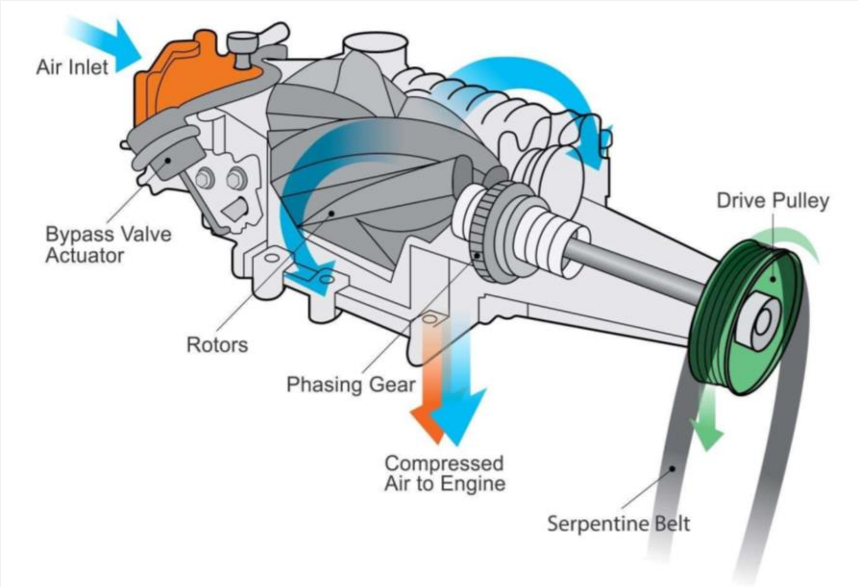
7. SUPERCHARGING AND TURBOCHARGING



7. SUPERCHARGING AND TURBOCHARGING

Superchargers

- Superchargers are mechanically driven directly off the engine crankshaft.
- They are generally positive displacement compressors running at speeds about the same as engine speed.
- The power to drive the compressor is a parasitic load on the engine output, and this is one of the major disadvantages compared with a turbocharger.
- Other disadvantages include higher cost, greater weight, and noise.
- A major advantage of a supercharger is very quick response to throttle changes.
- Being mechanically linked to the crankshaft, any engine speed change is immediately transferred to the compressor.



7. SUPERCHARGING AND TURBOCHARGING

Superchargers

- Some high-performance automobile engines and just about all large CI engines are supercharged.
- All two-stroke cycle engines that are not crankcase compressed (a form of supercharging) must be either supercharged or turbocharged.

When the first law of thermodynamics is applied to the air flowing through a supercharger compressor,

$$\dot{W}_{sc} = \dot{m}_a(h_{out} - h_{in}) = \dot{m}_a c_p(T_{out} - T_{in}) \tag{13}$$

where

$\dot{W}_{sc}$ = power needed to drive the supercharger
$\dot{m}_a$ = mass flow rate of air into the engine
c_p = specific heat of air
h = specific enthalpy
T = temperature

7. SUPERCHARGING AND TURBOCHARGING

This assumes that the compressor heat transfer, kinetic energy terms, and potential energy terms are negligibly small, true for most compressors. All compressors have isentropic efficiencies less than 100%, so the actual power needed will be greater than the ideal. In Fig. 19, process $1\text{–}2_s$ represents ideal isentropic compression, while process $1\text{–}2_A$ is the actual process with an increase in entropy. The isentropic efficiency η_s of the supercharger compressor is

$$(\eta_s)_{sc} = \dot{W}_{isen}/\dot{W}_{act} = [\dot{m}_a(h_{2s} - h_1)]/[\dot{m}_a(h_{2A} - h_1)]$$
$$= [\dot{m}_a c_p(T_{2s} - T_1)]/[\dot{m}_a c_p(T_{2A} - T_1)] = (T_{2s} - T_1)/(T_{2A} - T_1) \qquad (14)$$

Superchargers

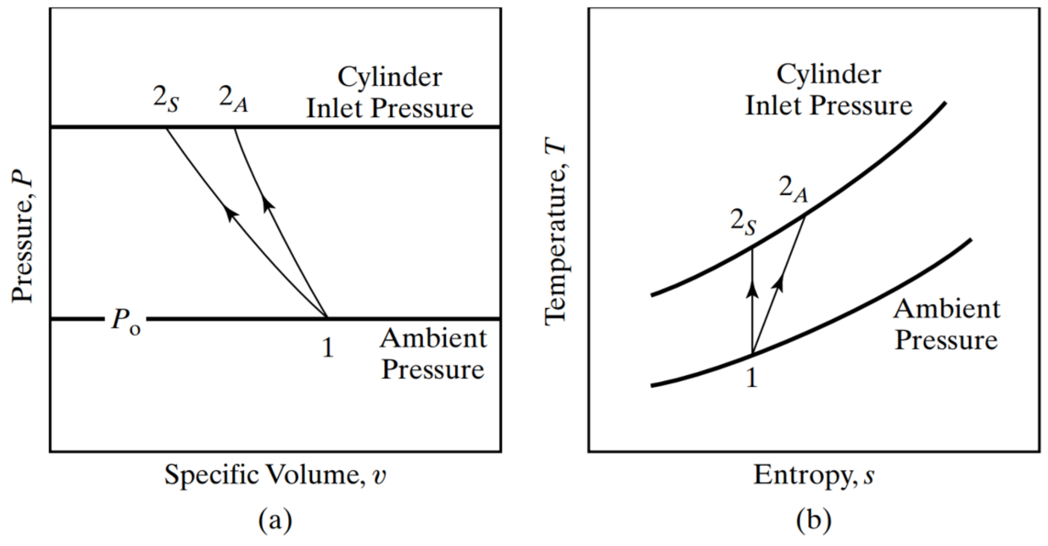


FIGURE 19

Ideal flow process ($1\text{–}2_s$) and actual flow process ($1\text{–}2_A$) through a supercharger or a turbocharger compressor in (a) pressure–volume coordinates, and (b) temperature–entropy coordinates.

7. SUPERCHARGING AND TURBOCHARGING

Superchargers

If the inlet temperature and pressure, as well as the designed output pressure, are known, the ideal gas isentropic relationship can be used to find T_{2s}:

$$T_{2s} = T_1(P_2/P_1)^{(k-1)/k} \tag{15}$$

The actual outlet temperature T_{2A} can then be calculated from Eq. (14) if the isentropic efficiency is known. When using Eq. (15), a value of $k = 1.40$ should be used because of the lower temperature at this point.

There is also a mechanical efficiency of less than 100% between the power taken from the engine and that delivered to the compressor:

$$\eta_m = (\dot{W}_{\text{act}})_{\text{sc}}/\dot{W}_{\text{from engine}} \tag{16}$$

7. SUPERCHARGING AND TURBOCHARGING

Superchargers

- The supercharger also raises the inlet air temperature by compressive heating.
- This is undesirable in SI engines. If the temperature at the start of the compression stroke is higher, all temperatures in the rest of the cycle will also be higher.
- Often, this will cause self-ignition and knocking problems during combustion.
- To avoid this, many superchargers are equipped with an aftercooler that cools the compressed air back to a lower temperature.
- The aftercooler can be either an air-to-air heat exchanger or an air-to-liquid heat exchanger.

7. SUPERCHARGING AND TURBOCHARGING

Superchargers

- Some superchargers are made up of two or more compressor stages with an aftercooler following each stage.
- Aftercoolers are not needed on superchargers used on CI engines because there is no concern about knock problems.
- Aftercoolers are costly and take up space in the engine compartment. For these reasons, the superchargers on some automobiles do not have aftercoolers.
- These engines generally have reduced compression ratios to avoid problems of self-ignition and knock

The effectiveness of an aftercooler can be defined as

$$\text{Eff} = (T_1 - T_2)/(T_1 - T_{\text{coolant}}) \tag{17}$$

where

T_1 = air temperature at aftercooler inlet
T_2 = air temperature at aftercooler exit

7. SUPERCHARGING AND TURBOCHARGING

Turbochargers

- The compressor of a turbocharger is powered by a turbine mounted in the exhaust flow of the engine.
- The advantage of this is that none of the engine shaft output is used to drive the compressor, and only waste energy in the exhaust is used.
- However, the turbine in the exhaust flow causes a more restricted flow, resulting in a slightly higher pressure at the cylinder exhaust port.
- This reduces the engine power output very slightly.
- Turbocharged engines generally have lower specific fuel consumption rates.
- They produce more power, while the friction power lost remains about the same.

7. SUPERCHARGING AND TURBOCHARGING

Turbochargers

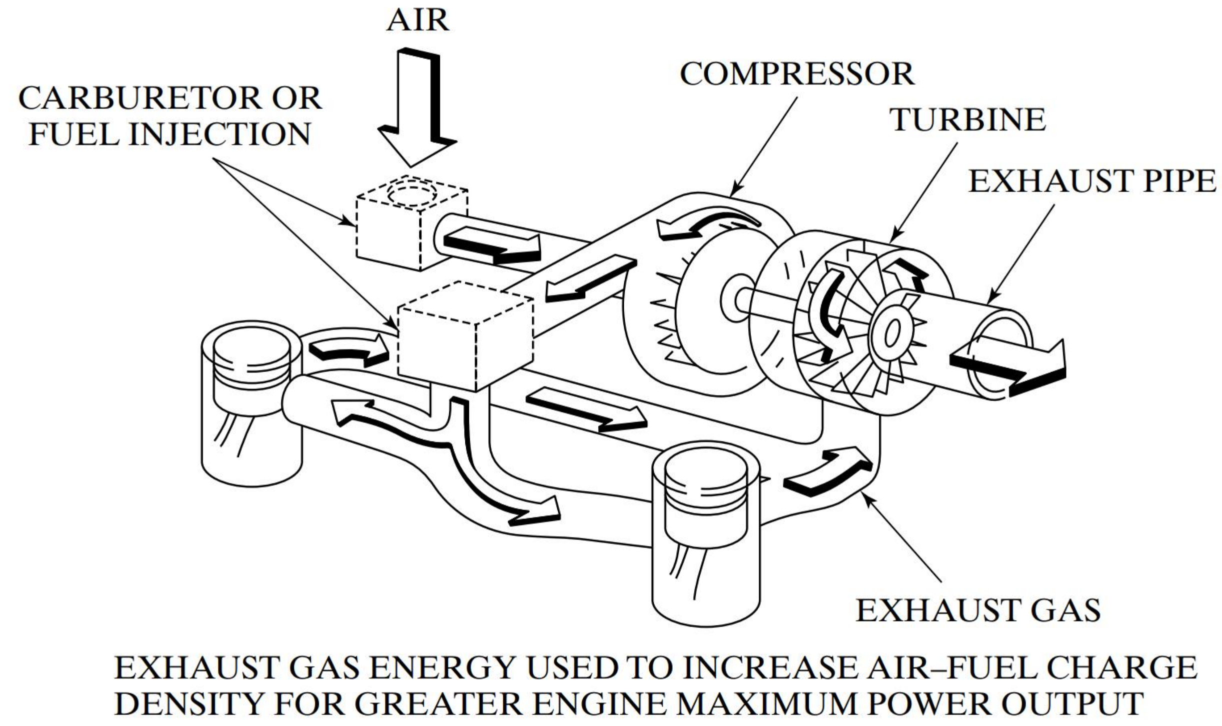


FIGURE 20

Schematic showing operation of turbocharger for an SI engine. Reprinted with permission from SAE Paper No. 780413 © 1978 SAE International, [136].

7. SUPERCHARGING AND TURBOCHARGING

Turbochargers

- A disadvantage of turbochargers is turbo lag, which occurs with a sudden throttle change.
- When the throttle is quickly opened to accelerate an automobile, the turbocharger will not respond quite as quickly as a supercharger.
- It takes several engine revolutions to change the exhaust flow rate and to speed up the rotor of the turbine.
- Turbo lag has been greatly reduced by using lightweight ceramic rotors that can withstand the high temperatures and that have very little mass inertia.

7. SUPERCHARGING AND TURBOCHARGING

Turbochargers

- Most turbochargers, like superchargers, are equipped with an aftercooler to again lower the compressed air temperature.
- Many also have a bypass that allows the exhaust gases to be routed around the turbocharger when an inlet air pressure boost is not needed.
- Some modern turbines have variable blade angle, which can be adjusted to give maximum efficiency for any air flow rate when engine speed or load is changed.

7. SUPERCHARGING AND TURBOCHARGING

Turbochargers

- The isentropic efficiency of a compressor is defined as:

$$(\eta_s)_{comp} = (\dot{W}_c)_{isen}/(\dot{W}_c)_{act}$$

Using Fig. 21 the turbine driving the compressor has an isentropic efficiency defined as

$$\begin{aligned}(\eta_s)_{turb} &= (\dot{W}_t)_{act}/(\dot{W}_t)_{isen}\\ &= [\dot{m}_a(h_1 - h_{2A})]/[\dot{m}_a(h_1 - h_{2S})] = (T_1 - T_{2A})/(T_1 - T_{2S}) \qquad (19)\end{aligned}$$

where

η_s = isentropic efficiency

$\dot{W}_c$ = power to drive compressor

$\dot{W}_t$ = turbine power

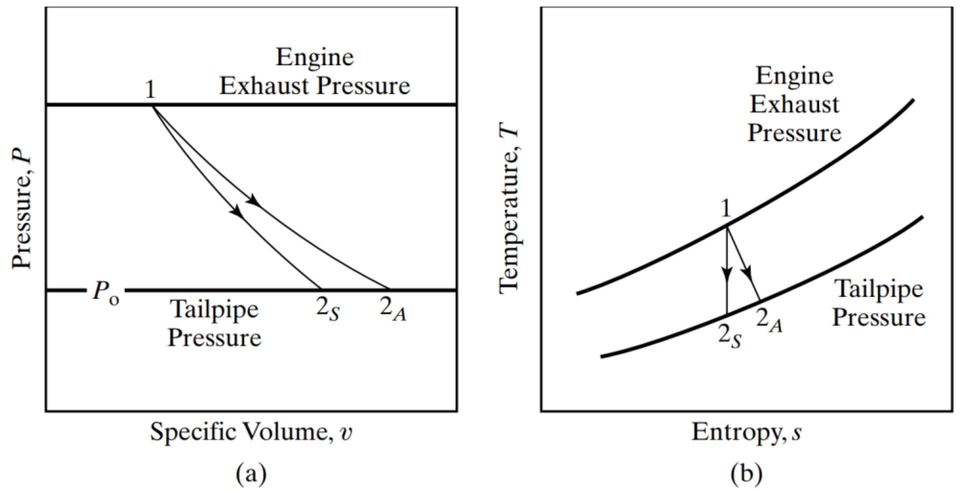


FIGURE 21

Ideal flow process ($1–2_s$) and actual exhaust flow process ($1–2_A$) through the turbine of a turbocharger in (a) pressure–volume coordinates, and (b) temperature–entropy coordinates. The inlet air flow through the compressor of the turbocharger is the same as shown in Fig. 19 for a supercharger.

7. SUPERCHARGING AND TURBOCHARGING

Turbochargers

The pulsing nature of the exhaust flow reduces this efficiency to less than steady-state flow values. There is a mechanical efficiency between the turbine and compressor:

$$\eta_m = (\dot{W}_c)_{\text{act}}/(\dot{W}_t)_{\text{act}} \tag{20}$$

The overall efficiency of the turbocharger can then be considered:

$$\eta_{\text{turbo}} = (\eta_s)_{\text{comp}}\,(\eta_s)_{\text{turb}}\eta_m \tag{21}$$

Values of overall efficiency range from 70% to 90%.

END OF THE LECTURE