INTERNAL COMBUSTION ENGINES

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Lecture # 10 (Fluid Motion and Exhaust System)

FLUID MOTION WITHIN COMBUSTION CHAMBER

1. TURBULENCE

- Due to the high velocities involved, all flows into, out of, and within engine cylinders are turbulent flows.
- As a result of turbulence,
  - thermodynamic transfer rates within an engine are increased
  - Heat transfer, evaporation, mixing, and combustion rates all increase.
- Turbulence in a cylinder is high during intake, but then decreases as the flow rate slows near BDC. It increases again during compression
- High Turbulence at TDC is desirable for combustion; Spreads the flames faster than laminar

1. TURBULENCE

- Turbulence intensity is a strong function of engine speed (Fig. 1).
- As speed is increased, turbulence increases, and this increases the rate of evaporation, mixing, and combustion.
- **Disadvantages of High Turbulence:**
  - Two Stroke – incoming air mixes more with the exhaust gases, and a greater exhaust residual will remain in the cylinder
  - Combustion – high turbulence enhances the convection heat transfer to the walls in the combustion chamber – More heat is lost

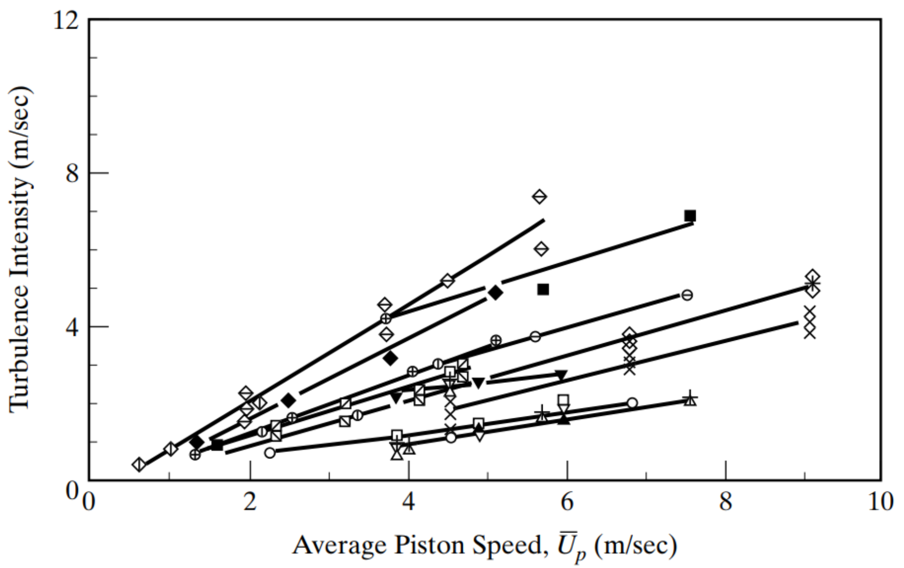
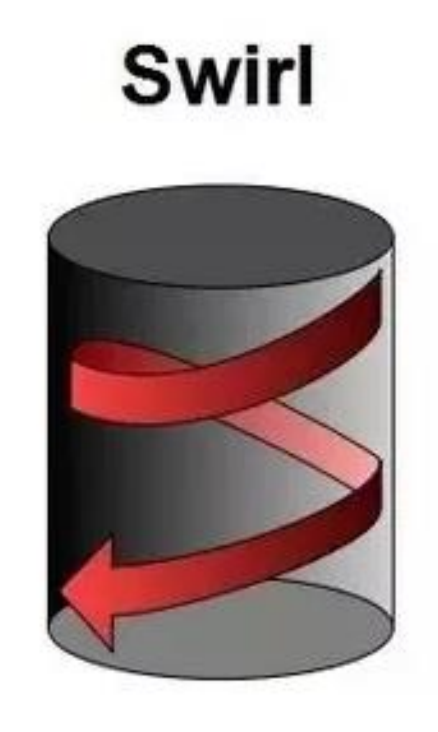


FIGURE 1

Turbulence intensity near TDC in combustion chamber as a function of average piston speed. Data represent experiments by several researchers using different engines, both with and without swirl. Turbulence was generally greater with swirl. Turbulence intensity increases with engine speed in most fluid flows within the engine. Reprinted with permission from SAE Paper No. 840375 © 1984 SAE International, [195].

2. SWIRL

- The main bulk mass motion within the cylinder is a rotational motion called swirl.
- Swirl greatly enhances the mixing of air and fuel to give a homogeneous mixture in the very short time available for this in modern high-speed engines.
- It is also a main mechanism for very rapid spreading of the flame front during the combustion process.



Swirl ratio is a dimensionless parameter used to quantify rotational motion within the cylinder. It is defined in two different ways in the technical literature:

$$(\mathrm{SR})_1 = (\text{angular speed})/(\text{engine speed}) = \omega/N \tag{1}$$

$$(\mathrm{SR})_2 = (\text{swirl tangential speed})/(\text{average piston speed}) = u_t/\overline{U}_p \tag{2}$$

2. SWIRL

It is generated by constructing the intake system to give a tangential component to the intake flow as it enters the cylinder (see Fig. 2).

This is done by shaping and contouring the intake manifold, valve ports, and sometimes even the piston face.

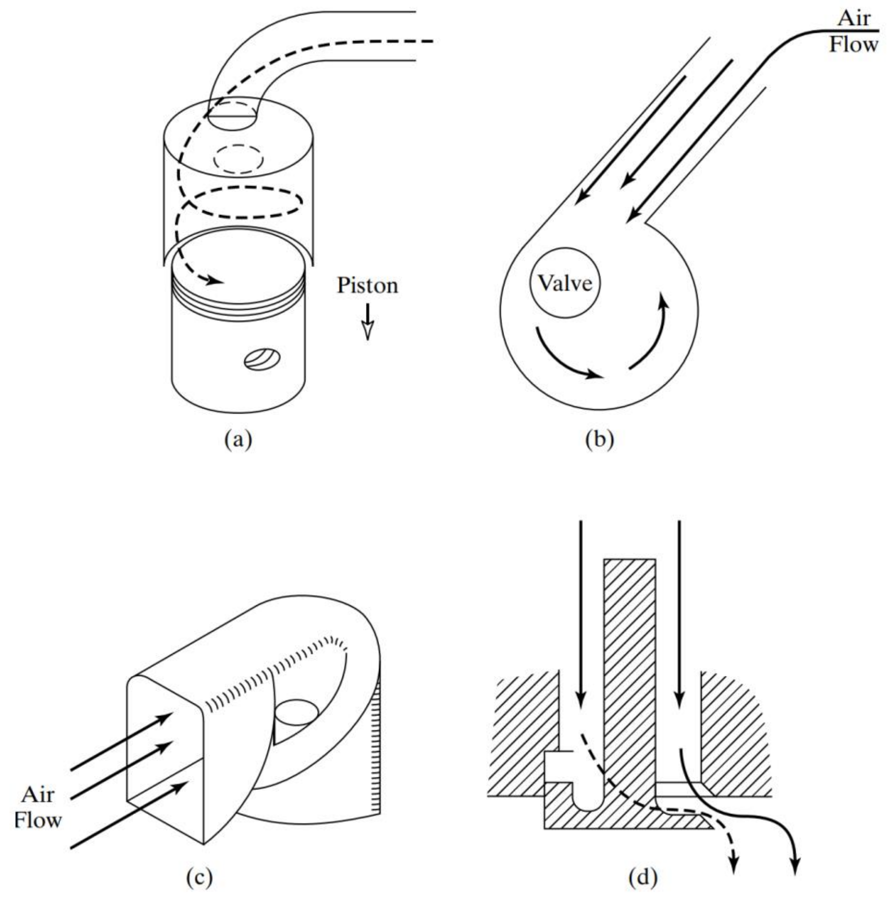


FIGURE 2

(a) Swirl motion within engine cylinder. Methods to generate swirl include (b) air entering cylinder from tangential direction, (c) contoured intake runner, (d) contoured valve.

2. SWIRL

- One simple way of modeling cylinder swirl is the paddle wheel model.
- The volume within the cylinder is idealized to contain an imaginary paddle wheel that has no mass.
- As the paddle wheel turns, the gas between the blades turns with it, resulting in a cylinder of gas all rotating at one angular velocity.
- The mass moment of inertia of this cylinder of gas is

$$I = mB^2/8 \qquad (3)$$

where

m = mass of gas mixture in the cylinder
B = bore = diameter of rotating mass

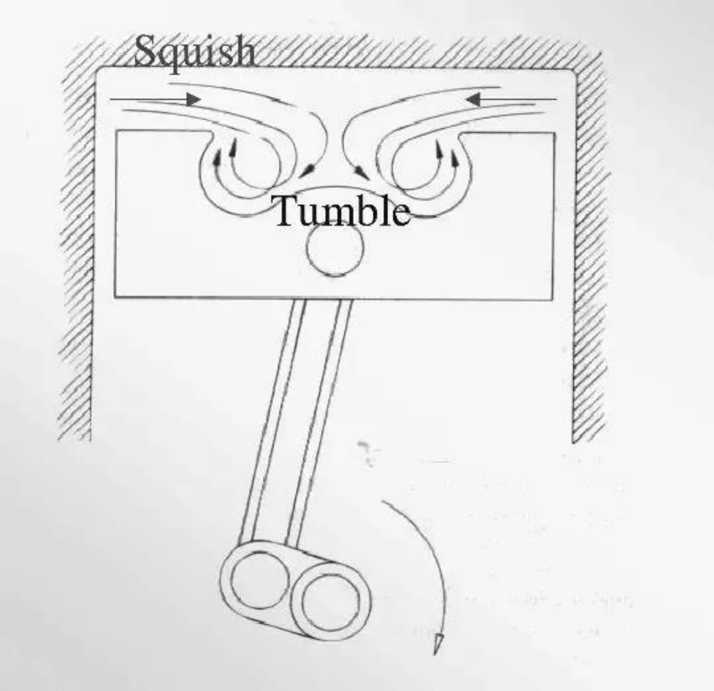
The angular momentum is

$$\Gamma = I\omega \qquad (4)$$

where ω = solid-body angular velocity

2. SQUISH AND TUMBLE

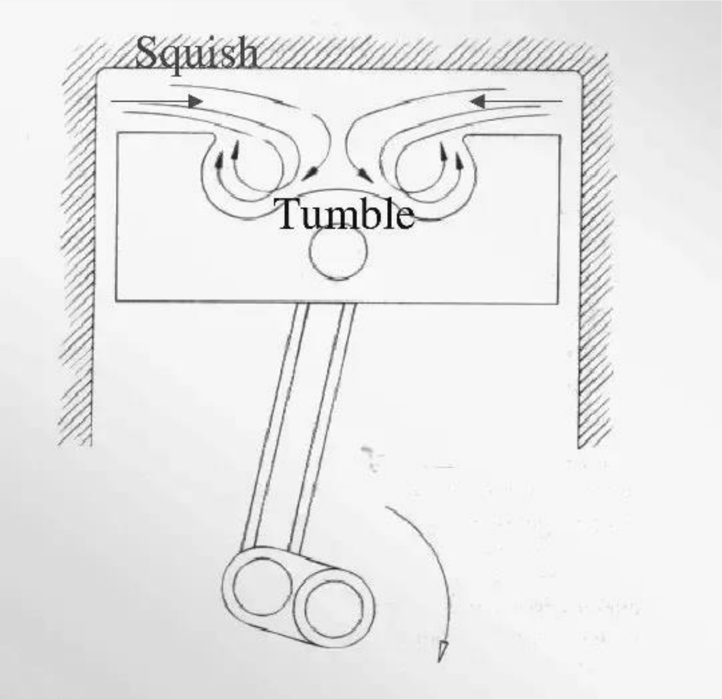
- As the piston approaches TDC, the gas mixture occupying the volume at the outer radius of the cylinder is forced radially inward as this outer volume is reduced to near zero.
- This radial inward motion of the gas mixture is called **squish**.
- It adds to other mass motions within the cylinder to mix the air and fuel, and to quickly spread the flame front.



2. SQUISH AND TUMBLE

- During combustion, the expansion stroke begins, and the volume of the combustion chamber increases.
- As the piston moves away from TDC, the burning gases are propelled radially outward to fill the now-increasing outer volume along the cylinder walls.

- This **reverse squish** helps to spread the flame front during the latter part of combustion.

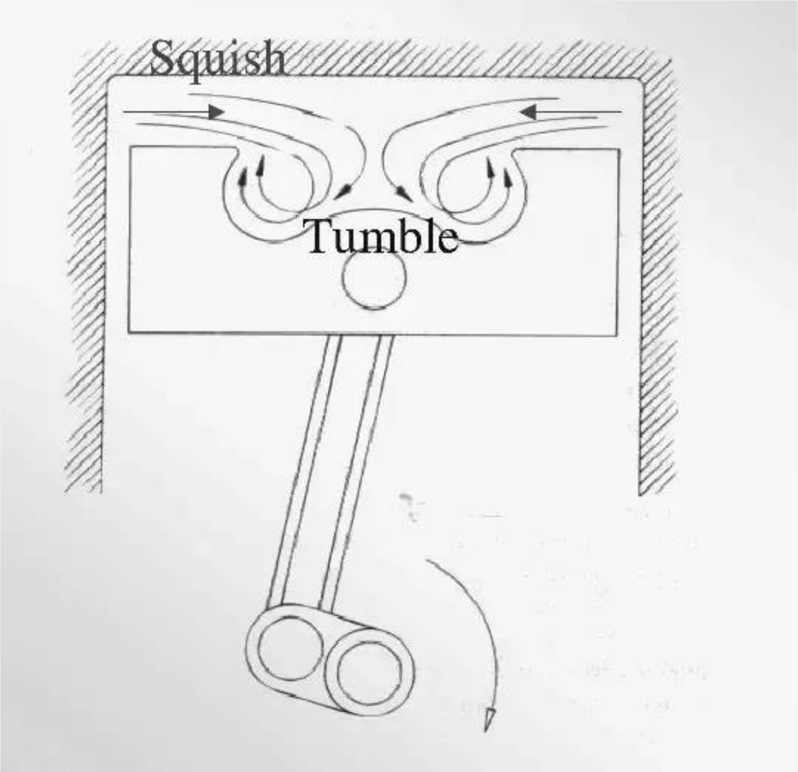


2. SQUISH AND TUMBLE

- As the piston nears TDC, squish motion generates a secondary rotational flow
- called **tumble**.
- This rotation occurs about a circumferential axis near the outer edge of the piston

Tumble ratio is the dimensionless parameter used to characterize the magnitude of tumble:

$$TR = (\text{angular speed of tumble})/(\text{engine speed}) = \omega_t/N \qquad (6)$$



3. PRESSURE CRANK DIAGRAM

- The gas that gets totally past the piston and ends up in the crankcase is called **blowby**.
- Figure 11 shows how the pressure in the combustion chamber, between the compression rings, and in the crankcase varies with crank angle in an engine cycle.
- Late in the power stroke, when the exhaust valve opens, pressure between the compression rings will be greater than in the combustion chamber, and some gases will be forced back into the chamber.
- This is called **reverse blowby**.

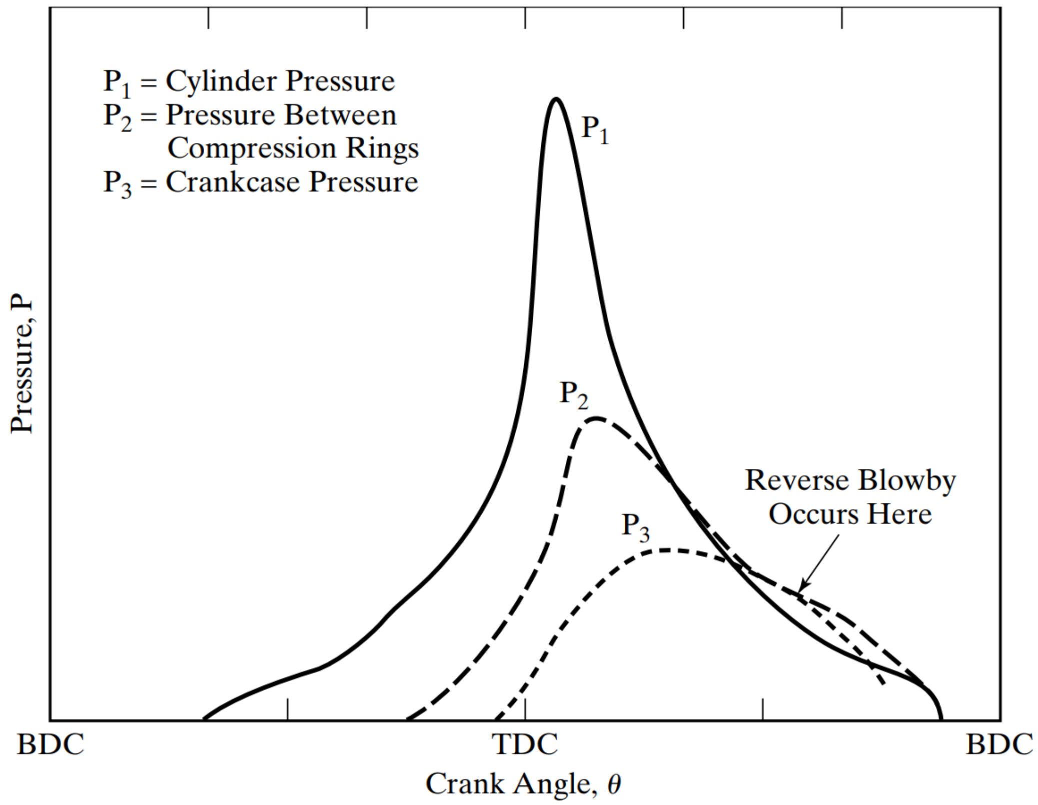


FIGURE 11

EXAMPLE PROBLEM 1

A four-cylinder, 3.2-liter engine running at 4500 RPM has a swirl ratio of 6 as defined by Eq. (1). The stroke and bore are related as $S = 1.06\ B$.
Calculate:

1. angular velocity of gas mixture in the cylinder using the paddle wheel model
2. swirl ratio as defined by Eq. (2)

EXAMPLE PROBLEM 2

An engine with pistons as shown in Fig. (7) operates at 3500 RPM, with each cylinder containing 0.0014 kg of air–fuel. When a piston approaches TDC, the gas inward squish velocity equals 7.66 m/sec. At TDC half of the cylinder gases then create a tumble rotation of 2.2 cm diameter. Calculate:

1. Angular momentum of gases in tumble rotation
2. Tumble ratio, assuming a paddlewheel model for the rotation

EXHAUST FLOW

1. BLOWDOWN

- Exhaust blowdown occurs when the exhaust valve starts to open towards the end of the power stroke, somewhere around 60° to 40° bBDC.

- At this time, pressure in the cylinder is still at about 4–5 atmospheres and the temperature is upwards of 1000 K.

- Pressure in the exhaust system is about one atmosphere, and when the valve is opened the resulting pressure differential causes a rapid flow of exhaust gases from the cylinder through the valve into the exhaust system (i.e., **exhaust blowdown**).

Flow at first will be choked, and the outflow velocity will be sonic. This occurs when the ratio of pressures across an orifice is greater than or equal to

$$(P_1/P_2) = [(k+1)/2]^{k/(k-1)} \tag{1}$$

where

P_1 = upstream pressure
P_2 = downstream pressure
k = ratio of specific heats

This ratio is equal to about 2 for most gases. $P_1/P_2 = 1.86$ for air with $k = 1.35$. Sonic velocity is equal to

$$c = \sqrt{kRT} \tag{2}$$

where

R = gas constant
T = temperature

1. BLOWDOWN

As the gas flows from the cylinder into the exhaust system, it experiences a pressure drop and a corresponding temperature drop due to expansion cooling. A model often used to calculate the temperature in the exhaust system is the ideal–gas isentropic expansion relationship between temperature and pressure, namely,

$$T_{ex} = T_{EVO}(P_{ex}/P_{EVO})^{(k-1)/k} \tag{3}$$

where

T_{ex}, P_{ex} = exhaust temperature and pressure

T_{EVO}, P_{EVO} = cylinder temperature and pressure when exhaust valve opens

Although the gases are not truly ideal and the blowdown process is not isentropic due to heat losses, irreversibility, and choked flow, Eq. (3) gives a fairly good approximation to gas temperature entering the exhaust system.

2. EXHAUST STROKE

- After exhaust blowdown, the piston passes BDC and starts towards TDC in the exhaust stroke.
- The exhaust valve remains open.
- Pressure in the cylinder resisting the piston in this motion is slightly above the atmospheric pressure of the exhaust system.
- The difference between cylinder pressure and exhaust pressure is the small pressure differential caused by the flow through the exhaust valves as the piston pushes the gases out of the cylinder.

2. EXHAUST STROKE

- In an ideal air-standard Otto cycle or Diesel cycle, the exhaust valve opens at BDC, and blowdown occurs instantaneously at constant volume (process 4–5 in Fig. 1).

- This does not happen in a real engine, where blowdown takes a finite length of time.

- The exhaust stroke can best be approximated by a constant-pressure process, with gas properties remaining constant at the conditions of point 7 in Fig. 1.

- Pressure remains about constant, slightly above atmospheric, with temperature and density constant at values consistent with Eq. (3)

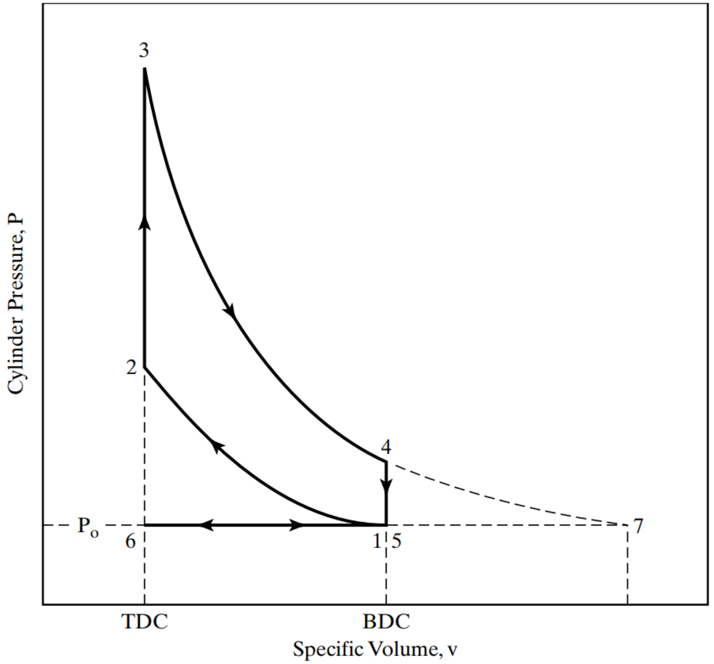


FIGURE 1
Air-standard Otto cycle on P–v coordinates showing exhaust gas after blowdown at hypothetical state 7.

3. EXHAUST VALVES

- Exhaust valves are made smaller than intake valves, although the same amount of mass must flow through each.
- The pressure differential across the intake valves of a naturally aspirated engine is less than one atmosphere
- while the pressure differential across the exhaust valves during blowdown can be as high as three or four atmospheres.
- We have for intake

$$A_i = (\text{constant})B^2(\overline{U}_p)_{\max}/c_i \qquad (4)$$

where

A_i = area of inlet valve(s)
$(\overline{U}_p)_{\max}$ = average piston speed at maximum engine speed
c_i = sonic velocity at inlet temperature
B = bore

Using this same equation to size exhaust valves yields

$$A_{ex} = (\text{constant})B^2(\overline{U}_p)_{\max}/c_{ex} \qquad (5)$$

where c_{ex} is sonic velocity at exhaust temperature.

3. EXHAUST VALVES

In multivalve engines, A_i and A_{ex} are the total valve areas of the intake valves of one cylinder and the exhaust valves of one cylinder, respectively. If Eq. (5) is divided by Eq. (4), the ratio of the valve areas is obtained. Everything cancels except the speed of sound, and by using Eq. (2), the ratio of the exhaust valve area to the intake valve area can be approximated as

$$\alpha = A_{ex}/A_i = c_i/c_{ex} = \sqrt{kRT_i}/\sqrt{kRT_{ex}} = \sqrt{T_i/T_{ex}} \tag{6}$$

In actual engines, α usually has a value of about 0.8 to 0.9. To find the valve diameters, we use the relationship

$$A/x = (\pi/4)d_v^2 \tag{7}$$

where

d_v = valve diameter
x = number of intake valves or number of exhaust valves

EXAMPLE PROBLEM 1

A 6.4-liter V8 engine with a compression ratio of 9:1 operates on an air-standard cycle and has the exhaust process shown in Fig. 1. Maximum cycle temperature and pressure are 2550 K and 11,000 kPa when operating at 3600 RPM. The exhaust valve effectively opens at 52° bBDC. Calculate:

1. time of exhaust blowdown
2. percent of exhaust gas that exits the cylinder during blowdown
3. exit velocity at the start of blowdown, assuming choked flow occurs

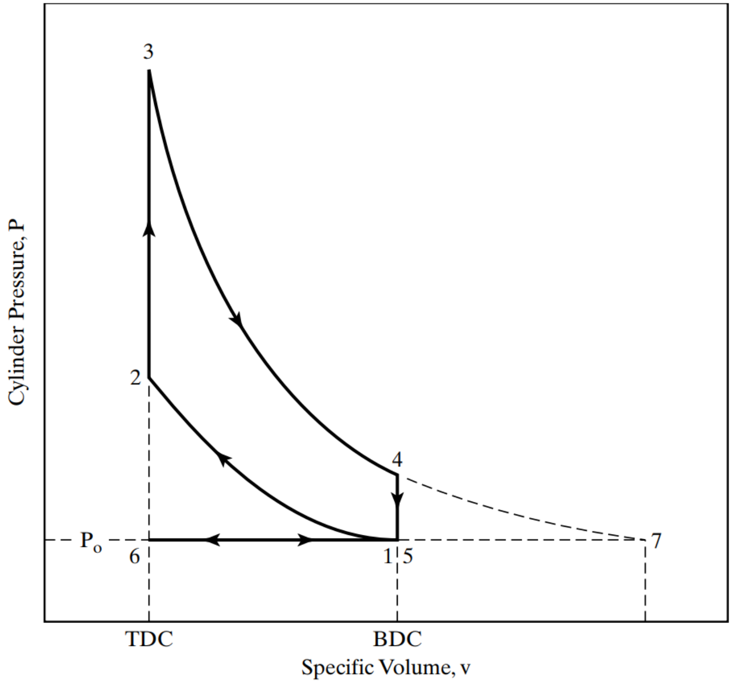


FIGURE 1

Air-standard Otto cycle on *P*–*v* coordinates showing exhaust gas after blowdown at hypothetical state 7.

END OF THE LECTURE