INTERNAL COMBUSTION ENGINE

Nazaruddin Sinaga

INTRODUCTION

What is IC Engine?

- An internal combustion engine is a thermal system (power plant) that converts heat obtained from chemical energy sources (gasoline, natural gas) into mechanical work.

Where are IC Engines Used?

- IC engines are used as the propulsion systems for land transport vehicles such as automobiles (cars, etc.), marine vehicles (boats, etc.) and small airplanes.
- IC engines are also used in portable electrical generators and as prime mover in grass cutting machine, etc.

INTRODUCTION

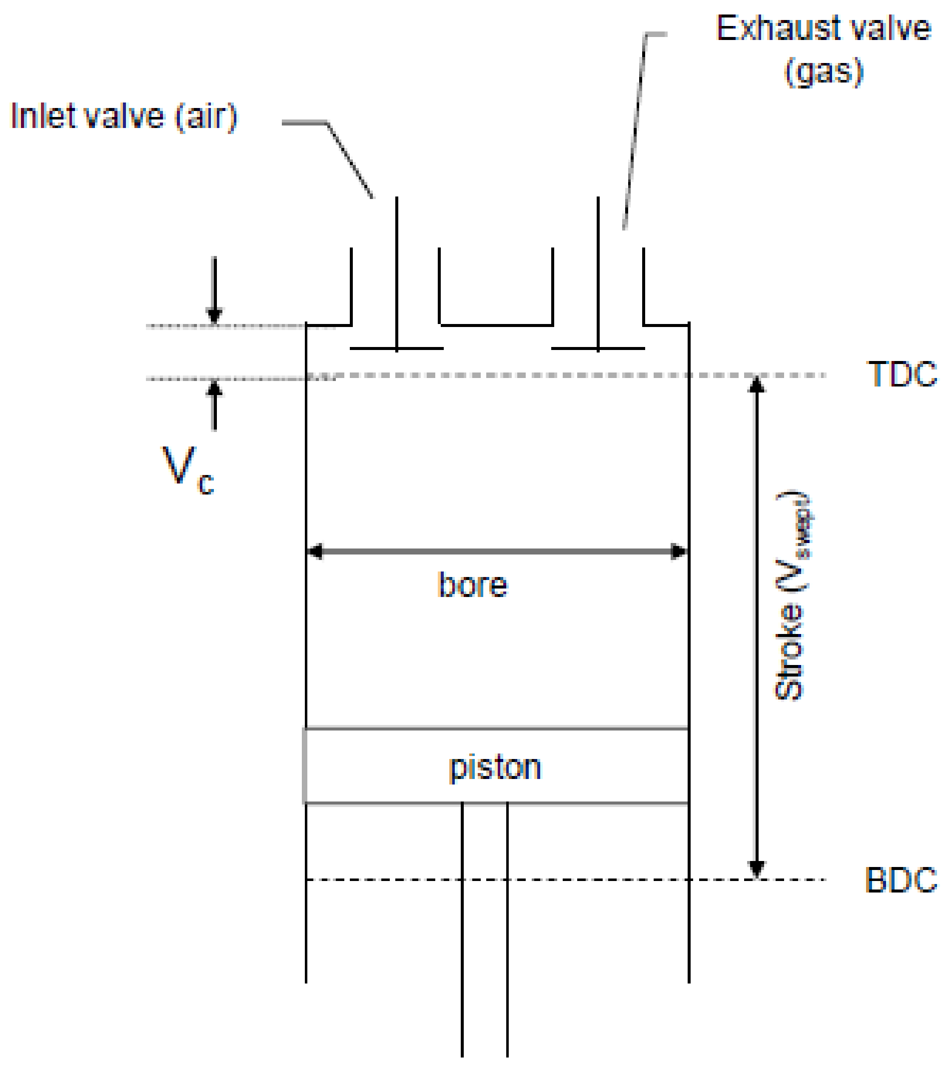
Basic Components of IC Engines

•Cylinder, piston, inlet valve and exhaust valve.

•Piston moves from the top dead center (TDC) to the bottom dead center (BDC).

• Clearance volume, Vc is a spacing between the top of the piston and the valve's heads when the piston is at the end of the delivery stroke.

•Swept volume or displacement volume, Vs is the volume between TDC and BDC.



ENGINE CLASSIFICATION

Reciprocating internal combustion (IC) engines are classified into two general categories, depending on how the combustion process in the cylinder is initiated, i.e.:

a) Spark-ignition (SI) engines;
b) Compression-ignition (CI) engines.

Description of SI Engines

- Run on liquid fuel such as gasoline or petrol, which is mixed with air.
- The air-fuel mixture enters the cylinder and is compressed to a highest pressure and temperature.

ENGINE CLASSIFICATION

Description of SI Engines

- A spark from a spark-plug ignites the combustible air- fuel mixture.
- It burns and combustion gases are produced.
- The high pressure of the gases pushes the piston downwards, producing a power stroke of the piston.
- The crankshaft transforms the reciprocating motion into rotational motion (rpm), which is carried by gears and drive shaft systems to the wheels, causing the vehicle to move.

ENGINE CLASSIFICATION

Description of CI Engines

Run on diesel liquid fuel.

- The fresh atmospheric air enters the cylinder in which it is compressed to about 1/22 of its original volume, causing its temperature to raise to about 540 oC or higher.
- Diesel fuel is then injected into the compressed air.
- The heat of compression of the air causes the diesel to burn.

ENGINE CLASSIFICATION

- Thus producing high temperature combustion gases.
- The combustion gases pushes the piston downward during the power stroke of the piston.
- As in the SI engines, the reciprocating motion is transformed into rotational motion.

IN BOTH ENGINES, THE COMBUSTION GASES ARE EVENTUALLY EXHAUSTED OUT OF THE CYLINDER SO THAT FRESH-AIR MIXTURE CAN BE INDUCED INTO THE CYLINDER TO CONTINUE THE THERMODYNAMICS CYCLES

– therefore working on an open cycle is the characteristics of all internal combustion engines since the working fluid does not undergo a complete thermodynamic cycle.

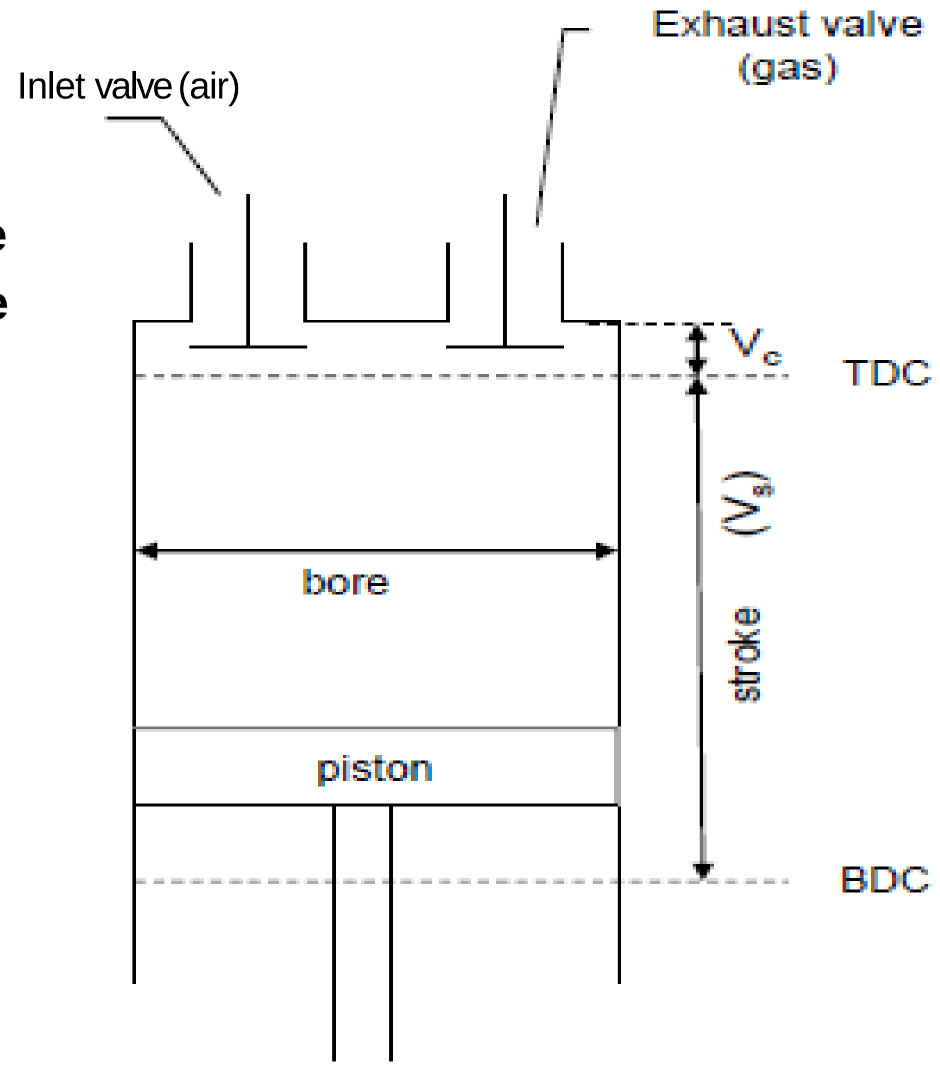
PERFORMANCE CRITERIA

Compression Ratio, r_v

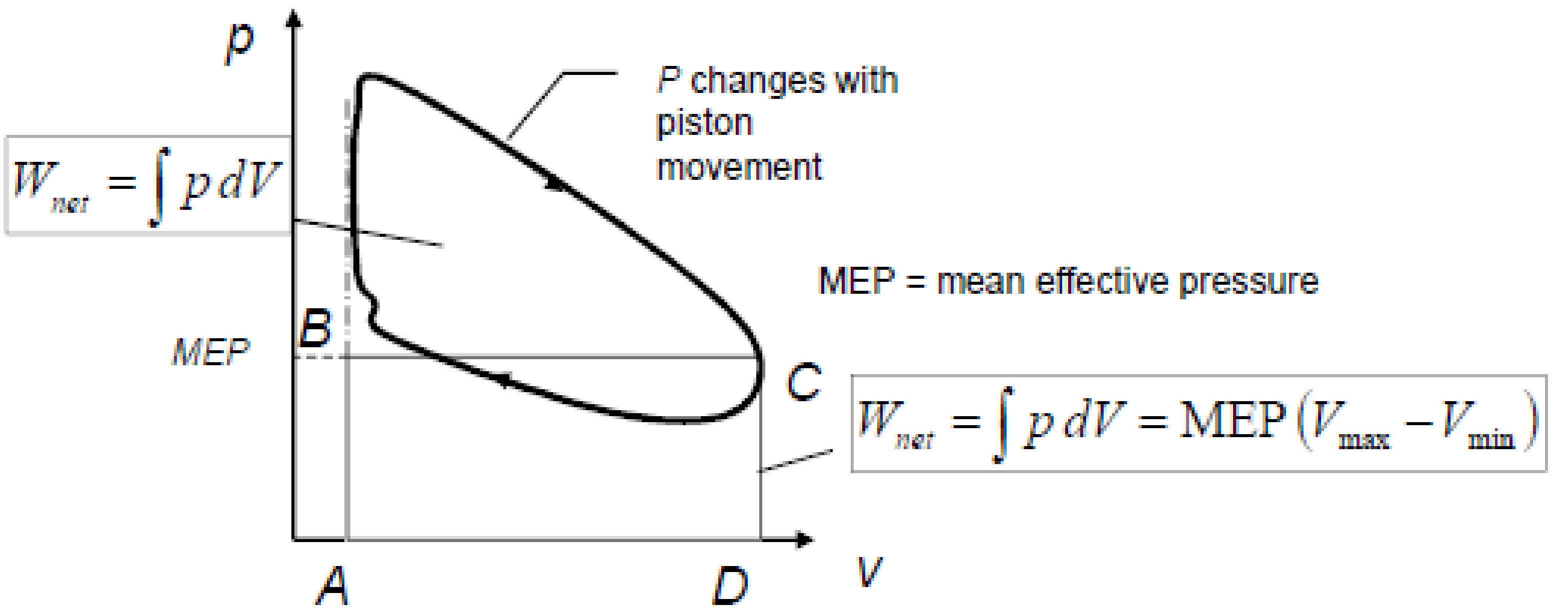
Compression ratio = $\dfrac{\text{Maximum volume}}{\text{Minimum volume}}$

$$r_v = \frac{V_c + V_s}{V_c}$$

Note: compression ratio is volume ratio and it is not a pressure ratio.

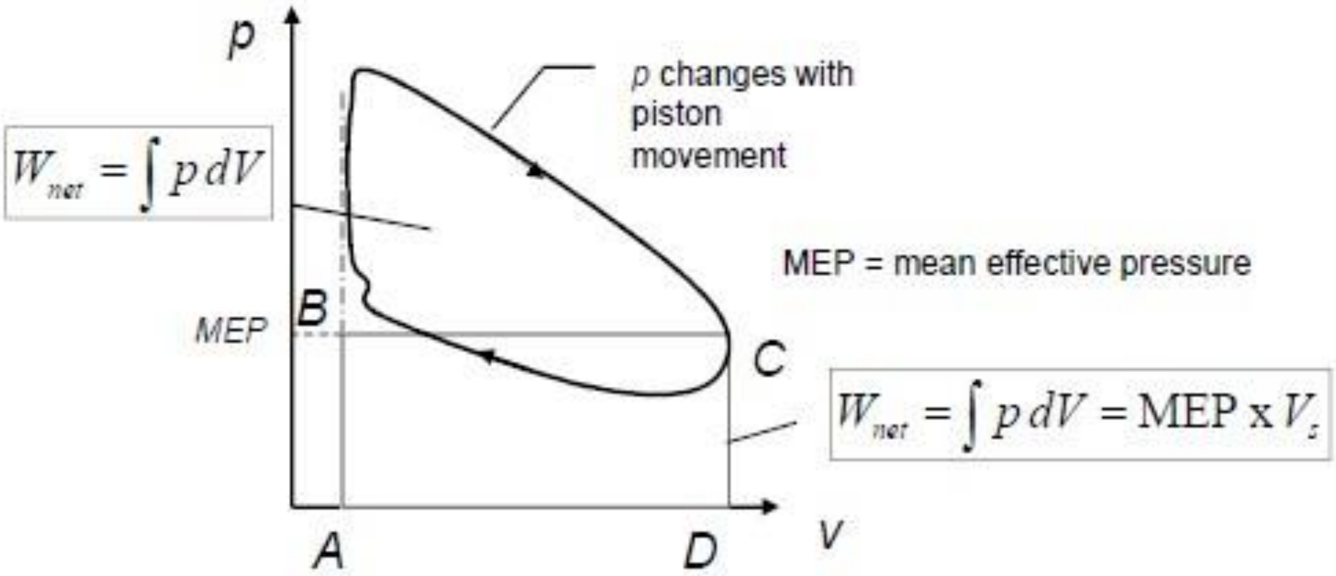


Mean Effective Pressure, MEP



- Mean effective pressure (MEP) is a conceptual/fictitious pressure.
- If it acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.

PERFORMANCE CRITERIA



- For the same engines size, MEP can be used as a criteria or parameter to compare the engines performance.
- The engine with a larger value of MEP delivers more net work per cycle and thus performs better.

PERFORMANCE CRITERIA

$$
\begin{aligned}
Work &= \text{force x distance} \\
&= F \text{ x } L \\
&= PA \text{ x } L \\
&= P \text{ x } AL \\
&= P \text{ x } V
\end{aligned}
$$

ie. $W_{net} = \text{MEP x displacement volume}, V_s$

$$\therefore \quad \text{MEP} = \frac{W_{net}}{V_s} = \frac{W_{net}}{V_{\max} - V_{\min}}$$

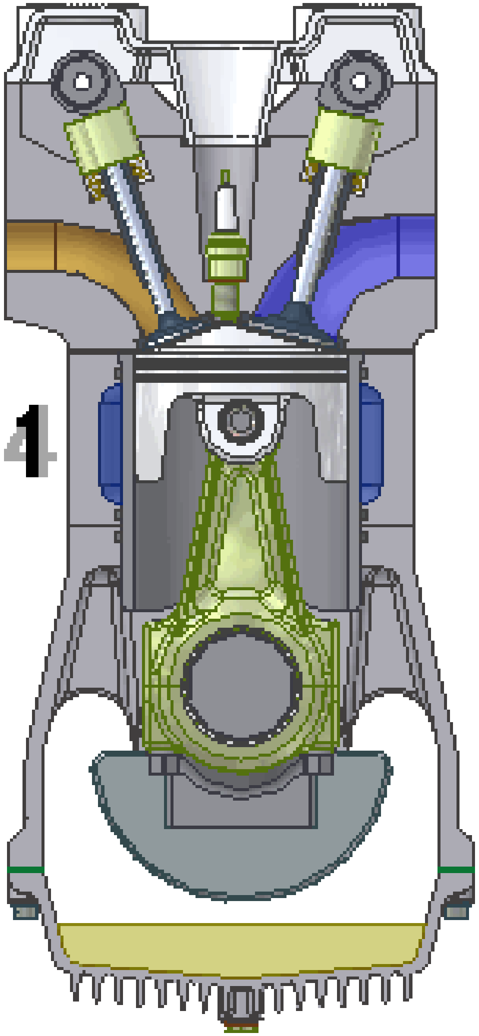
CLASSIFICATION BY CYCLES

Reciprocating internal combustion engines operate either on two-stroke or four-stroke cycle.

Four-stroke Cycle

- Most automotive engines operate on a 4-stroke cycle.
- Every fourth piston stroke is the power stroke.
- The crankshaft makes two revolutions to complete the cycle.

CLASSIFICATION BY CYCLES



4-Stroke

1. Requires 4 stroke of piston to complete a cycle

   1-2 Induction stroke

   Inlet valve open. Exhaust valve is closed. BDC to TDC. Air + fuel is induced.

   2-3 Compression stroke

   Air + fuel is compressed to TDC. Spark occurred at S and combustion occurs mainly at constant volume. Large increase in pressure and temperature.

   3-4 Working stroke

   Hot gas expand pushing the piston down to BDC. Exhaust valve open at E to assist exhaustion. Inlet valve is still closed.

   4-1 Exhaust stroke

   The gas is force to exit the cylinder. Piston moved to TDC. Inlet valve is still closed.

2. 2 revolution of crank shaft per cycle

CLASSIFICATION BY CYCLES

Four-stroke Cycle

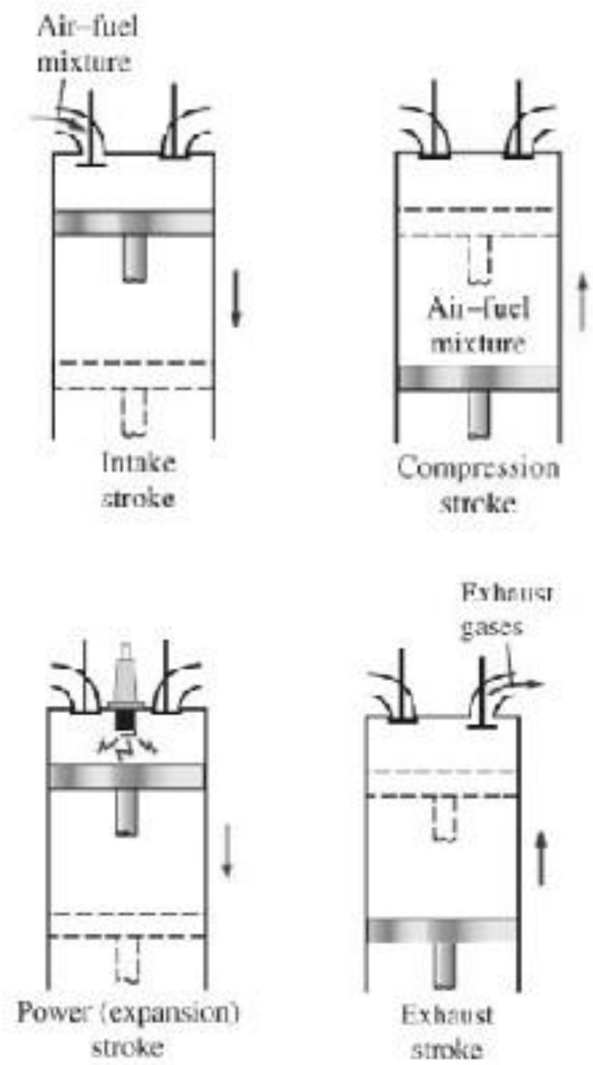
The sequence of events in this cycle is as follows:

1) Intake stroke: The intake valve opened. The piston moving downward, allowing the air fuel mixture to enter the cylinder.

2) Compression stroke: The intake valve closed. The piston is moving upward, compressing the mixture.

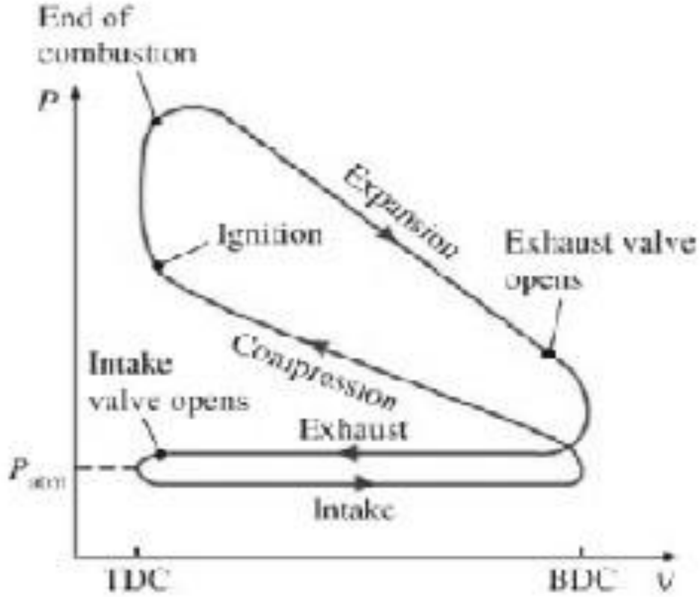
3) Power stroke: The ignition system delivers a spark to the spark plug to ignite the compressed mixture. As the mixture burns, it creates high pressure that pushes the piston down.

4) Exhaust stroke: The exhaust valve opened. The piston moves upward as the burned gases escape from the cylinder.

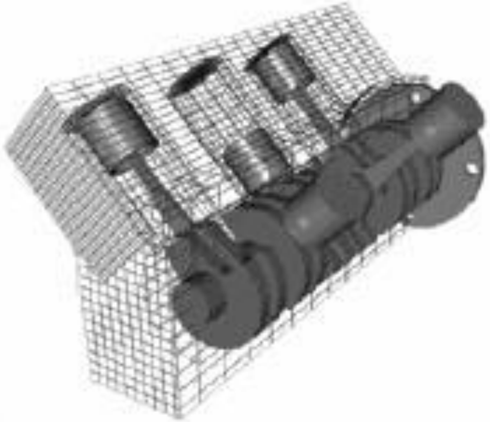


CLASSIFICATION BY CYCLES

- The ignition occurs before the compression process end.
  $P_{sys} > P_{atm}$ during the exhaust stroke.
- $P_{sys} < P_{atm}$ during the intake stroke.

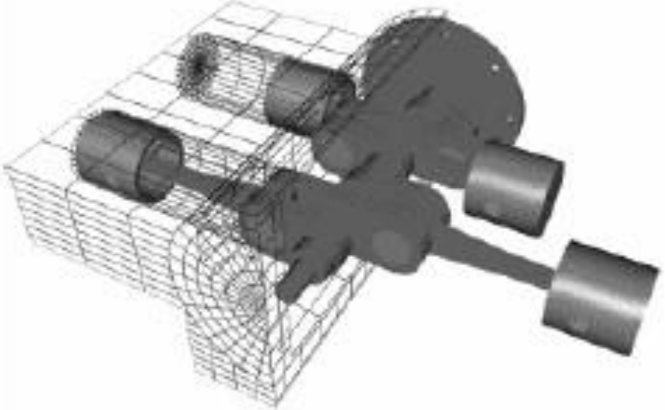


CLASSIFICATION BY CYCLES



The cylinders are arranged in 2 banks set at an angle to one another

The cylinders are arranged in a line in a single bank

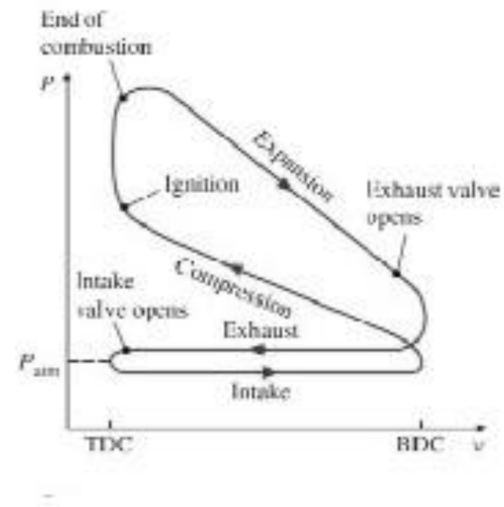


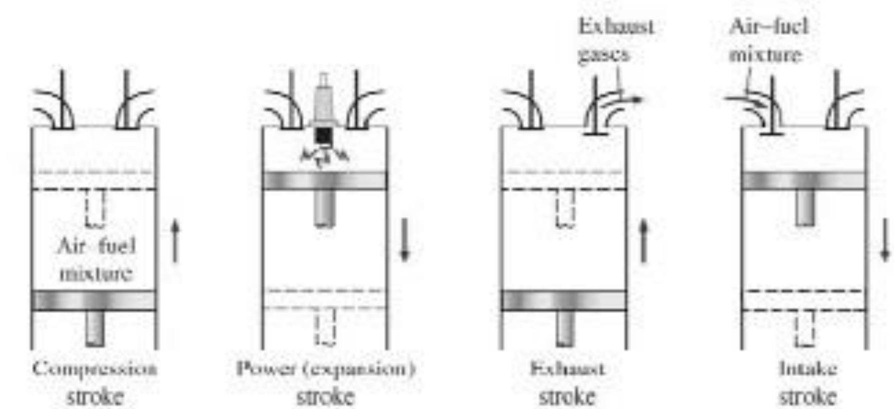
The cylinders are arranged in 2 banks on opposite sides of the engine

THE AIR STANDARD CYCLES

Actual Cycles

- Difficult to analyze due to the presence of complicating effects, such as friction.
- The working fluid remains a gas throughout the entire cycle, therefore involves chemical analysis, causes more complicated analysis.
- The engines obtain energy from the burning fuel within the system boundaries.
- The working fluid does not undergo a complete thermodynamic cycle, it is thrown out of the engine at some point in the cycle (as exhaust gases) instead of being returned to the initial state.
- Working on an open cycle.





(a) Actual four stroke spark ignition engine

Ideal Cycle

- To make an analytical study of a cycle practicable, the complexities are kept at a manageable level and utilize some idealizations.
- Models developed from these idealizations are simple and able to study the effects of major parameters towards actual engines performance, since they still retain the general characteristics of the actual engines they represent.
- Such a cycle is called an ideal cycle.

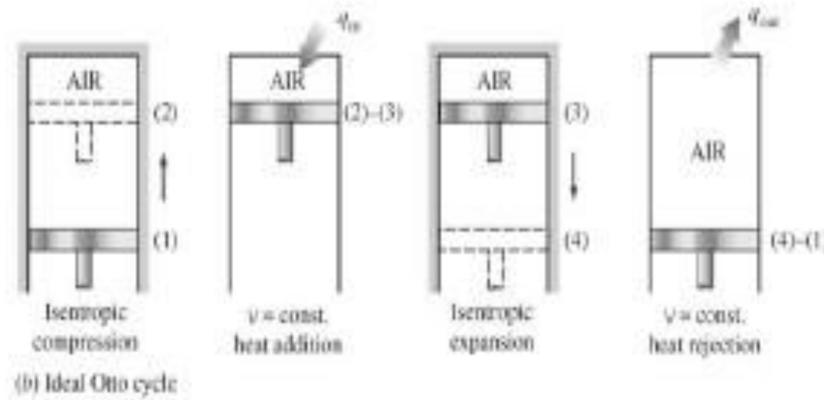
THE AIR STANDARD CYCLES

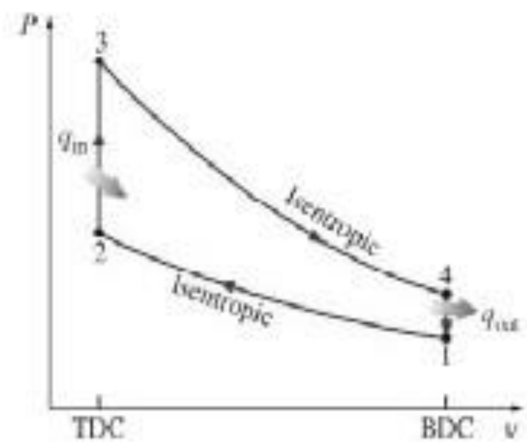
- Ideal cycles utilize some approximations as follows:

1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
2. All the processes that make up the cycle are internally reversible.
3. The combustion process is replaced by a heat-addition process from an external source.
4. The exhaust gas is replaced by a heat-rejection process that restores the working fluid to its initial state.

- Those assumptions are called <u>air-standard assumptions</u>.

Another assumption is to assume air has constant specific heats whose values are determined at room temperature, 300K. This assumption is called <u>cold-air-standard assumption</u>





Carnot Cycle

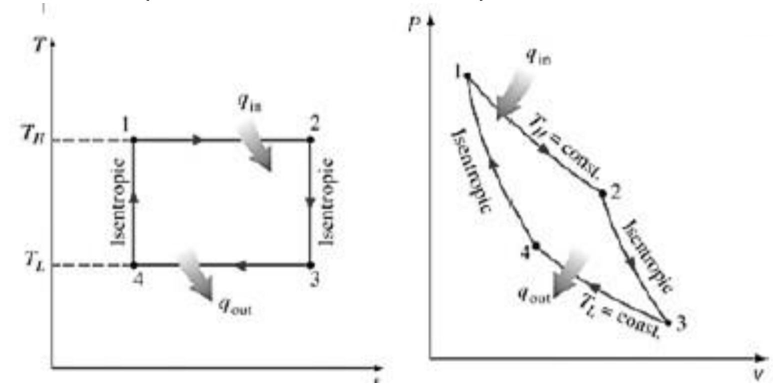
Recall -The Carnot Cycle

- Is the most efficient cycle that can be executed between a heat source, T_H and a heat sink, T_L
- Operate on a totally reversible cycle.

The Carnot cycle is composed of 4 reversible processes:

1 - 2: isothermal heat addition
2 – 3: isentropic expansion
3 – 4: isothermal heat rejection
4 – 1: isentropic compression

$$\eta_{th_{carnot}} = 1 - \frac{T_L}{T_H}$$



Why do we not use the Carnot cycle as the model cycle for all heat engines?

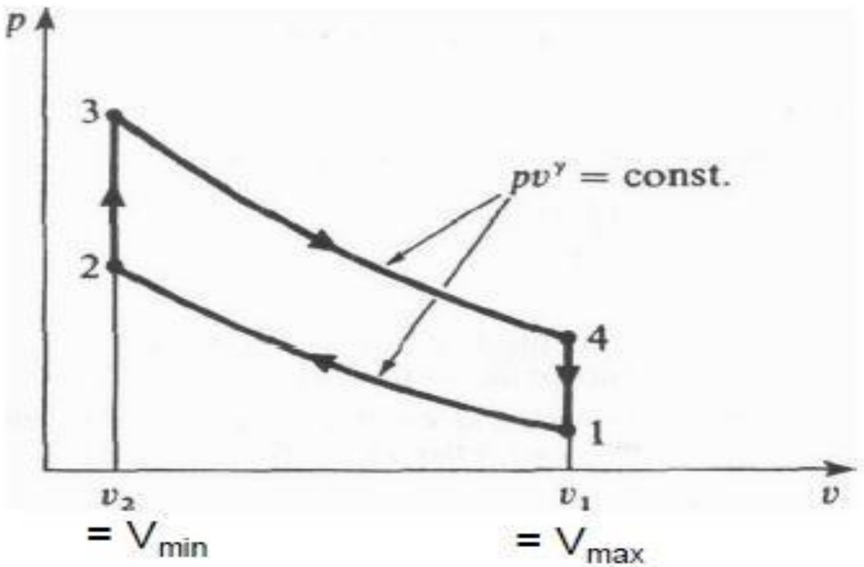
- Hard-ware related.
- Reversible isothermal heat transfer is very difficult to achieve in reality since it would require very large heat exchanger and it would take a very long time.

Why do we bother with the Carnot cycle?

The thermal efficiency relation for the Carnot cycle conveys an important message that is equally applicable to both ideal and actual cycle: thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system.

The Otto Cycle

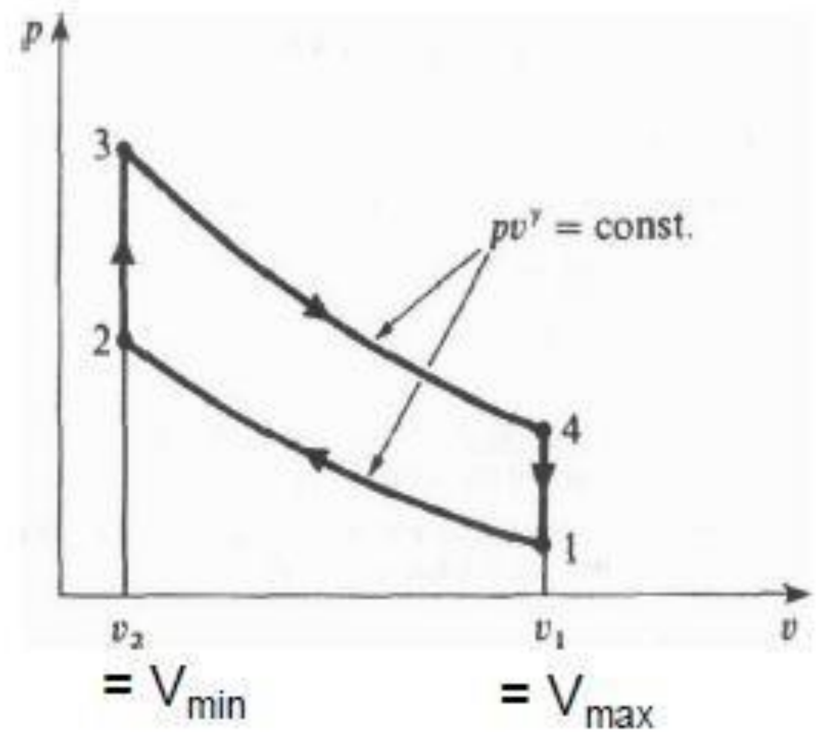
- The ideal cycle, which closely resembles the actual operating conditions of spark-ignition (SI), or petrol engine, or gas engine, or high-speed oil engines, is the Otto cycle.
- The cycle is shown on a pressure- volume (p-v) diagram.



THE AIR STANDARD CYCLES

The Process Sequence

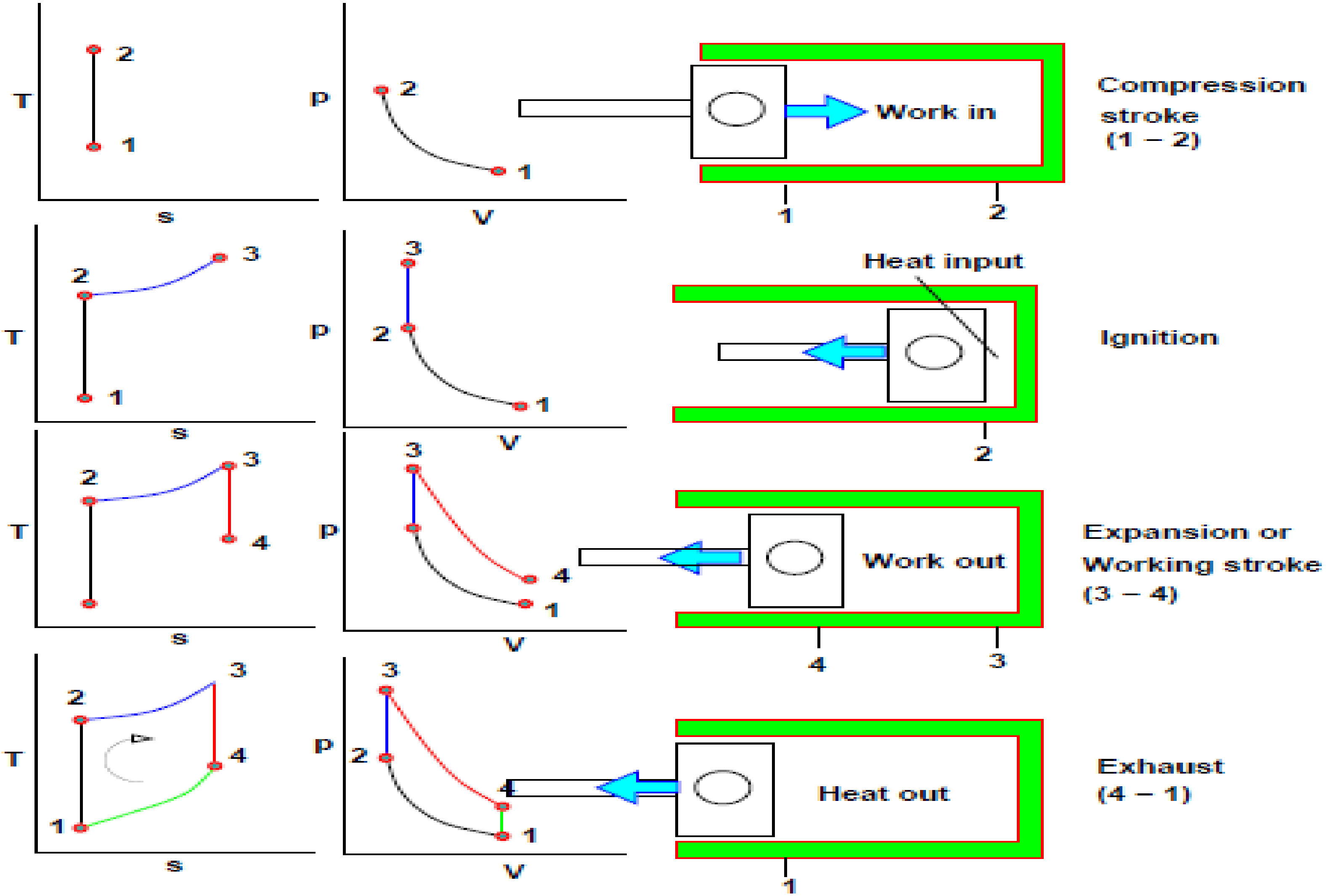
It consists of four internally reversible processes: 1-2 Isentropic compression; 2-3 Constant-volume heat addition 3-4 Isentropic expansion; 4-1 Constant-volume heat rejection



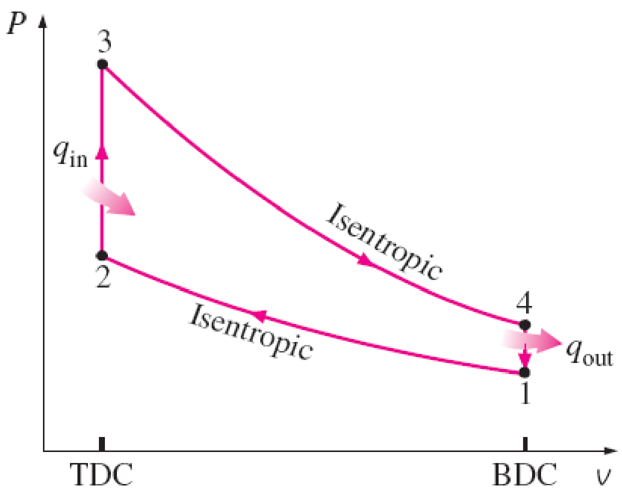
Note:
In the Otto cycle, the working fluid is alternate expanded and compressed in a piston-cylinder device, therefore, equations pertaining to closed systems are used in the analysis.

THE AIR STANDARD CYCLES

Otto Cycle



Thermal Efficiency of Otto Cycle



The **heat supplied** to the working fluid during constant-volume heating (combustion),

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$

The **heat rejected** from the working fluid during constant-volume cooling (exhaust),

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1} = \left(\frac{v_3}{v_4}\right)^{k-1} = \frac{T_4}{T_3}$$

efficiency

$$\eta_{th,Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}}$$

Cold-air standard assumption.

Compression ratio,

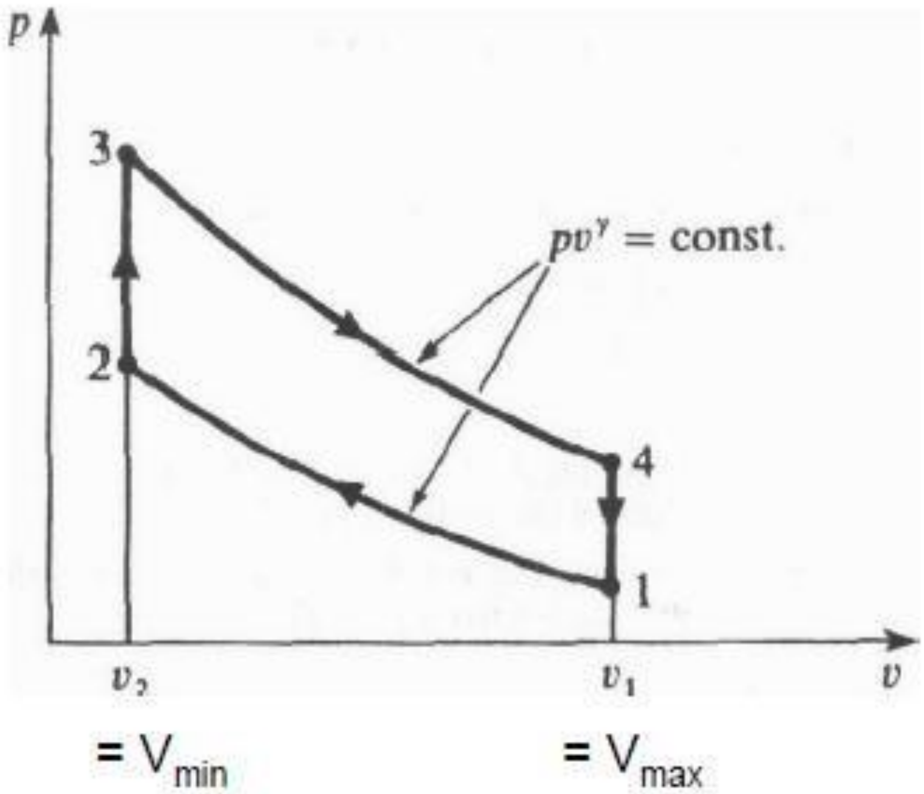
$$r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$

THE AIR STANDARD CYCLES

The Otto Cycle Analysis

Compression / expansion index under the <u>cold air-standard assumptions</u>

$$k = \frac{c_p}{c_v}$$

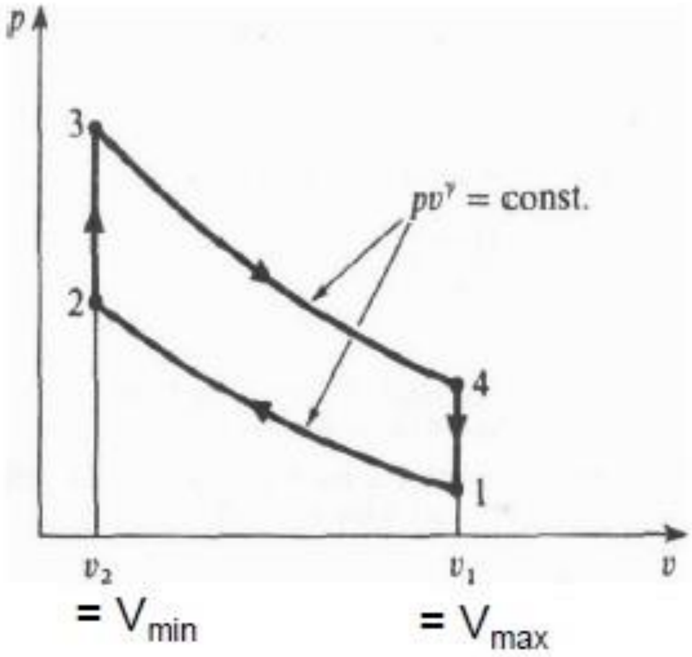


The Otto Cycle Analysis

$$\text{Compression ratio} = \frac{\text{Maximum volume}}{\text{Minimum volume}}$$

$$= \frac{\text{Clearance volume} + \text{Swept volume}}{\text{Clearance volume}}$$

ie. $$r_v = \frac{v_1}{v_2} = \frac{V_1}{V_2}$$



THE AIR STANDARD CYCLES

Under the <u>cold-air standard assumptions</u>, the relations between 'initial' and 'final' states of isentropic expansion process or isentropic compression process can be related by the following equations.

Ideal Gas Equations

1) $pv = RT$

2) $\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$

3) $\frac{v_1}{v_2} = \left(\frac{p_2}{p_1}\right)^{\left(\frac{1}{k}\right)}$

4) $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\left(\frac{k-1}{k}\right)}$

5) $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{(k-1)}$

THE AIR STANDARD CYCLES

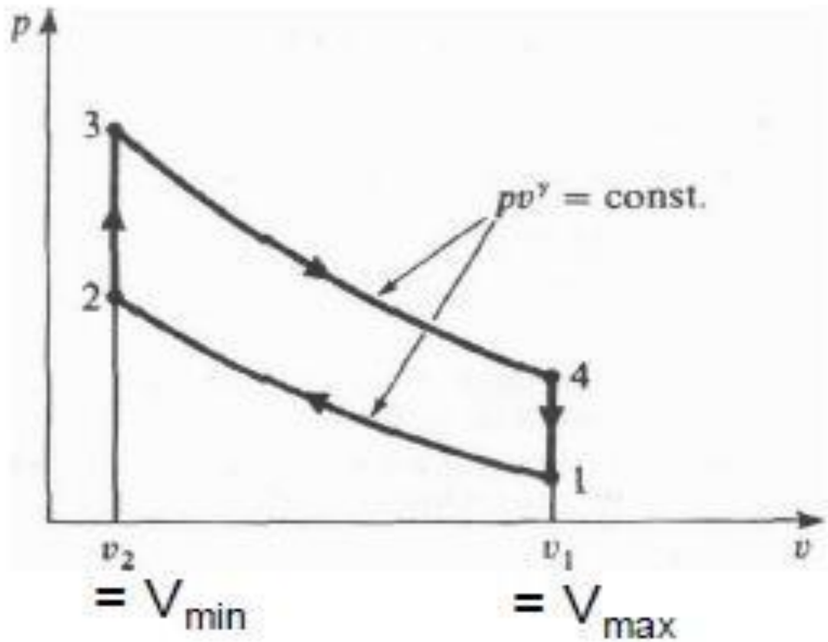
The Otto Cycle Analysis

Thermal efficiency of the ideal Otto cycle under the cold air-standard assumptions

$$\eta_{otto} = \frac{W_{net}}{Q_{supply}} = \frac{Q_{23} - Q_{41}}{Q_{23}}$$

$$= 1 - \frac{Q_{41}}{Q_{23}}$$

$$= 1 - \frac{m\,c_v(T_4 - T_1)}{m\,c_v(T_3 - T_2)}$$



$$\therefore \quad \eta_{otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

THE AIR STANDARD CYCLES

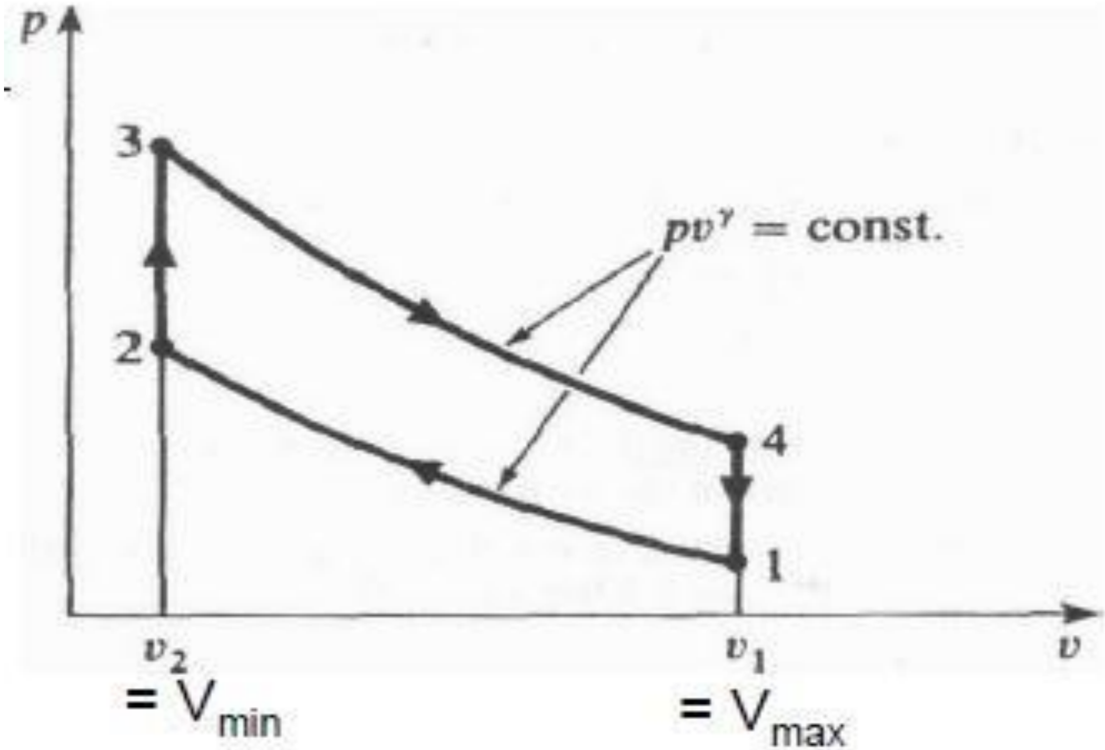
The Otto Cycle Analysis

Since processes 1-2 and 3-4 are both isentropic (under the cold air- standard assumptions), then,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

and

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{k-1}$$

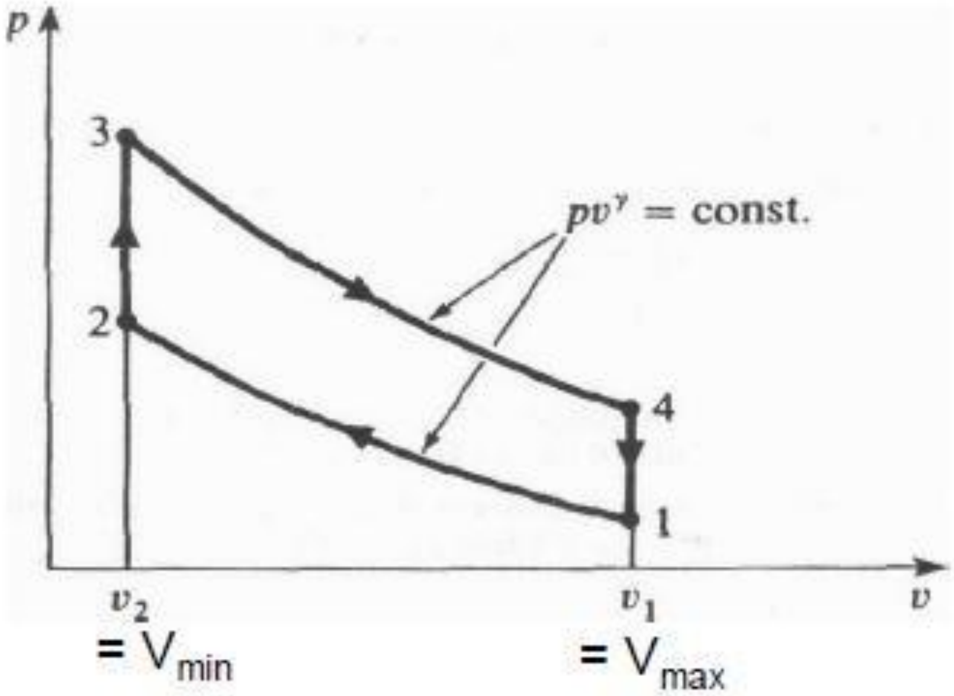


The Otto Cycle Analysis

But,

$$v_4 = v_1 \text{ and } v_3 = v_2$$

$$\frac{T_3}{T_4} = \left(\frac{v_1}{v_2}\right)^{k-1} = \frac{T_2}{T_1}$$



THE AIR STANDARD CYCLES

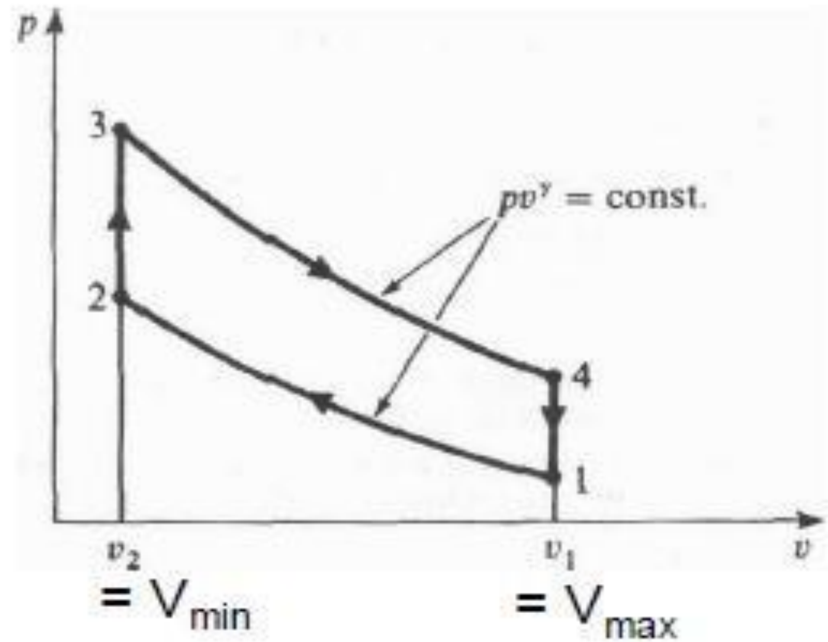
The Otto Cycle Analysis

Thermal efficiency of the ideal Otto cycle under the cold air-standard assumptions

$$\eta_{otto} = \frac{W_{net}}{Q_{supply}} = \frac{Q_{23} - Q_{41}}{Q_{23}}$$

$$= 1 - \frac{Q_{41}}{Q_{23}}$$

$$= 1 - \frac{m\,c_v(T_4 - T_1)}{m\,c_v(T_3 - T_2)}$$



$$\therefore \quad \eta_{otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

THE AIR STANDARD CYCLES

The Otto Cycle Analysis

ie., $\dfrac{T_3}{T_4} = \dfrac{T_2}{T_1}$ rearrange $\dfrac{T_2}{T_3} = \dfrac{T_1}{T_4}$

or $1 - \dfrac{T_2}{T_3} = 1 - \dfrac{T_1}{T_4}$

or $\dfrac{T_3 - T_2}{T_3} = \dfrac{T_4 - T_1}{T_4}$

or $\dfrac{(T_4 - T_1)}{(T_3 - T_2)} = \dfrac{T_4}{T_3}$

$$\therefore\ \eta_{otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_4}{T_3} = 1 - \frac{1}{\left(\dfrac{v_1}{v_2}\right)^{k-1}}$$

ie., $\eta_{\text{otto}} = 1 - \dfrac{1}{(r_v)^{k-1}}$

The above equation is only valid for the ideal Otto cycle under <u>the cold air-standard assumptions</u>.

The above equation shows that under the cold air- standard assumptions, the thermal efficiency of an ideal Otto cycle depends on the compression ratio of the engine and the specific heat ratio of the working fluid.

THE AIR STANDARD CYCLES

The Otto Cycle Analysis

Summary

$$\eta_{otto} = \frac{W_{net}}{Q_{in}} \quad \cdots \text{basic}$$

$$\eta_{otto} = 1 - \left(\frac{T_4 - T_1}{T_3 - T_2} \right) \quad \cdots \text{function of temperatures}$$

$$\eta_{otto} = 1 - \frac{1}{r_v^{k-1}} \quad \cdots \text{function of compression ratio and index } k$$

These two equations are only valid for the ideal Otto cycle under the cold air-standard assumptions.

Example

An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 95 kPa and 27°C, and 750 kJ/kg of heat is transferred to air during the constant-volume heat-addition process.

Under the cold air- standard assumptions, determine,

a) the pressure and temperature at the end of the heat addition;
b) the net work output;
c) the thermal efficiency;
d) the mean effective pressure for the cycle.

Example

The compression ratio of an air-standard Otto cycle is 9.5. Prior to the isentropic compression process, the air is100 kPa, 35°C, and 600 cm^3. The temperature at the end of the isentropic expansion process is 800 K.

Using specific heat values at room temperature, determine:

(a) the highest temperature and pressure in the cycle;

(b) the amount of heat transferred in, in kJ;

(c) the thermal efficiency; and

(d) the mean effective pressure.

Example

An Otto cycle has an inlet pressure and temperature of 100 kN/m^2 and 17 ^oC respectively. The compression ratio is 8/1. If 800 kJ/kg heat is supplied to the system at constant volume calculate,

a) The maximum cycle temperature;

b) The maximum cycle pressure;

c) The net work;

d) The engine thermal efficiency;

e) The mean effective pressure.

For air, $c_v = 0.718$ kJ/kgK and $k = 1.4$.

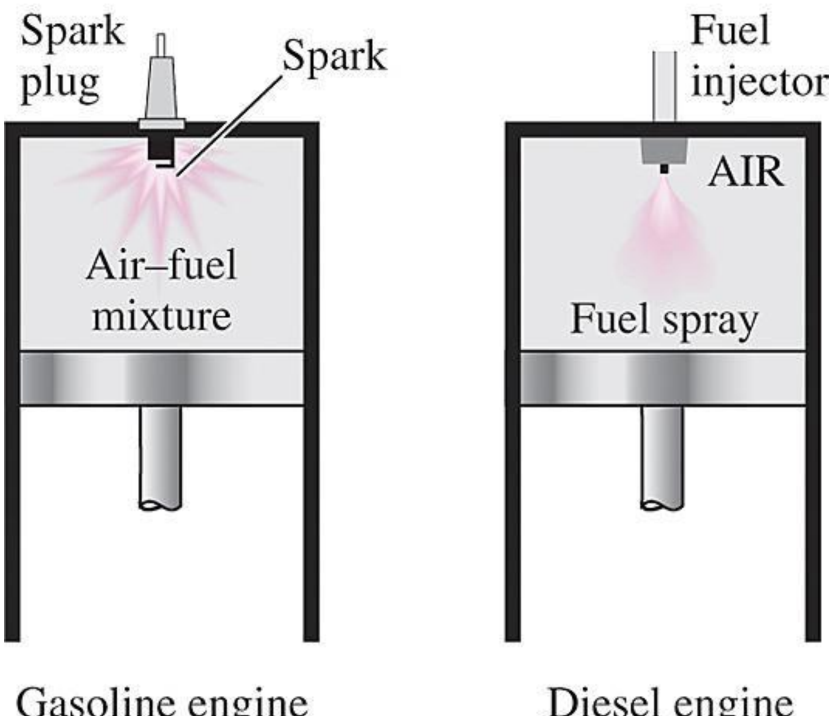
Example

An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The minimum and maximum temperature in the cycle are 300 and 1340 K. Accounting for the variation of specific heats with temperature, determine,

a. the amount of heat transferred to the air during the heat-addition process
b. the thermal efficiency, and
c. the thermal efficiency of a Carnot cycle operating between the same temperature limits

Diesel Cycle: Ideal Cycle for CI Engines

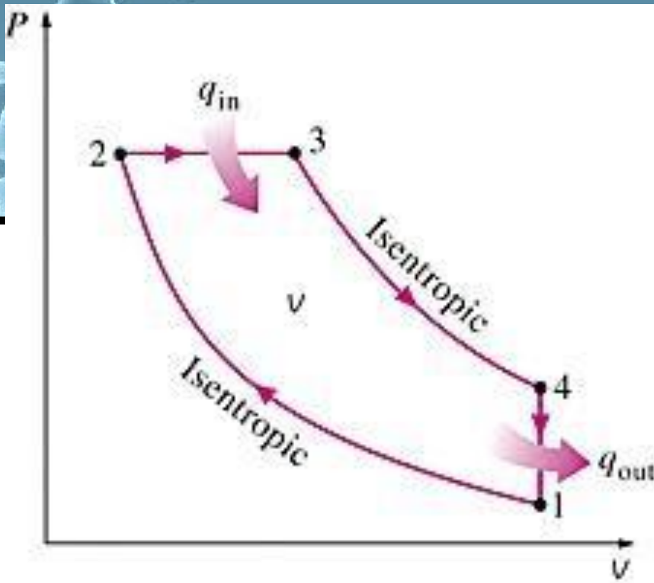
- In diesel engines, **only air** is compressed during the compression stroke, eliminating the possibility of autoignition. These engines can be designed to operate at higher compression ratios, typically between **12** and **24**.
- Fuels that are **less refined** (thus less expensive) can be used in diesel engines.



The combustion process takes place over a **longer** interval - fuel injection starts when the piston approaches TDC and continues during the first part of power stroke.

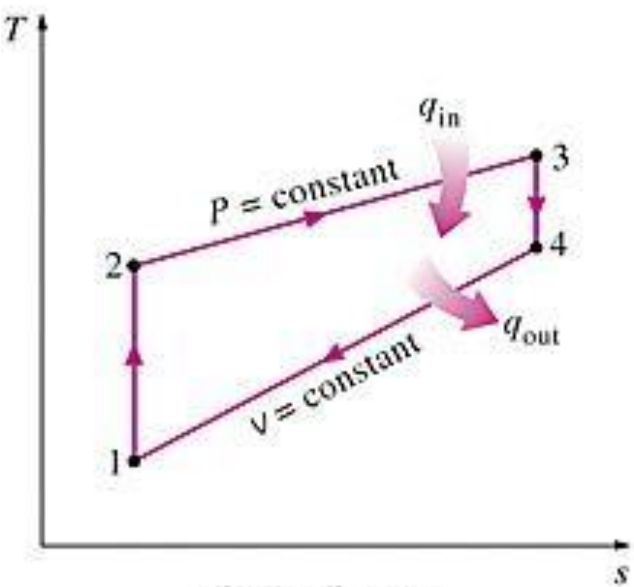
Hence, **combustion** process in the ideal Diesel cycle is approximated as a **constant-pressure** heat-addition process.

Sequence of processes:



(a) P- v diagram

1-2	Isentropic compression
2-3	Constant-pressure heat addition
3-4	Isentropic expansion
4-1	Constant-volume heat rejection.



(b) T-s diagram

Note:

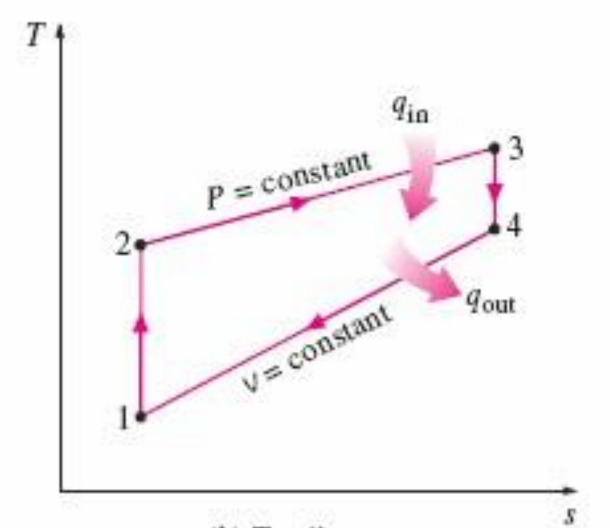
Petrol and diesel engines differ only in the manner the heat addition (or combustion) process takes place.

It is approximated as a constant volume process in the petrol engine cycle and as a constant pressure process in the Diesel engine cycle.

FIGURE 9–21

T-s and *P-v* diagrams for the ideal Diesel cycle.

Thermal Efficiency of Diesel Cycle



(b) T-s diagram

Heat supplied to the working fluid during the constant-pressure heating (combustion),

$$q_{in} = P_2(v_3 - v_2) + (u_3 - u_2)$$
$$= h_3 - h_2 = c_p(T_3 - T_2)$$

Heat rejected from the working fluid during the constant-volume cooling (exhaust),

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

Thermal efficiency of Diesel cycle (general),

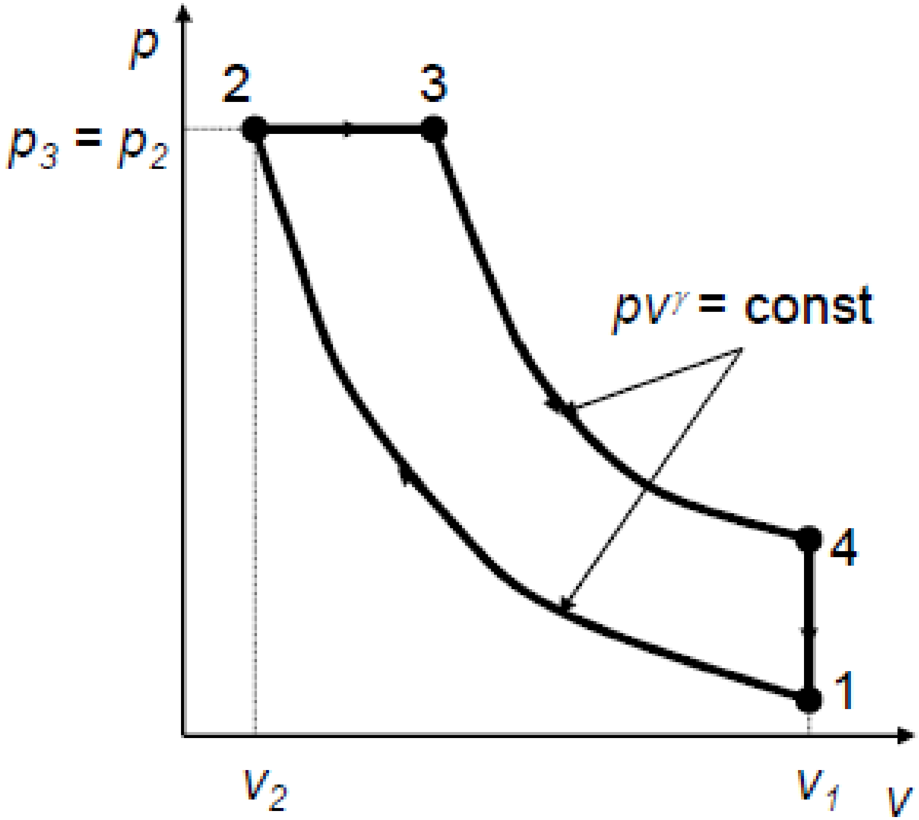
$$\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$ - constant specific heats

$$r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$$

The Diesel Cycle

Diesel cycle is an ideal air-standard cycle for compression-ignition (CI) engines.



THE AIR STANDARD CYCLES

The Diesel Cycle

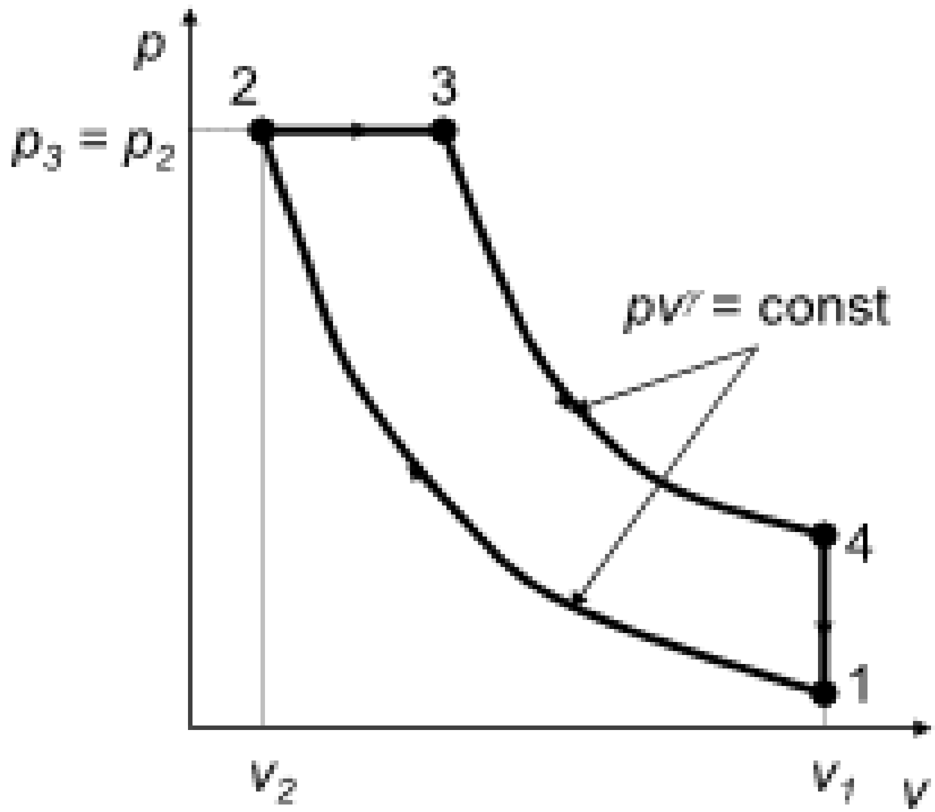
The Process Sequence

The processes making up the air-standard Diesel cycle are,

1-2 Isentropic compression

2-3 Constant pressure heat addition 3-4 Isentropic expansion

4-1 Constant volume heat rejection

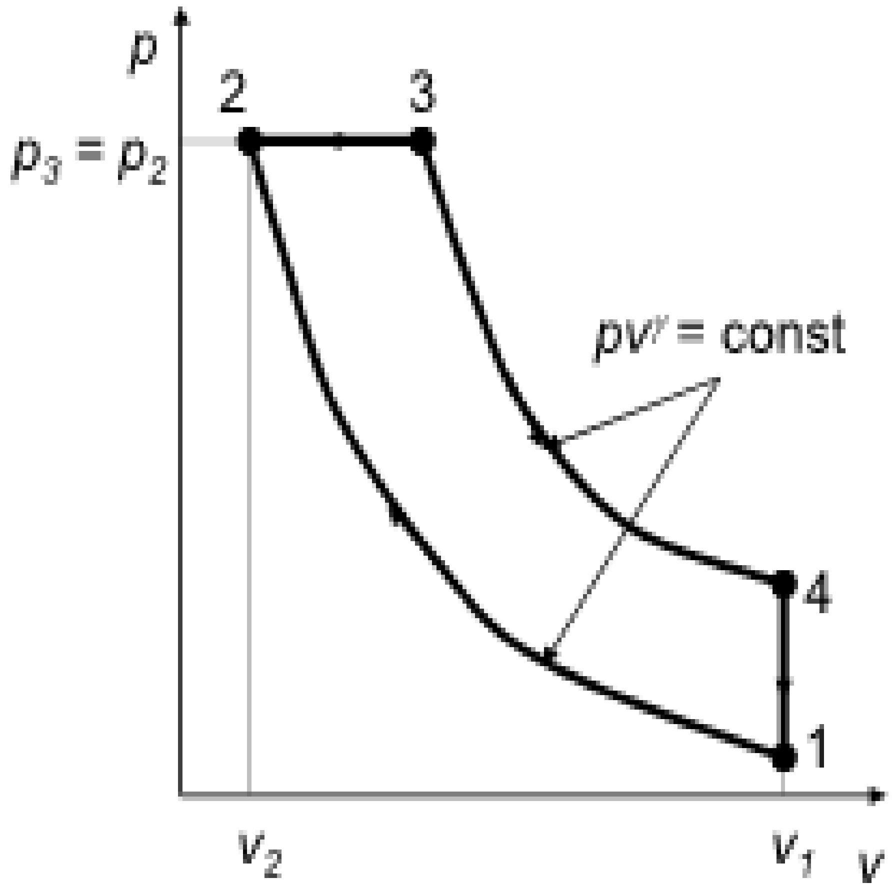


THE AIR STANDARD CYCLES

The Diesel Cycle Analysis

Compression / expansion index under the <u>cold</u> <u>air-standard assumptions</u>

$$k = \frac{c_p}{c_v}$$



THE AIR STANDARD CYCLES

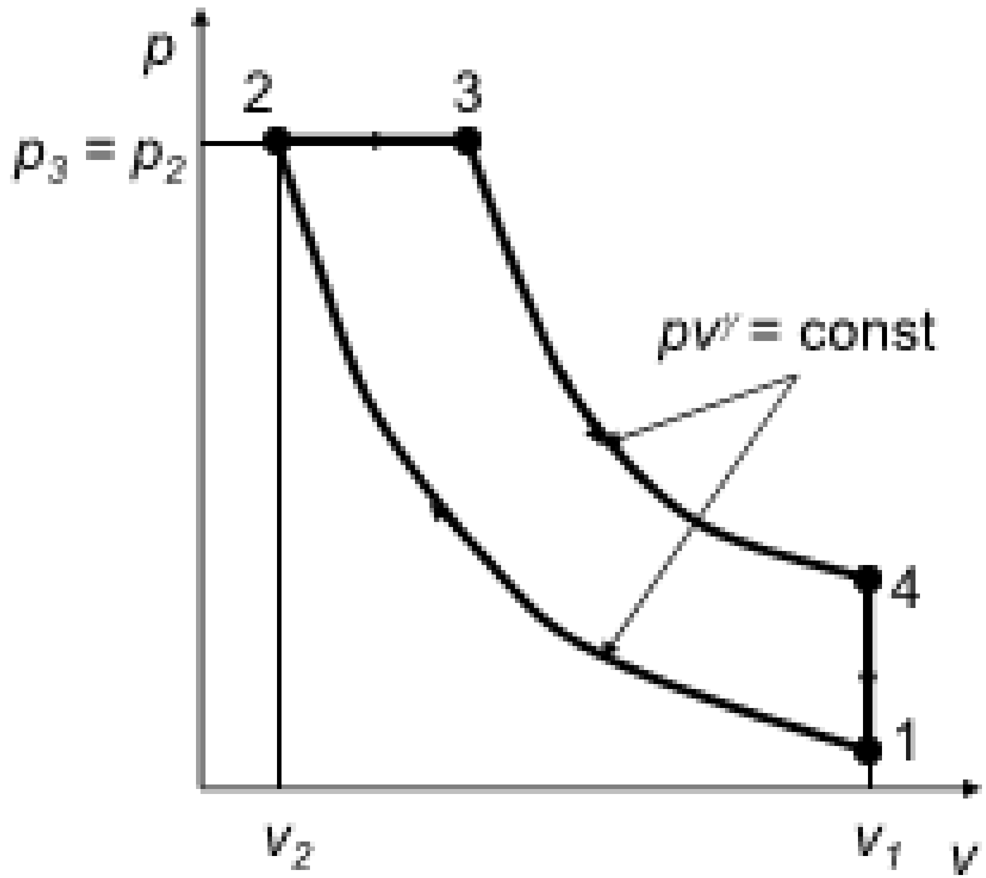
The Diesel Cycle Analysis – under the cold air-standard assumptions

Heat added to the engine

$$Q_{23} = m.c_p\left(T_3 - T_2\right)$$

Heat rejected from the engine

$$Q_{41} = m.c_v\left(T_4 - T_1\right)$$



The Diesel Cycle Analysis

Thermal efficiency under <u>the cold air-standard assumptions</u>

$$\eta_{Diesel} = \frac{W_{net}}{Q_{in}} \quad \text{or} \quad \eta_{Diesel} = \frac{Q_{23} - Q_{41}}{Q_{23}} \quad \cdots \text{ basic}$$

or

$$\eta_{Diesel} = 1 - \frac{Q_{41}}{Q_{23}} = 1 - \frac{m.c_v\left(T_4 - T_1\right)}{m.c_p\left(T_3 - T_2\right)} = 1 - \frac{\left(T_4 - T_1\right)}{k\left(T_3 - T_2\right)}$$

ie.,

$$\boxed{\eta_{Diesel} = 1 - \frac{\left(T_4 - T_1\right)}{k\left(T_3 - T_2\right)}} \quad \text{function of temperatures}$$

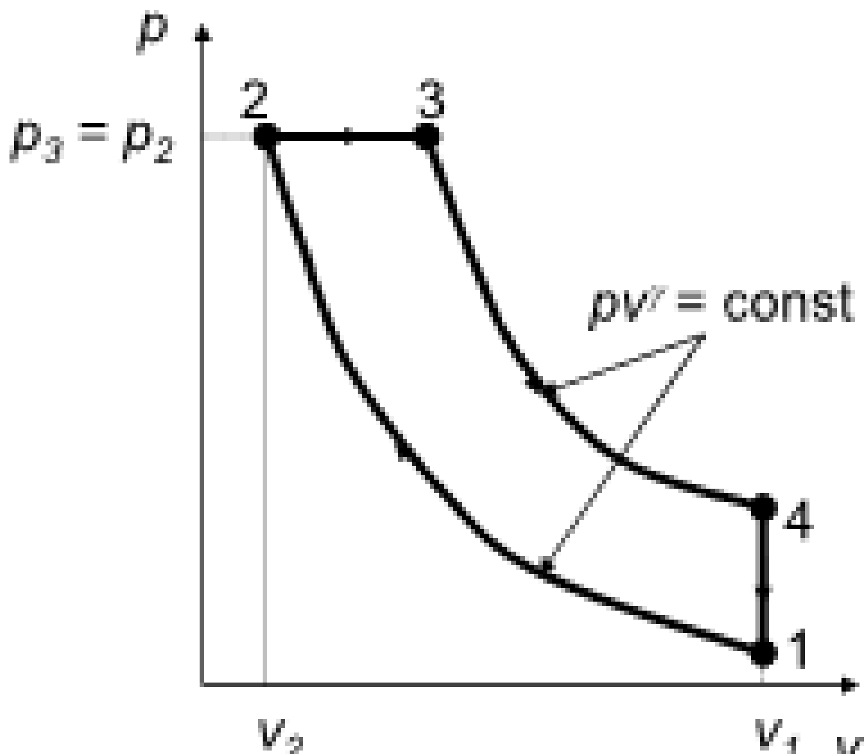
The Diesel Cycle Analysis

Thermal efficiency in terms of compression ratio r_v and cut-off ratio, r_c - under the <u>cold air-standard assumptions</u>

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} \rightarrow T_1 = \frac{T_2}{\left(\frac{v_1}{v_2}\right)^{k-1}} \rightarrow T_1 = \frac{T_2}{r_v^{k-1}}$$

$$\boxed{\frac{T_3}{T_2} = \frac{v_3}{v_2} = r_c}$$ ... cut - off ratio for isobaric process $2 \rightarrow 3$

ie $T_3 = T_2 r_c$



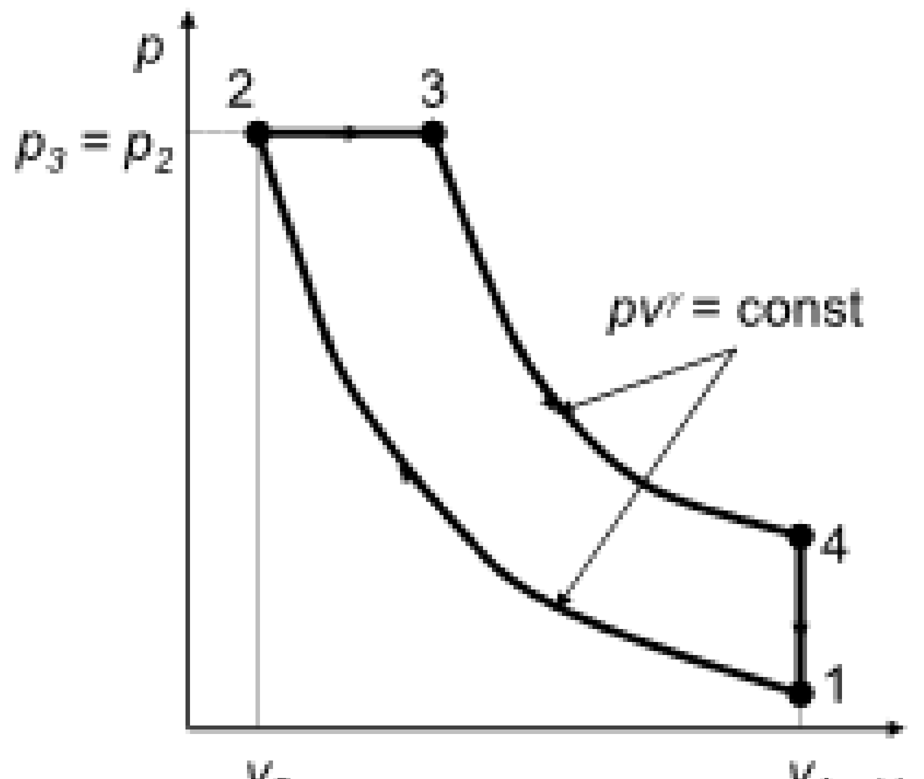
The Diesel Cycle Analysis

Thermal efficiency in terms of compression ratio r_v and cut-off ratio, r_c - under the <u>cold air-standard assumptions</u>

$$\text{Also, } \frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{k-1} = \left(\frac{v_3}{v_2}\, x\, \frac{v_2}{v_4}\right)^{k-1} = \left(\frac{r_c}{r_v}\right)^{k-1}$$

$$\text{ie } T_4 = T_3\left(\frac{r_c}{r_v}\right)^{k-1} = T_2\, r_c \left(\frac{r_c}{r_v}\right)^{k-1} = T_2\left(\frac{r_c^{\,k}}{r_v^{\,k-1}}\right)$$

$$\therefore \quad \eta_{Diesel} = 1 - \frac{\left[r_c^{\,k} - 1\right]}{r_v^{\,k-1}\left[k\left(r_c - 1\right)\right]}$$



EXAMPLE

An ideal diesel engine has a compression ratio of 20 and uses air as the working fluid. The state of air at the beginning of the compression process is 95 kPa and 20°C. If the maximum temperature in the cycle is not to exceed 2200 K, determine:

a) the thermal efficiency, and

b) the mean effective pressure.

Assume constant specific heats for air at room temperature.

EXAMPLE

An air-standard Diesel cycle has a compression ratio of 16 and a cutoff ratio of 2. At the beginning of the compression process, air is at 95 kPa and 27°C. Accounting for the variation of specific heats with temperature, determine:

a) the temperature after the heat-addition process,
b) the thermal efficiency, and
c) the mean effective pressure.

THE AIR STANDARD CYCLES

For the same compression ratio, thermal efficiency of Otto cycle is **greater** than that of the Diesel cycle.

As the cutoff ratio decreases, the thermal efficiency of the Diesel cycle increases.

When r_c =1, *the* efficiencies of the Otto and Diesel cycles are identical.

$$\eta_{th,Otto} > \eta_{th,Diesel}$$

Thermal efficiencies of large diesel engines range from about **35 to 40** percent.

Higher efficiency and **lower fuel costs** make diesel engines attractive in applications such as in locomotive engines, emergency power generation units, large ships, and heavy trucks.

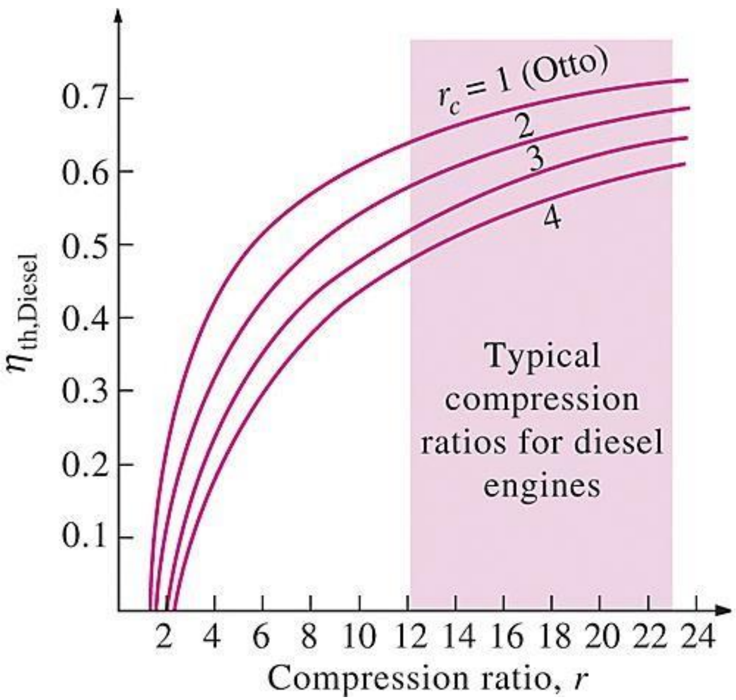


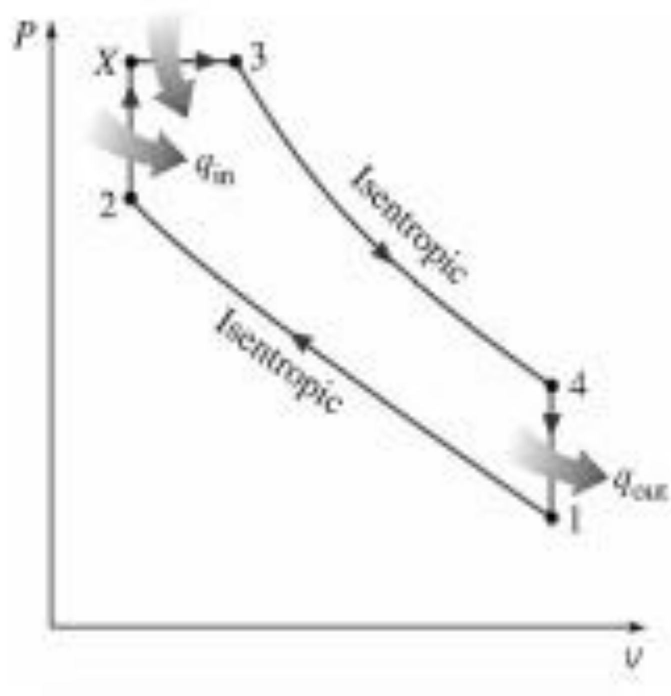
FIGURE 9–22

Thermal efficiency of the ideal Diesel cycle as a function of compression and cutoff ratios (k = 1.4).

THE AIR STANDARD CYCLES

Dual Cycle: Realistic Ideal Cycle for CI Engines

Approximating the combustion process as a constant-volume or a constant-pressure heat addition process is overly simplistic and not quite realistic.
A better approach would be to model the combustion process in both SI and CI engines as a combination of two heat- transfer processes, one at constant volume and the other at constant pressure.
The ideal cycle based on this concept is called the dual cycle.



Note: Both the Otto and the Diesel cycles can be obtained as special cases of the dual cycle.

THE AIR STANDARD CYCLES

- Known as the mixed cycle or semi-diesel cycle
- The working cycle of modern diesel engine invented by Ackroyd-stuart in 1888, where it is a combination of the otto and diesel cycle.

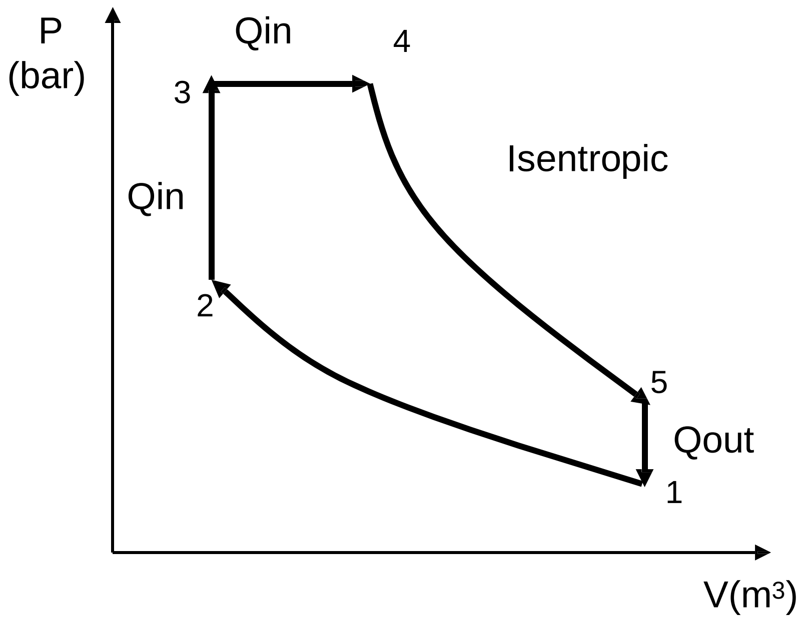
1-2: Isentropic compression (adiabatic and reversible)

2-3: Heat addition at constant volume

3-4: Heat addition at constant Pressure

4-5: Isentropic expansion

5-1: Heat rejection at constant volume



EXAMPLE

An air-standard Dual cycle has a compression ratio of 18 and a cutoff ratio of 1.1. The pressure ratio during constant volume heat addition process is 1.1. At the beginning of the compression process, air is at 90 kPa, 18°C and V is 0.003m^3. How much power will this cycle produce when it is executed 4000 times per minutes?

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