MCE535
Thermal Power and Propulsive Systems

Lecture 03: 28/09/2017

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Class: Thursday (3 – 5 pm)

Etiquettes and MOP

- Attendance is a requirement.
- There may be class assessments, during or after lecture.
- Computational software will be employed in solving problems
- Conceptual understanding will be tested
- Lively discussions are integral part of the lectures.

Lecture content

Gas Power Cycles:

- Basic considerations in power cycle analysis
- The Carnot cycle/Air-standard assumptions
- Otto Cycle: The ideal cycle for spark-ignition engines
- Diesel Cycle: The ideal cycle for compression ignition engines

Recommended Textbook:

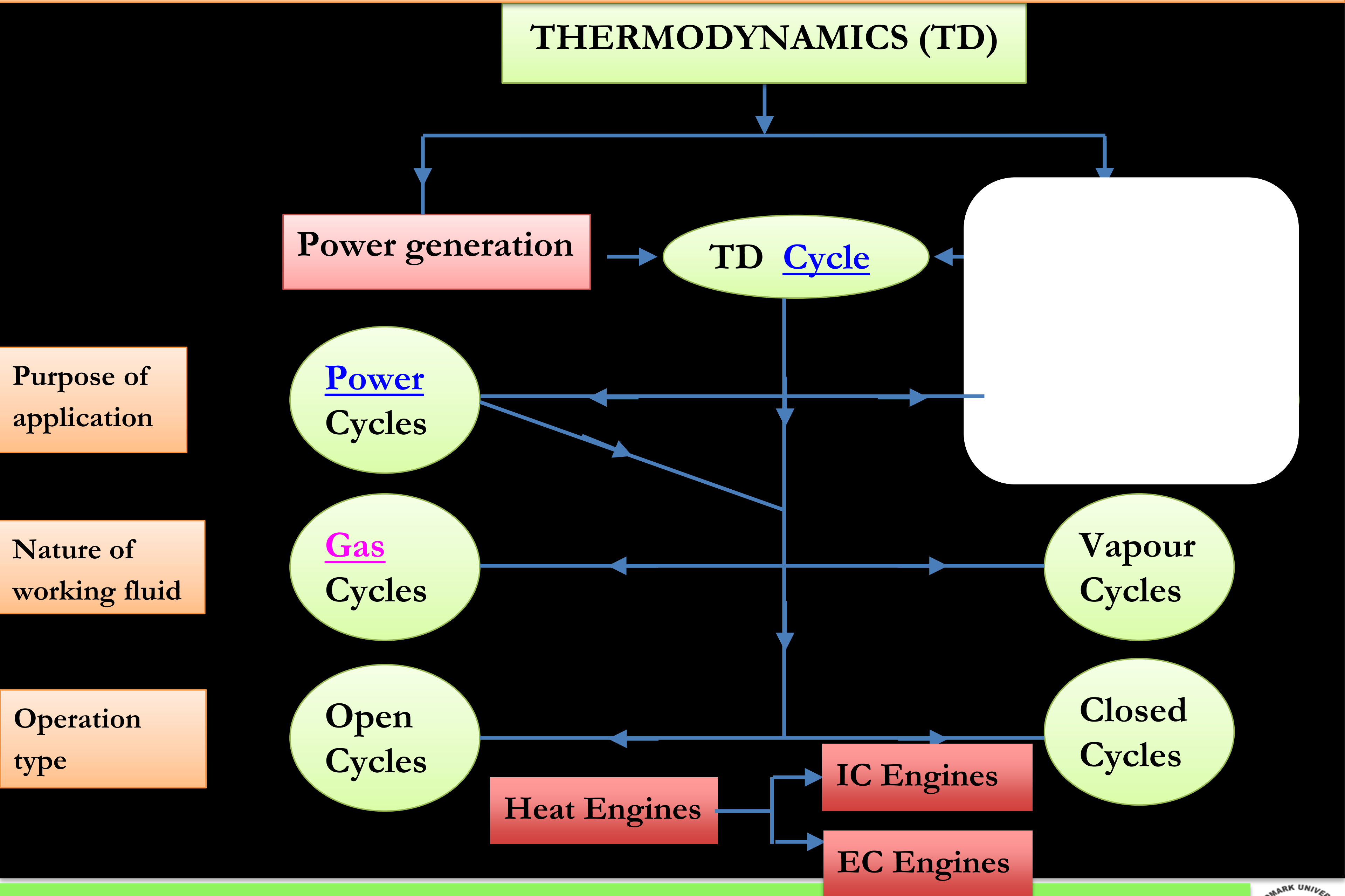
- Thermodynamics: An Engineering Approach by Cengel Y.A. & Boles M.A. 8th Edition

HANDS-ON ACTIVITY

- Nitrogen gas at 60 kPa and 7 °C enters an adiabatic diffuser steadily with a velocity of 275 m/s and leaves at 85 kPa and 278C. Determine (*a*) the exit velocity of the nitrogen and (*b*) the ratio of the inlet to exit area *A*1/*A*2.

- Reconsider the question above Using EES (or other) software, investigate the effect of the inlet velocity on the exit velocity and the ratio of the inlet-to-exit area. Let the inlet velocity vary from 210 to 350 m/s. Plot the final results against the inlet velocity, and discuss the results.

AN OVERVIEW OF THERMODYNAMIC CYCLES



POWER CYCLES: BASIC CONSIDERATIONS

- **Idealizations**: thermodynamic cycles are modeled as ideal cycles so as to simplify the analysis of actual cycles.
- The effects of major parameters are the emphases of ideal cycles allowing conclusions obtained thereof to be applicable to actual cycles.

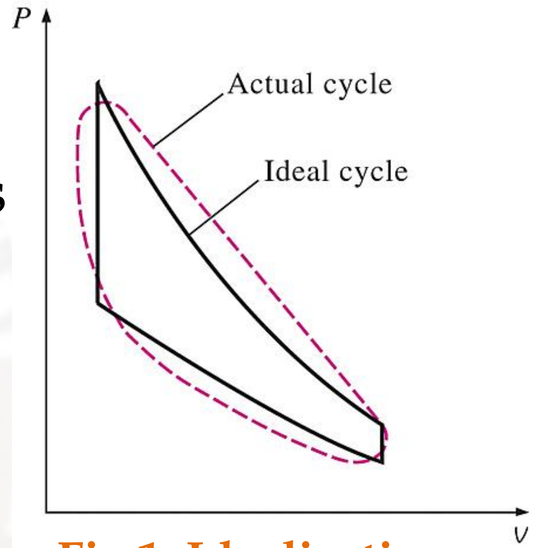


Fig 1: Idealization concept

- **Heat Engines (HE)** convert thermal energy to work. Their thermal efficiency, η_{th}, Eq.(P.1).

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad \text{or} \quad \eta_{th} = \frac{w_{net}}{q_{in}} \qquad \text{(P.1)}$$

- Pls note that heat engines, such as the **Carnot cycle**, that are totally reversible have the highest η_{th} of all HE operating between the same temperature levels

Why then don't we use Carnot cycle as the model cycle for all HE?

Summary of idealizations and simplifications used in power cycle analysis

1. The cycle does not involve any **friction**. Therefore, the working fluid does not experience any pressure drop as it flows in pipes or heat exchangers.
2. All expansion and compression processes take place in a **quasi-equilibrium** manner.
3. The pipes connecting the various components of a system are **well insulated**, so heat transfer through them is negligible.
4. Changes in the **kinetic** and **potential energies** of the working fluid are also negligible with the exception of *nozzles* and *diffusers*.

THE CARNOT CYCLE

- The Carnot cycle is the most efficient HE that can operate between a heat source at temperature, T_H, and a sink at temperature T_L and it consist of four reversible processes namely:

Carnot Cycle

Process	Description
1-2	Isothermal heat addition
2-3	Isentropic expansion
3-4	Isothermal heat rejection
4-1	Isentropic compression

- Thermal efficiency for Carnot cycle is shown in Eq.(P.2)

$$\eta_{th} = 1 - \frac{T_L}{T_H} \quad \text{(P.2)}$$

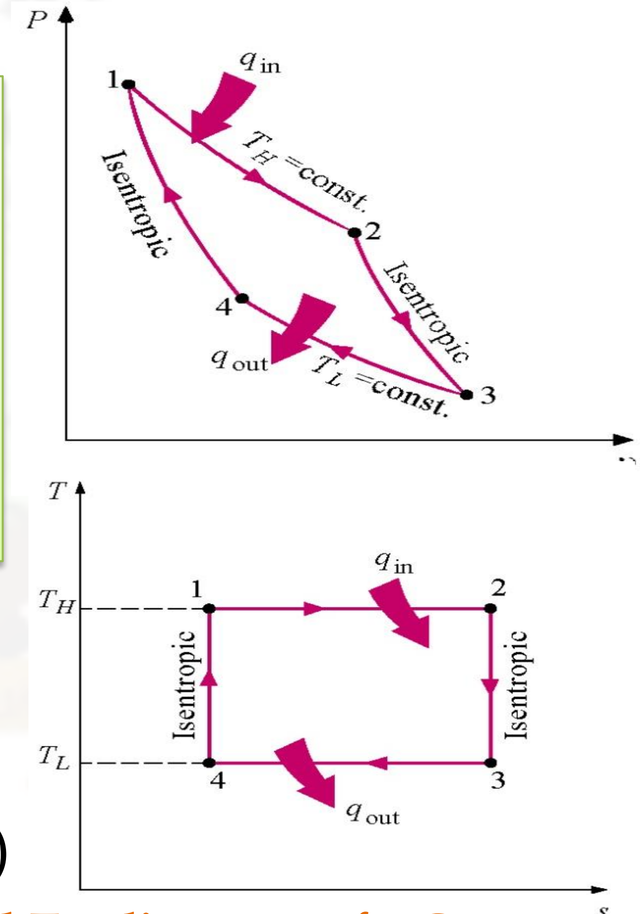


Fig 2: *P-v* and *T-s* diagrams of a Carnot cycle

LIST OF IDEAL AND ACTUAL CYCLES

- Table 1 is a list of ideal cycles and the actual cycles they represent.

Table 1: Ideal versus actual cycles and their applications

Working fluid nature	Ideal cycles	Actual cycles	Proponents	Application
Gas-power cycles	Otto cycle	Spark-ignition engine	Nikolaus Otto (1876)	Cars, small generators
	Diesel cycle	Compression-ignition engine	Rudolph Diesel (1890s)	Heavy-duty machines, trucks
	Brayton cycle	Gas-turbine engine	George Brayton (1870)	Light aircraft, Electric power generation
Vapour-power cycles	Rankine cycle	Steam power plant	William Rankine	Electric power generation

GAS POWER CYCLES: AIR-STANDARD ASSUMPTIONS

- Actual cycles are really complex; so some approximations, often referred to as **air-standard assumptions**, are made as follows.

Air-standard assumptions

- The working fluid, circulating in a closed loop, is air, and it behaves as an ideal gas.
- All the processes in the cycle are internally reversible.
- The combustion process is replaced by heat-addition from external source.
- The exhaust process is replaced by heat rejection to the surroundings and it restores working fluid to initial state.

- When it is assumed that air has constant specific heats and the values at room temperature (25°C) are used, then it is referred to as **cold-air-standard assumptions**.

GAS POWER CYCLES

- The heat engines used mostly in gas power cycles are reciprocating engines (RE).
- The following are useful terminologies in the study of RE: top dead center (TDC), bottom dead center (BDC), stroke, bore, intake valve, exhaust valve, clearance volume, displacement volume, compression ratio, and mean effective pressure.

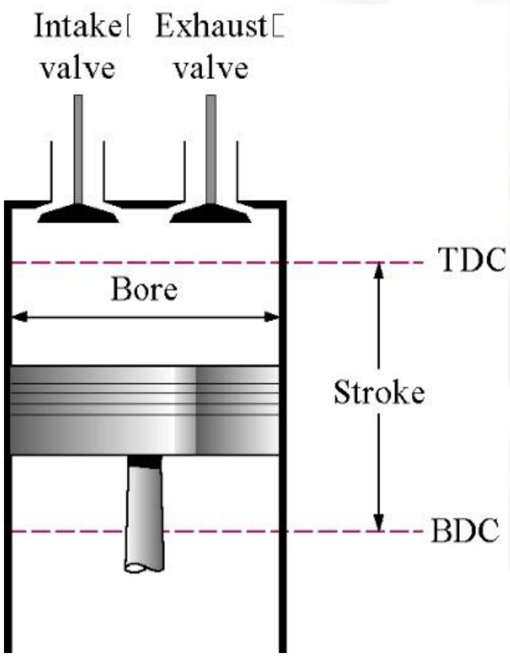


Fig 3a Nomenclature for reciprocating engines

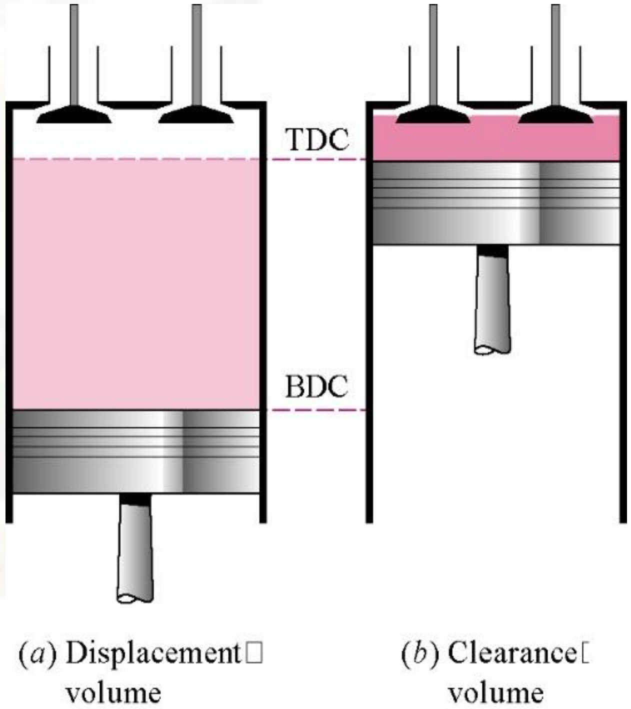


Fig 3b Displacement and clearance volumes of a reciprocating engine

- The *compression ratio*, *r*, of an engine is the ratio of the maximum to the minimum volume formed in the cylinder.

$$r = \frac{V\max}{V\min} = \frac{V_{BDC}}{V_{TDC}} \qquad (P.3)$$

- The *mean effective pressure* **(MEP)** is a fictitious pressure that, if it operated on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.

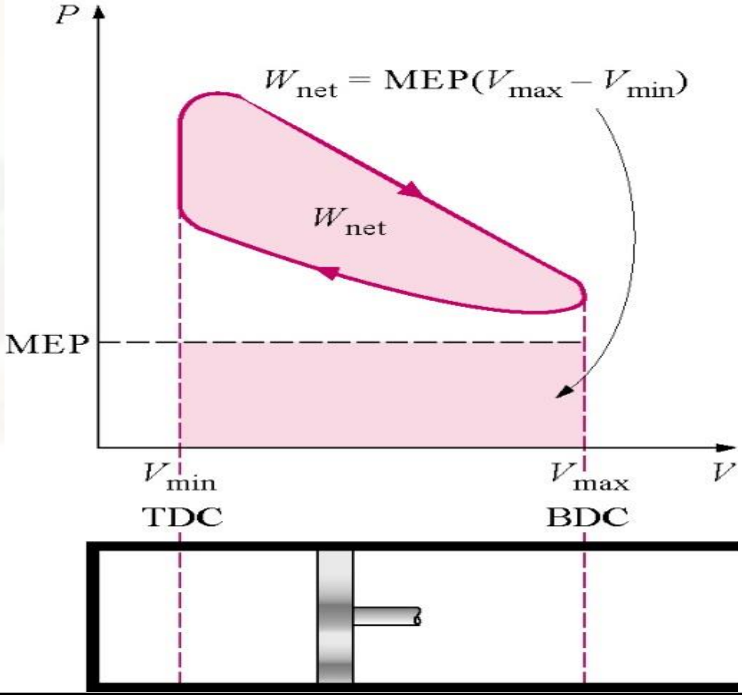


Fig 4 The network output of a cycle is equivalent to the product of the mean effective pressure and the displacement volume

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}} = \frac{w_{net}}{v_{\max} - v_{\min}} \qquad (P.4)$$

- Most SI engines executes four complete strokes (four-stroke ICE)

  <u>Processes</u>

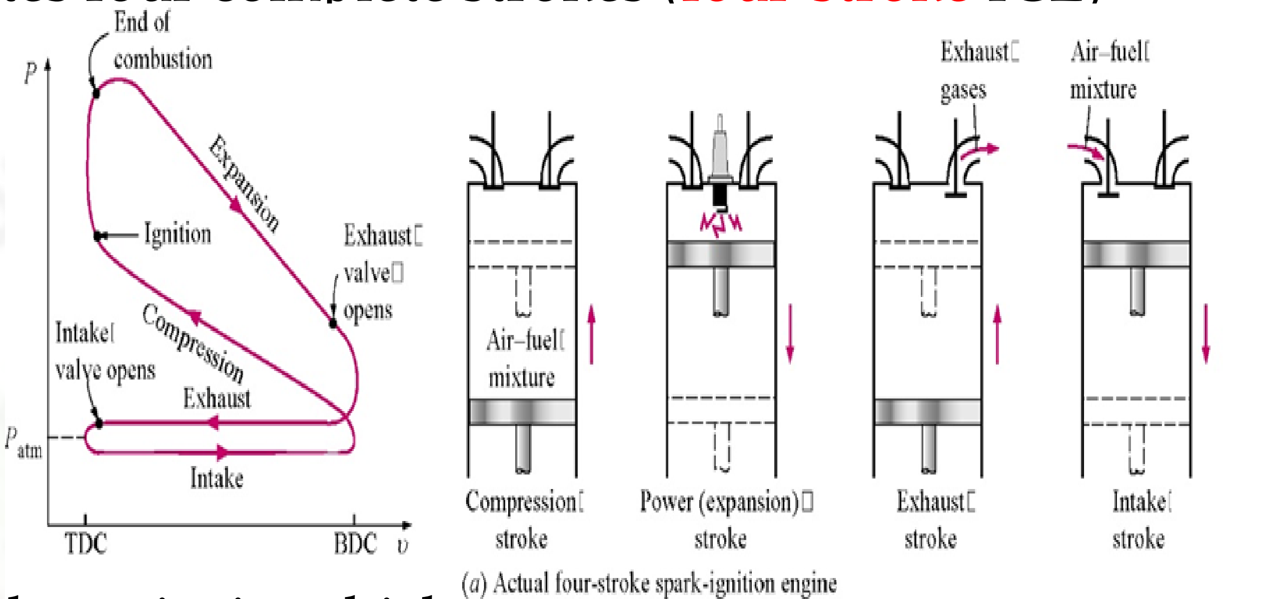
  Intake stroke

  Compression stroke

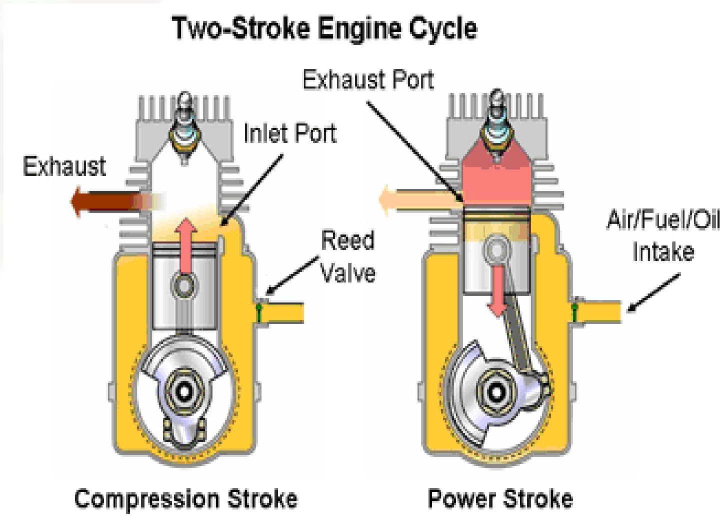
  Power stroke

  Exhaust stroke

  Fig 5 Actual four-stroke SI engine



- Two-stroke engines also exist in which the four strokes are reduced to two: power and compression strokes
- Two-stroke engines are comparatively less efficient.
- But they are relatively simple, inexpensive and have a high power-to-weight ratio.



OTTO CYCLE: IDEAL CYCLE FOR SPARK-IGNITION ENGINES

- The analysis of actual four- or two-stroke cycles are rather complex but are significantly simplified by the air-standard assumptions.
- The resulting cycle, is an ideal Otto cycle, which has four processes

Otto Cycle

Process	Description
1-2	Isentropic compression
2-3	Constant volume heat addition
3-4	Isentropic expansion
4-1	Constant volume heat rejection

- The $P - v$ diagram for an Otto cycle in a piston-cylinder device is shown in Fig 6.

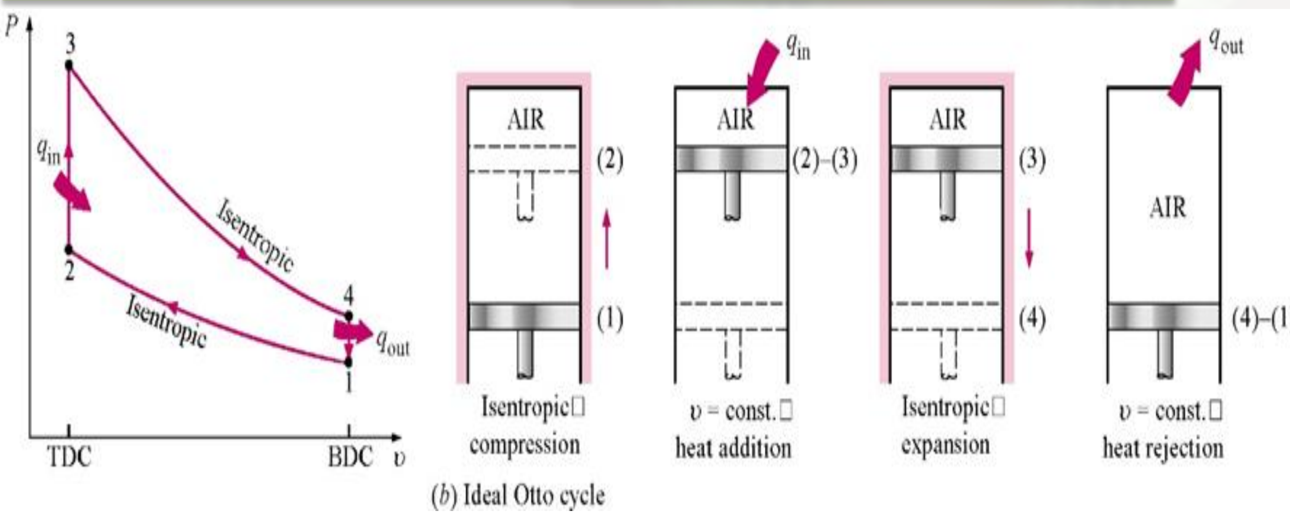


Fig 6 Ideal Otto cycle

THERMAL EFFICIENCY OF THE OTTO CYCLE

- The thermal efficiency of the Otto cycle may be computed as

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \qquad \text{(P.5)}$$

- The Otto cycle is executed in a closed system. Ignoring changes in KE & PE, and applying the *energy balance* (*first law*) relation to processes 2-3 and 1-4 on a unit-mass basis and substituting the resulting expression into Eq P.5 yields Eq P.6

Is this the same as the Carnot cycle efficiency?

- The Otto cycle efficiency, η_{th}

$$\eta_{th,\,Otto} = 1 - \frac{T_1}{T_2} \qquad \text{(P.6)}$$

- Since process 1-2 is isentropic,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{k-1} = \left(\frac{1}{r}\right)^{k-1}$$

THERMAL EFFICIENCY OF THE OTTO CYCLE

- where *compression ratio*, $r = V_1/V_2$ ∴, *thermal efficiency*, η_{th}, yields

$$\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}} \qquad \text{(P.7)}$$

- Eqn. P.7 shows that under the ***cold-air-standard assumptions*** the *thermal efficiency* of an ideal Otto cycle increases with the *compression ratio, r,* of the engine and the *specific heat ratio, k,* of the fuel. However, there is a limit on ***r*** depending upon the fuel.

- Fuels under high temp resulting from high compression ratios will *prematurely ignite*, causing **engine** knock.

- The thermal efficiency of actual SI engine ranges from about 25-30%

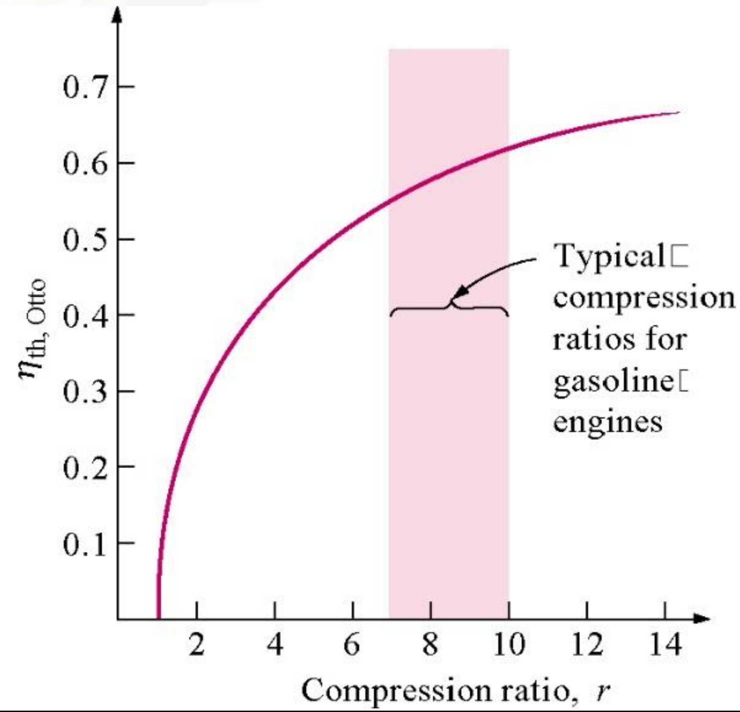


Fig 7 Thermal efficiency of the ideal Otto cycle as a function of compression ratio ($k = 1.4$)

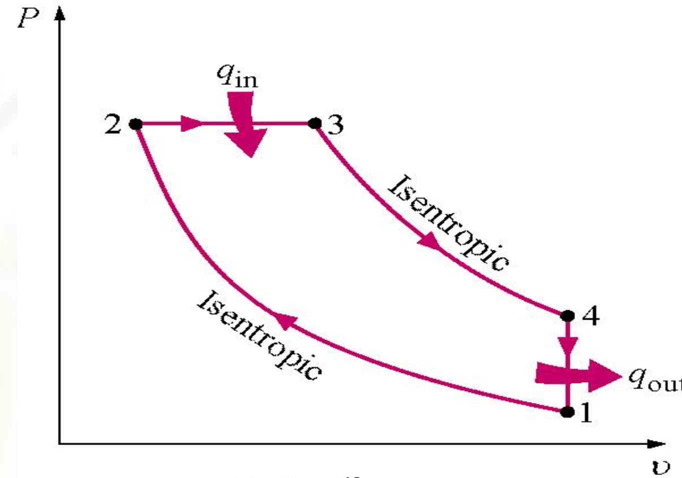
CLASSWORK

1. An ideal Otto cycle has a compression ratio of 8. A the beginning of the compression process, air is at 100 kPa and 17 °C, and 800 kj/kg of heat is transferred to air during the constant-volume heat-addition process. Accounting for the variation of specific heats of air with temperature, determine the
   (a) maximum temperature and pressure that occur during the cycle,
   (b) net work output,
   (c) thermal efficiency, and
   (d) mean effective pressure for the cycle.

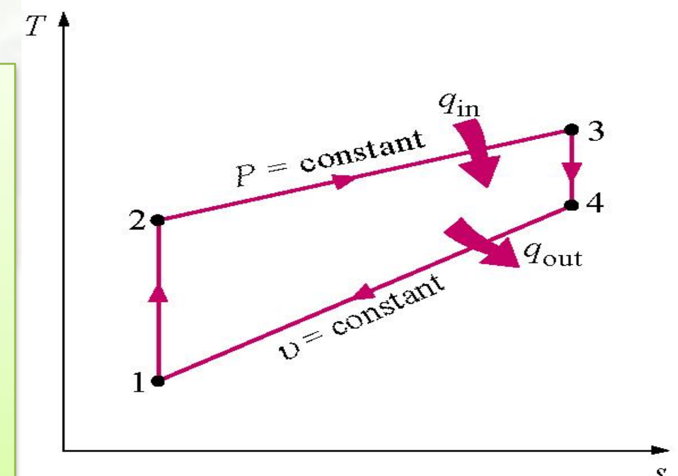
- Combustion initiation method, main difference between SI and CI.
- The compression ratio, *r*, in CI engines (typically 12 to 24) are relatively higher than in SI engines (typically 8 to 11).
- In Diesel engines, the combustion process takes place over a longer interval and therefore the ideal Diesel cycle is approximated as a ***constant-pressure heat-addition process***.

Diesel Cycle

Process	Description
1-2	Isentropic compression
2-3	***Constant pressure heat addition***
3-4	Isentropic expansion
4-1	Constant volume heat rejection



(a) P-υdiagram



(b) T-s diagram

Fig 8 The P – v and T – s diagrams for a Diesel cycle

THERMAL EFFICIENCY OF THE DIESEL CYCLE

- The thermal efficiency of the Diesel cycle is given as

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \qquad \text{(P.8)}$$

- Again applying *energy balance* (*first law*) relation to processes 2-3 and 1-4 to obtain Q_{in} and Q_{out} respectively, and slotting into Eq P.8, yields

- The Diesel cycle efficiency, η_{th}

$$= 1 - \frac{mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)} \qquad = 1 - \frac{1}{k}\frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)} \qquad \text{(P.9)}$$

$$\frac{P_3V_3}{T_3} = \frac{P_2V_2}{T_2} \quad \text{where } P_3 = P_2$$

$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = r_c$$

Where r_c is the cutoff ratio, a measure of the duration of the heat addition at constant pressure. And it can be related to the number of degrees the crank rotated during the fuel injection into the cylinder.

- Thermal efficiency of Diesel engines could be as high as 35-40%.

THERMAL EFFICIENCY OF THE DIESEL CYCLE

- Following a few manipulations, we obtain Eq. P.10

$$\eta_{th,\,Diesel} = 1 - \frac{1}{k}\frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)} = 1 - \frac{1}{k}\frac{T_1}{T_2}\frac{r_c^{\,k} - 1}{(r_c - 1)} = 1 - \frac{1}{r^{k-1}}\frac{r_c^{\,k} - 1}{k(r_c - 1)} \qquad \text{(P.10)}$$

- When $r_c > 1$ for a fixed r, $\eta_{th,\,Diesel} < \eta_{th,\,Otto}$. But, since $r_{Diesel} > r_{Otto}$ $\eta_{th,\,Diesel} > \eta_{th,\,Otto}$.

How does the thermal efficiency of an Otto cycle compare with a Diesel cycle for the same compression ratio?

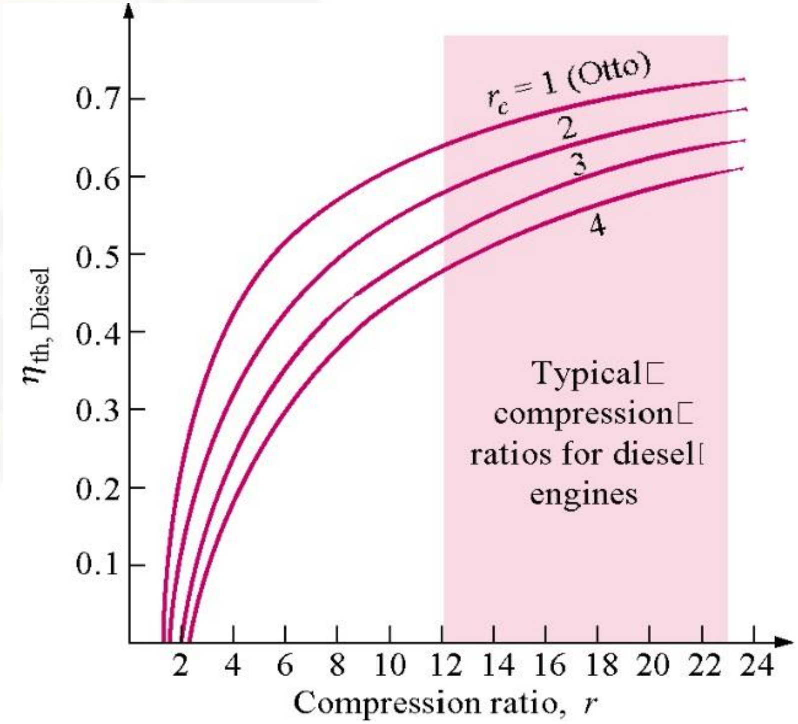


Fig 9 $P - v$ and $T - s$ diagram for ideal Diesel cycle

CLASSWORK

2. An ideal Diesel cycle with air as the working fluid has a compression ratio of 18 and a cutoff ratio of 2. at the beginning of the compression process, the working fluid is at 100kPa, 27°C, and 1917 cm^3. Utilizing the cold-air-standard assumptions, determine (a) the temperature and pressure of air at the end of each process, (b) the net work output and the thermal efficiency, and (c) the mean effective pressure.

Assignment

Thermodynamics: An Engineering Approach by Cengel Y.A. & Boles M.A. 8th Edition

From the above textbook, pp. 539-540 answer 1-5

1. Question 9-23C to 9-26C, 9-28C, 9-30C
2. Question 9-42C to 9-45C
3. Question 9-33 & 9-34 (Group A)
4. Question 9-55 & 9-56 (Group B)
5. What is an ideal dual cycle? (Not more than 60 words, Include relevant $P - v$ diagram)

S/N	GROUP A	GROUP B
1	13BE002731	13BE002743
2	13BE002703	13BE002719
3	13BE002725	13BE002734
4	13BE002716	