Introduction to Aerospace Propulsion

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Lecture No - 17

In this lecture ...

- Gas power cycles
- The Carnot cycle and its significance
- Air-standard assumptions
- An overview of reciprocating engines
- Otto cycle: the ideal cycle for spark-ignition engines
- Diesel cycle: the ideal cycle for compression-ignition engines
- Dual cycles

Gas power cycles

- Study of power cycles of immense importance in engineering.
- Actual cycles: irreversibilities (like friction etc.),not in thermodynamic equilibrium, non-quasi static processes etc.
- For thermodynamic analysis we assume none of the above effects present: ideal cycles
- Ideal cycle analysis starting point of in-depth analysis.

Gas power cycles

- The ideal cycles are internally reversible, but, unlike the Carnot cycle, they are not necessarily externally reversible.
- Hence, the thermal efficiency of an ideal cycle, in general, is less than that of a totally reversible cycle operating between the same temperature limits.
- But, the thermal efficiency is ideal cycles is higher than that of actual cycles.

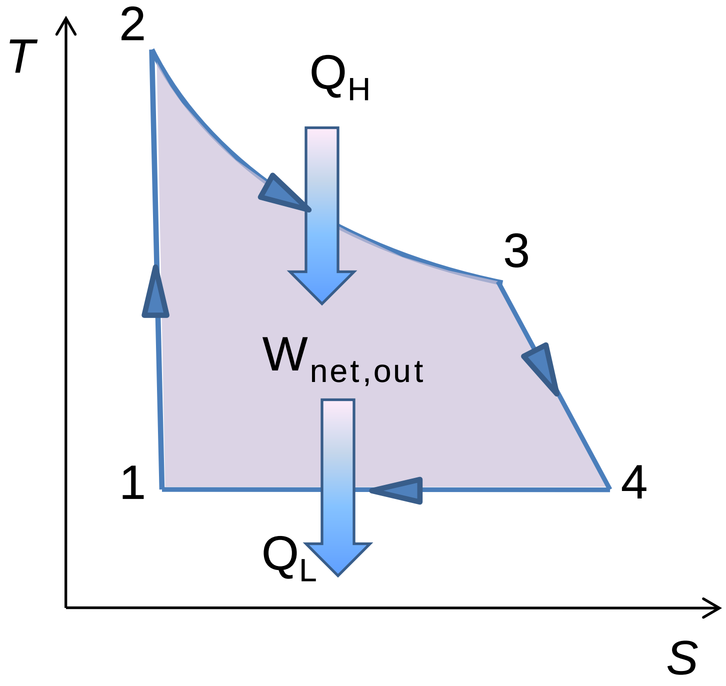
Gas power cycles

- Gas power cycles are usually represented on *P*-*v* and *T*-*s* diagrams.
- On these diagrams the area enclosed by the process curves represent the net work done by the cycle.
- For a cyclic process this is also equal to the net heat transferred during the cycle.
- In an ideal power cycle, the only effect that can change the entropy of the working fluid during a process is heat transfer.

Gas power cycles

- On a T-s diagram, Q_{in} proceeds in the direction of increasing entropy and Q_{out} proceeds in the direction of decreasing entropy.
- The difference between areas under Q_{in} and Q_{out} is the net heat transfer, and hence the net work of the cycle.
- The ratio of the area enclosed by the cyclic curve to the area under the heat-addition process curve represents the thermal efficiency of the cycle.

Gas power cycles



Net heat input,
Q_H = area under curve 2-3

Net work output,
W_{net} = (area under curve 2-3) – (area under curve 1-4)

Hence, thermal efficiency,
$\eta_{th} = W_{net}/Q_H$

The Carnot cycle and its significance

- The Carnot cycle consists of four reversible processes: two reversible adiabatics and two reversible isotherms.
- Carnot efficiency is a function of the source and sink temperatures.

$$\eta_{th} = 1 - \frac{T_L}{T_H}$$

- The efficiency of a Carnot heat engine increases as T_H is increased, or as T_L is decreased.

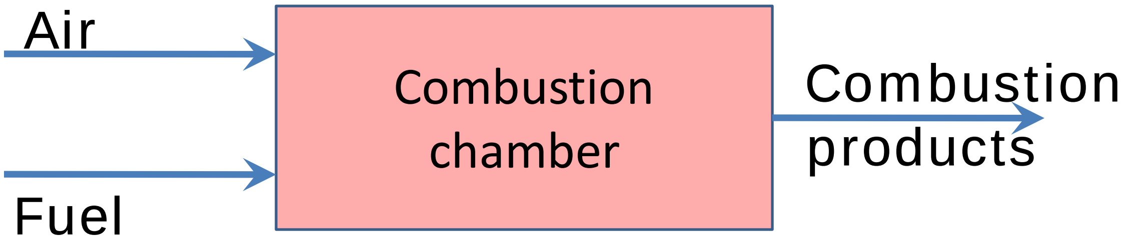
The Carnot cycle and its significance

- The Carnot cycle serves as a standard against which actual cycle performance can be compared.
- In practice the source and sink temperatures are also limited.
- Source temperature limited by the materials that are used in these devices.
- Sink temperature limited by the temperature of the medium to which heat is rejected like atmosphere, lake, oceans etc.

Air standard assumptions

- To simplify analysis, the following assumptions are made:
  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 process is replaced by a heat-rejection process that restores the working fluid to its initial state.

Air standard assumptions

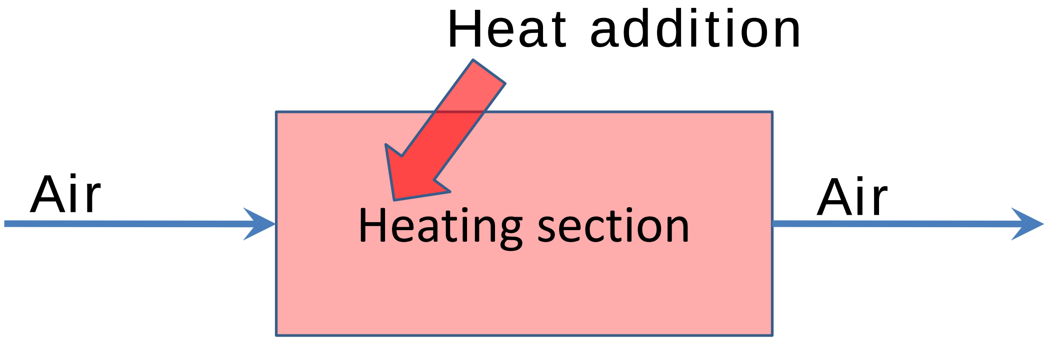

Air

Fuel

Combustion chamber

Combustion products

Actual process


Heat addition

Air

Heating section

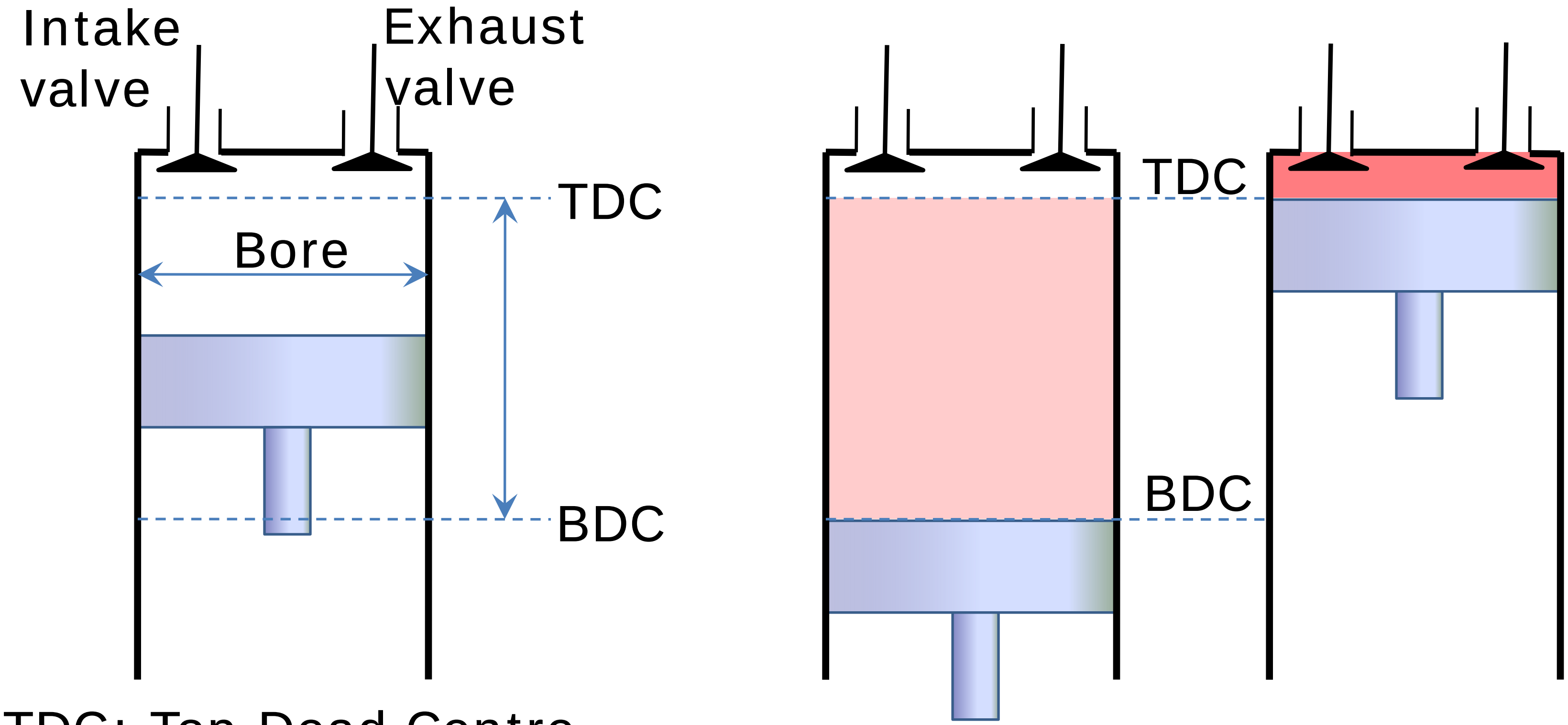
Air

Ideal process

Overview of reciprocating engines

- Reciprocating engines are one of the most commonly used power generating devices.
- These engines can operate on a variety of thermodynamic cycles.
- Piston and cylinder form the basic components of reciprocating engines, besides valves, connecting rods, flywheels and several other components.

Overview of reciprocating engines



TDC: Top Dead Centre
BDC: Bottom Dead Centre

Displacement volume

Clearance volume

Nomenclature for reciprocating engines

Overview of reciprocating engines

- The minimum volume formed in the cylinder when the piston is at TDC is called the clearance volume.
- The volume displaced by the piston as it moves between TDC and BDC is called the displacement volume.
- The ratio of the maximum volume formed in the cylinder to the minimum (clearance) volume is called the compression ratio, r of the engine:

$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_{BDC}}{V_{TDC}}$$

Overview of reciprocating engines

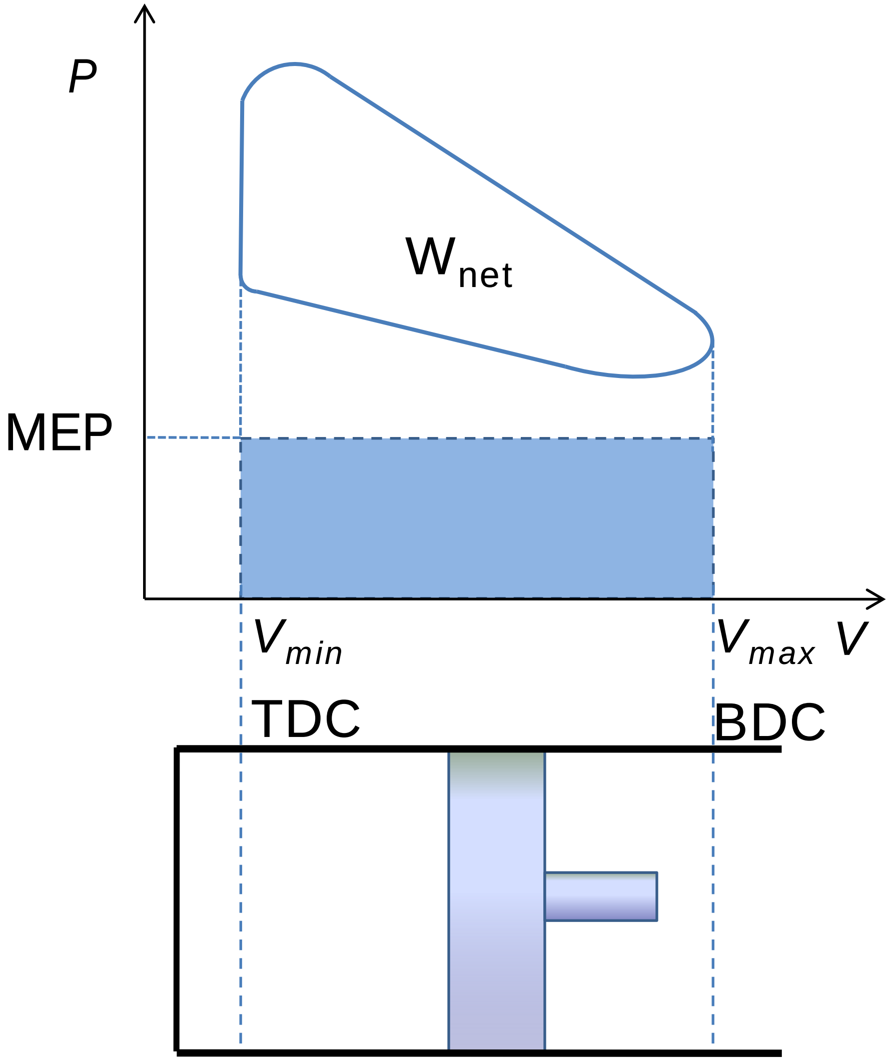
- Mean Effective Pressure (MEP): is a fictitious pressure that, if it acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.

$$W_{net} = MEP \text{ x } Piston\ area \text{ x } Stroke$$

$$= MEP \text{ x } Displacement\ volume$$

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}} = \frac{w_{net}}{v_{\max} - v_{\min}}$$

Overview of reciprocating engines



$$W_{net} = MEP \times (V_{max} - V_{min})$$

The net work output of a cycle is equivalent to the product of the mean effective pressure and the displacement volume.

Overview of reciprocating engines

- Two types of reciprocating engines: Spark Ignition (SI) engines and Compression Ignition (CI) engines
- SI engines: the combustion of the air–fuel mixture is initiated by a spark plug.
- CI engines, the air–fuel mixture is self-ignited as a result of compressing the mixture above its self-ignition temperature.

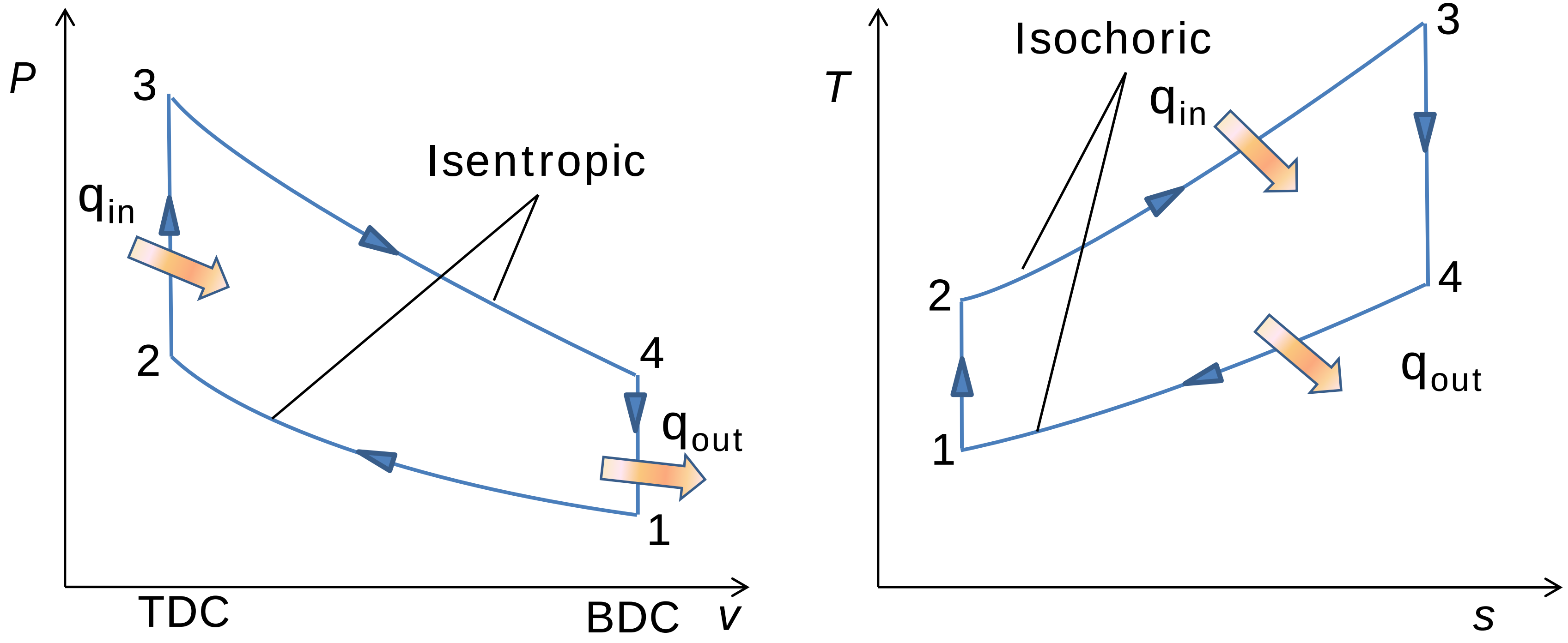
Otto cycle

- Otto cycle is the ideal cycle for spark-ignition reciprocating engines.
- Named after Nikolaus A. Otto, who built a successful four-stroke engine in 1876 in Germany.
- Can be executed in two or four strokes.
- Four stroke: Intake, compression, power and exhaust stroke
- Two stroke: Compression and power strokes.

Otto cycle

- Otto cycle consists of four processes:
  - Isentropic compression (1-2)
  - Isochoric (constant volume) heat addition (2-3)
  - Isentropic expansion (3-4)
  - Isochoric (constant volume) heat rejection (4-1)
- All the processes are internally reversible.
- Currently we shall analyse the ideal Otto cycle.
- Practical implementation and the actual cycle will be discussed in later chapters.

Otto cycle



Ideal Otto cycle on *P*-*v* and *T*-*s* diagrams

Otto cycle

- Applying energy balance and assuming KE and PE to be zero:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta u$$

The heat transfer to and from the working fluid can be written as :

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

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

Otto cycle

- The thermal efficiency of the ideal Otto cycle under the cold air standard assumptions becomes:

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

Processes 1-2 and 3-4 are isentropic and

$v_2 = v_3$ and $v_4 = v_1$.

Therefore, $\dfrac{T_1}{T_2} = \left(\dfrac{v_2}{v_1}\right)^{\gamma-1} = \left(\dfrac{v_3}{v_4}\right)^{\gamma-1} = \dfrac{T_4}{T_3}$

Otto cycle

- Substituting these equations into the thermal efficiency relation and simplifying:

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

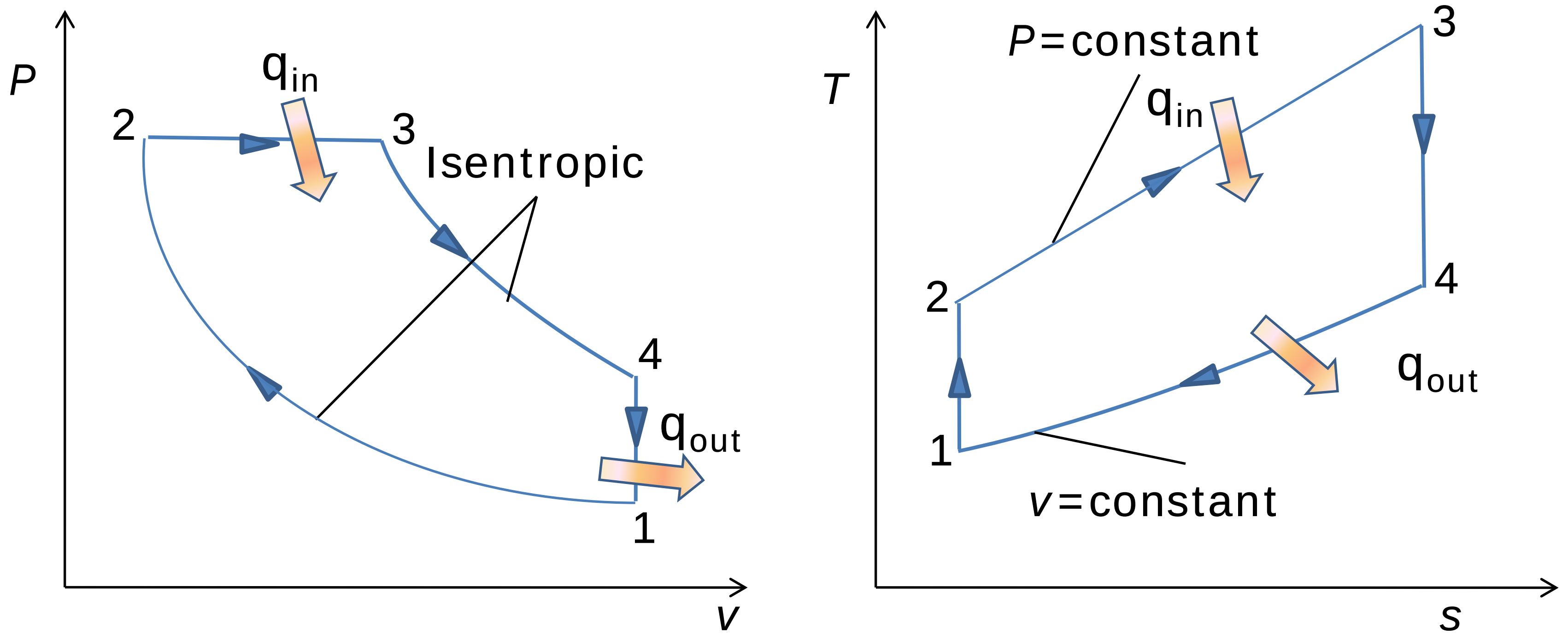
where, $r = \frac{V_{\max}}{V_{\min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$ is the compression ratio.

And γ is the ratio of specific heats c_p / c_v.

Diesel cycle

- The Diesel cycle is the ideal cycle for CI reciprocating engines proposed by Rudolph Diesel in the 1890s.
- In SI, the air–fuel mixture is compressed to a temperature that is below the autoignition temperature of the fuel, and the combustion process is initiated by firing a spark plug.
- In CI engines, the air is compressed to a temperature that is above the autoignition temperature of the fuel, and combustion starts on contact as the fuel is injected into this hot air.

Diesel cycle



Ideal Diesel cycle on *P*-*v* and *T*-*s* diagrams

Diesel cycle

- Diesel cycle consists of four processes:
  - Isentropic compression (1-2)
  - Isobaric (constant pressure) heat addition (2-3)
  - Isentropic expansion (3-4)
  - Isochoric (constant volume) heat rejection (4-1)
- All the processes are internally reversible.
- Thermodynamically the Otto and Diesel cycles differ only in the second process (2-3).
- For Otto cycle, 2-3: constant volume and for Diesel cycle, 2-3: constant pressure.

Diesel cycle

- Applying energy balance and assuming KE and PE to be zero:

$$(q_{in}-q_{out})+(w_{in}-w_{out})=\Delta u$$

The heat transfer to and from the working fluid can be written as :

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

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

Diesel cycle

- The thermal efficiency of the ideal Diesel cycle under the cold air standard assumptions becomes:

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

$$= 1 - \frac{T_1(T_4 / T_1 - 1)}{\gamma T_2(T_3 / T_2 - 1)}$$

- The cutoff ratio r_c, as the ratio of the cylinder volumes after and before the combustion process: $r_c = v_3/v_2$

Diesel cycle

- Substituting these equations into the thermal efficiency relation and simplifying:

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

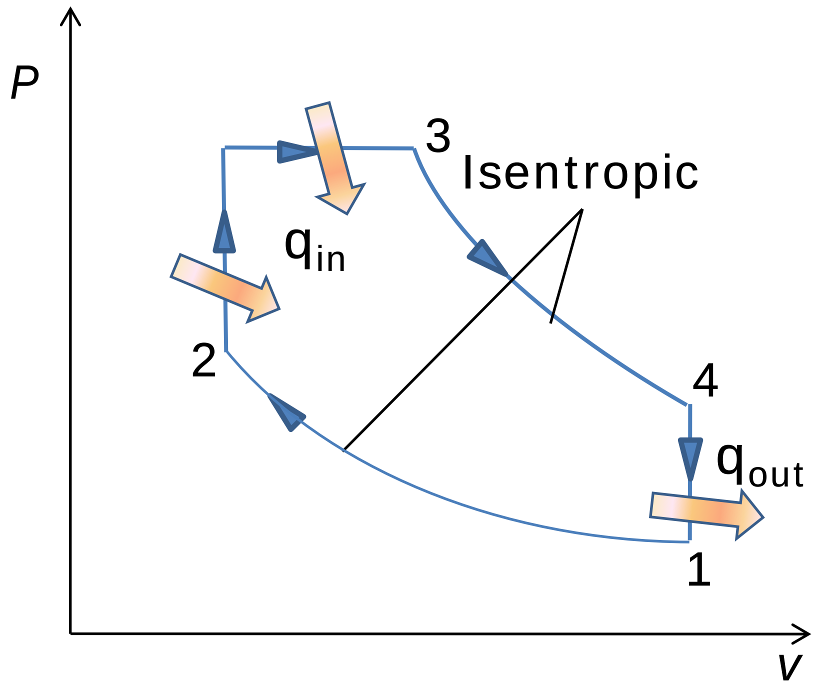
$$\text{Where, } r \text{, is the compression ratio} = \frac{V_{\max}}{V_{\min}}$$

- The quantity in the brackets is always >0 and therefore $\eta_{th,Diesel} > \eta_{th,Otto}$ for the same compression ratios.

Dual cycle

- Approximating heat addition by a constant pressure or constant volume process is too simplistic.
- Modelling the heat addition process by a combination of constant pressure and constant volume processes: dual cycle.
- The relative amounts of heat added during the two processes can be appropriately adjusted.
- Both Otto and Diesel cycle can be obtained as a special case of the dual cycle.

Dual cycle



What will this cycle look like on T-s diagram?

What is the thermal efficiency of such a cycle?

Ideal dual cycle on *P*-*v* diagram

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In the next lecture …

- Stirling and Ericsson Cycles
- Brayton Cycle: The Ideal Cycle for Gas-Turbine Engines
- The Brayton Cycle with Regeneration
- The Brayton Cycle with Intercooling, Reheating, and Regeneration
- Rankine Cycle: The Ideal Cycle for Vapor Power Cycles