Week 7: GAS POWER CYCLES

Energy Systems and Conversion

EGR3030

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Objectives

- Define and classify gas power cycles
- Understand the operation of reciprocating engines.
    - Otto
    - Diesel
- Brayton cycles.

Gas power cycles - introduction

- A cycle during which a net amount of work is produced during which the working fluid remains a gas throughout

- The maximum efficiency is determined by considering operations in a cycle between a heat source at temperature T_H and a sink at T_L – at the efficiency *of* the Carnot cycle.

Gas power cycles - air-Standard assumptions

- The working fluid circulate in a closed loop and behaves as an ideal gas
- The processes that make up the cycle are internally reversible
- The combustion process is replaced by a heat-addition process from an external source and exhaust process by heat-rejection process that restores the working fluid to its initial state

Gas power cycles

Are the basis of internal combustion engines

Reciprocating Engines

Spark ignition (SI) engines

Combustion of the air-fuel mixture is initiated by a spark plug

Compression-ignition (CI) engines

Compressing the air-fuel mixture above its self-ignition temp causes self-ignition.

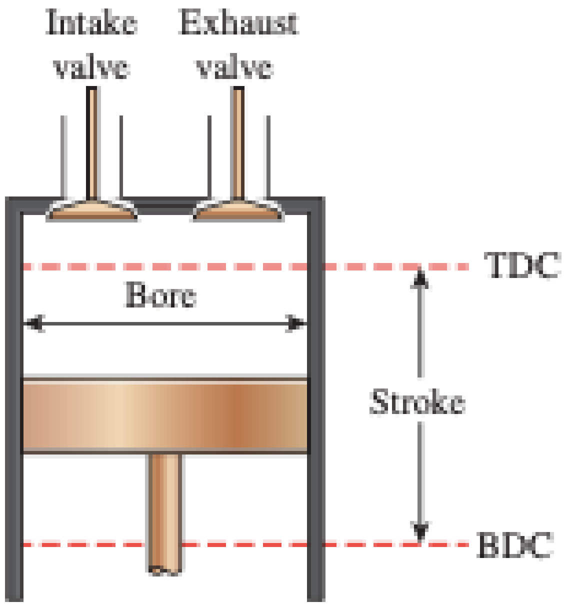
Turbine (or jet) engines

- Brayton cycle

Terminologies of reciprocating IC Engines

- BDC (*Bottom Dead Center)*: Position of the piston where it forms the largest volume.
- Stroke: *Distance between TDC and BDC*
- Bore: *Diameter of the piston (internal diameter of the cylinder)*
- Clearance volume: minimum volume formed when piston is at TDC.
- Compression ratio (r): ratio of maximum volume to minimum volume.
  i.e. V_{BDC}/V_{TDC}.

- Displacement volume: volume displaced by the piston as it moves between TDC and BDC.

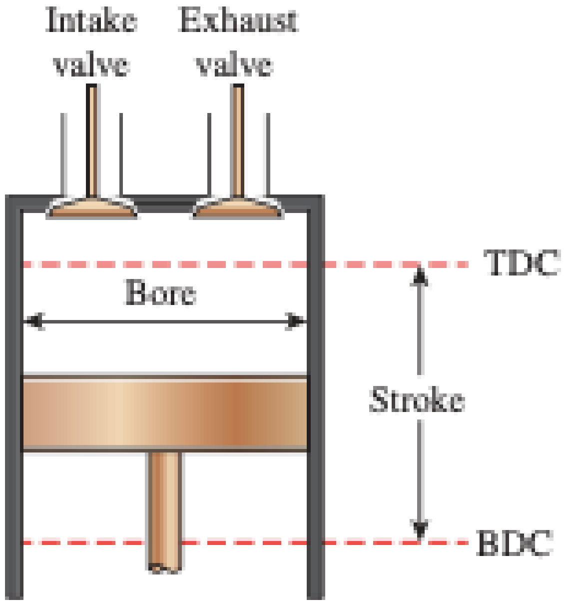


Terminologies of reciprocating IC Engines

MEP (mean effective pressure) - is a constant theoretical pressure that acts on piston to produce work the same as that during an actual cycle. The net work done in IC engines:

$$W_{net} = MEP \times Piston\ area \times Stroke$$
$$= MEP \times Displacement\ volume$$

$$MEP = \frac{W_{net}}{V_{max} - Vmin} = \frac{w_{net}}{v_{max} - vmin} \quad (KPa)$$



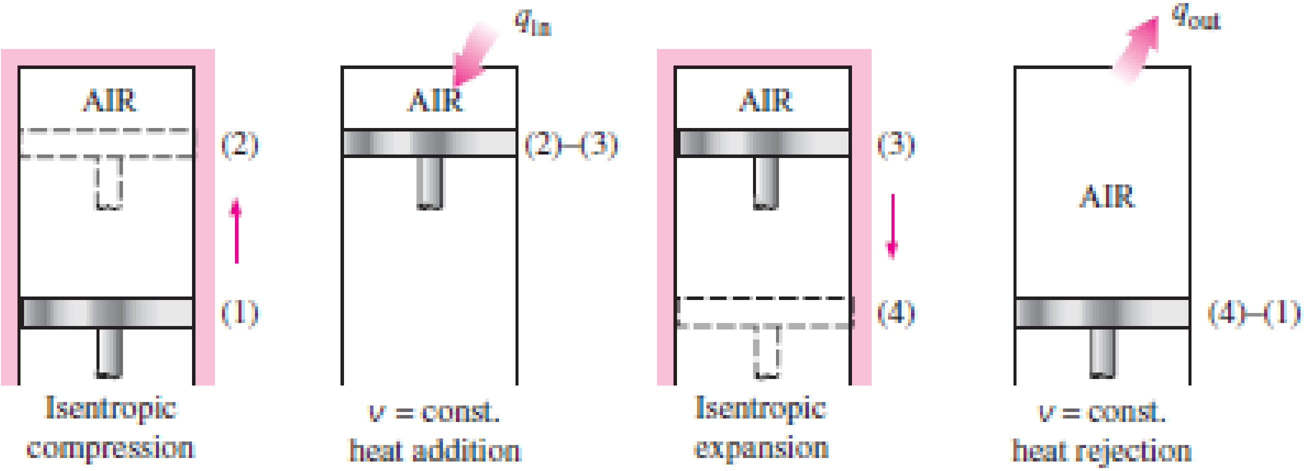
The Otto cycle

- The Otto cycle is the ideal cycle for ***spark-ignition*** reciprocating engines. It is named after Nikolaus A. Otto, who built a successful four-stroke engine in 1876 in Germany using the cycle proposed by Frenchman Beau de Rochas in 1862.

- A 4-stroke cycle where air and fuel mixes and flows through inlet valve and exhaust through exhaust valve

- Converts reciprocating motion to rotary motion using piston and crank shaft.

The ideal Otto cycle

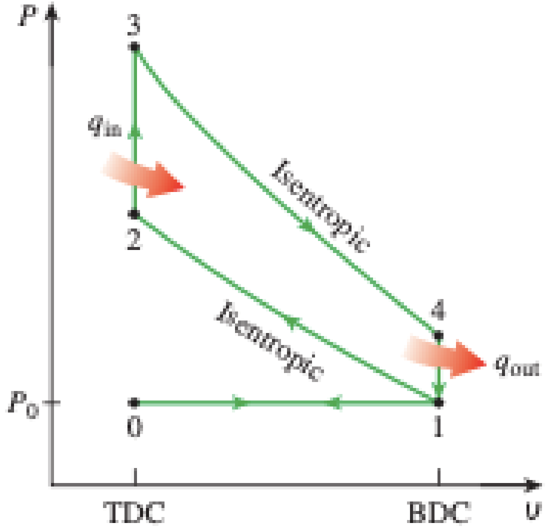


Consists of four internally reversible process:

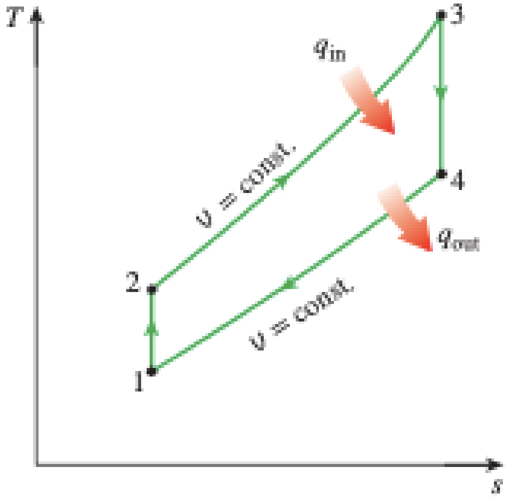
- 1-2 Isentropic compression
- 2-3 Constant-volume heat addition
- 3-4 Isentropic expansion
- 4-1 Constant-volume heat rejection

The energy balance is:

$(q_{in} - q_{out}) + (w_{in} - w_{out})$ = Δu (KJ/Kg) … (1)



P-v diagram



T-s diagram

Efficiency of the ideal Otto cycle

$$\eta_{th,\,id.Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

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

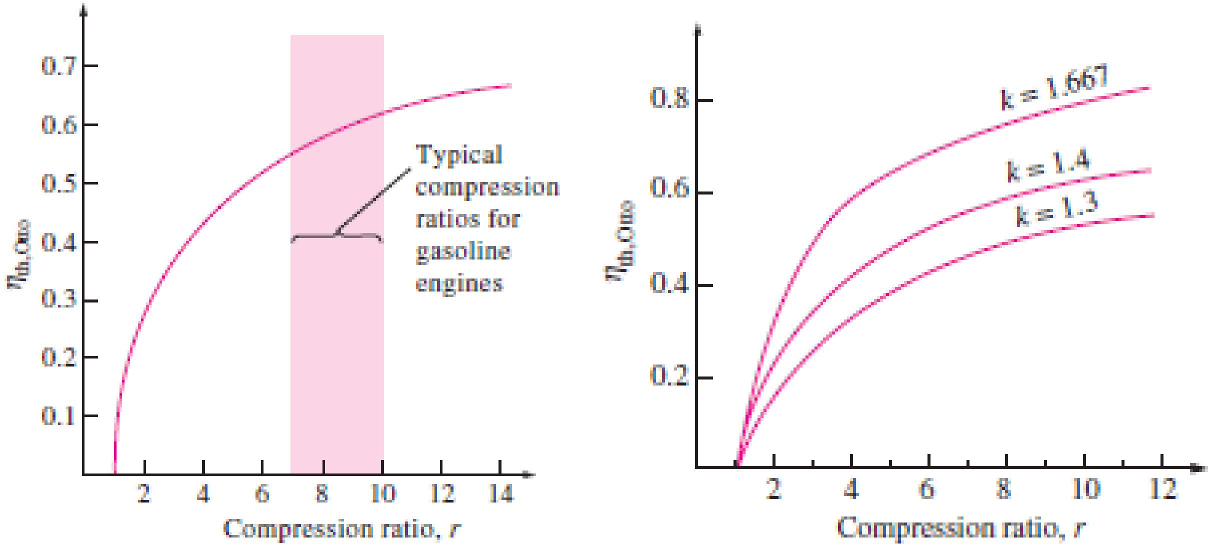
Processes 1-2 and 3-4 are isentropic, and v2 = v3 and v4 = v1. Thus,

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

Substituting these equations into the thermal efficiency relation and simplifying give

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

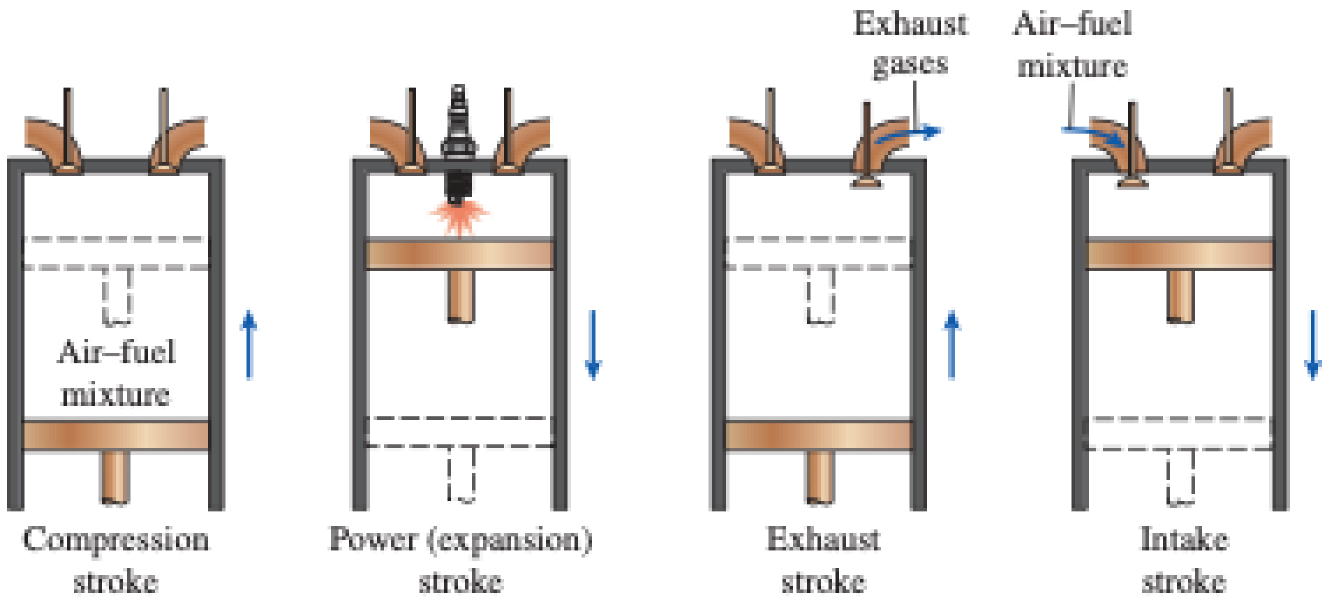
For higher efficiency, higher compression ratios are required, as shown below;

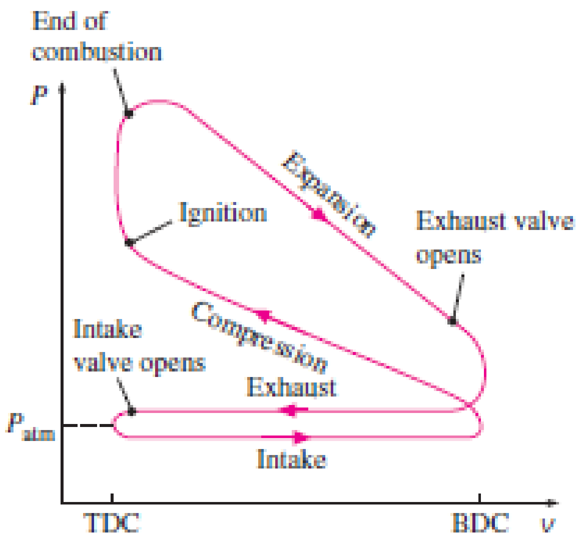


However, increase in pressure ratios, would increase the air-fuel temperature above the temperature at which the mixture can auto-ignite.

This would result in '**engine-knock**', reducing the performance of the engine. To avoid such situations, additives are generally added which increases the auto-ignition temperature.

The real Otto cycle





- In the real Otto cycle, heat addition is replaced by spark ignition
- Cycle is extended by the valve opening phase of the compression stroke

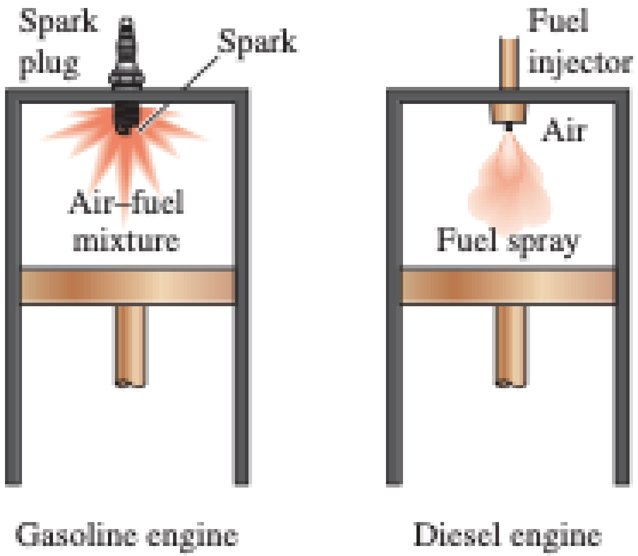
The Diesel cycle

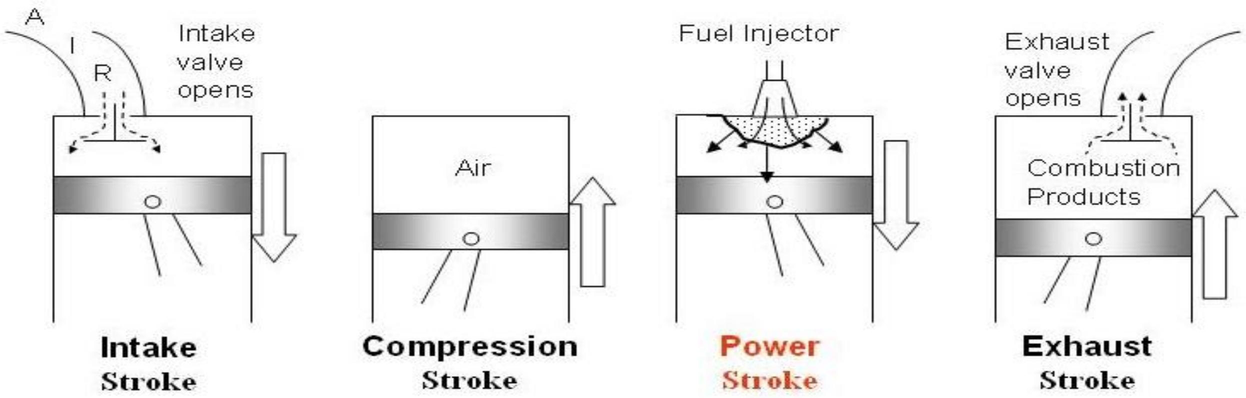
In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process

Here the fuel is injected when the piston approaches TDC, i.e. when the air is at maximum temperature due to compression, the combustion process starts

The fuel is injected after the piston starts moving down. The volume increases, and the fuel evaporates to fill the volume – keeping the pressure roughly the same.

Hence the combustion can be considered to occur at constant pressure





4 stroke CI engine

Efficiency of the ideal Diesel cycle

Noting that the Diesel cycle is executed in a piston–cylinder device, which forms a closed system, the amount of heat transferred to the working fluid at constant pressure and rejected from it at constant volume can be expressed as

$$q_{in} - w_{b,out} = u_3 - u_2 \rightarrow q_{in} = P_2(v_3 - v_2) + (u_3 - u_2)$$

$$\square \; h_3 - h_2 = cp(T_3 - T_2)$$

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

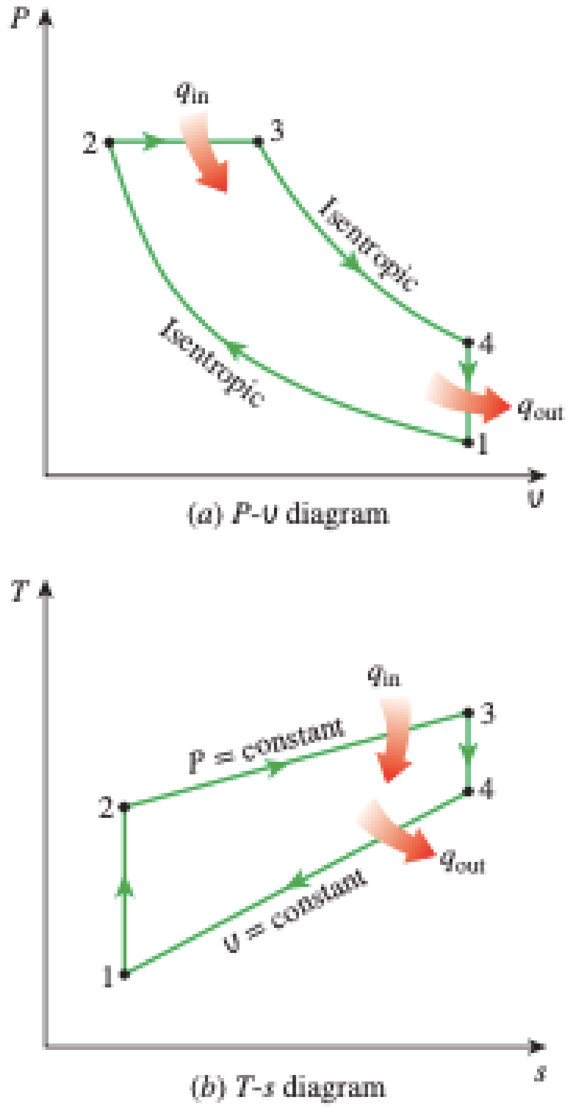
$$\eta_{th,\,id.Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$

Now defining a new quantity, the ***cut-off ratio*** r_c, as the ratio of the cylinder volumes after and before combustion:

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

Using this definition and the isentropic ideal-gas relations for processes 1-2 and 3-4, we see that the thermal efficiency relation reduces to

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



(a) P-v diagram

(b) T-s diagram

Efficiency of the ideal Diesel cycle

Note that the efficiency of a Diesel cycle differs from the efficiency of an Otto cycle by the quantity in the brackets. This quantity is always greater than 1. Therefore,

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

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

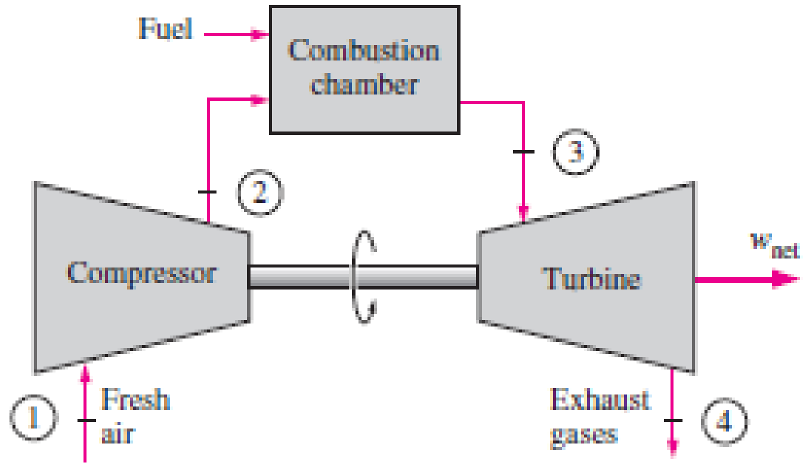
For r $> 1\, value,$

$$-\frac{1}{k}\left[\frac{r_c^k - 1}{(r_c - 1)}\right] > 1$$

Therefore, the efficiency of the diesel cycle is less than that of the otto cycle for the same compression ratio. However, the advantages of Diesel over petrol engines is that we can operate at higher compression ratios without auto ignition.

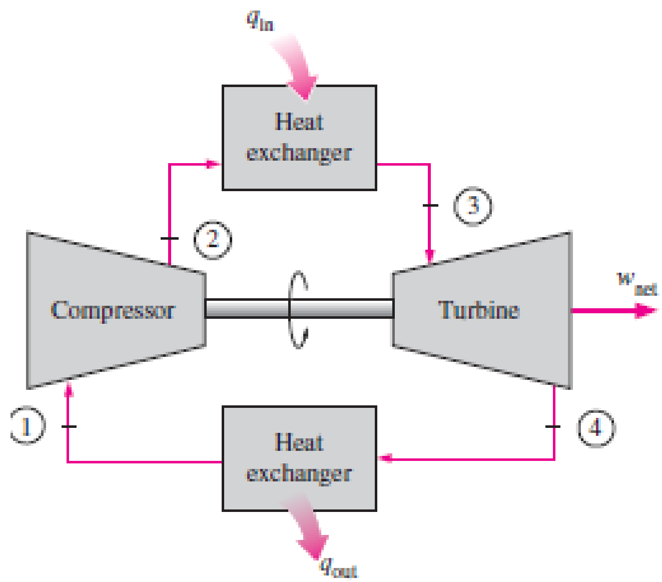
The Brayton Cycle

The Brayton cycle was first proposed by George Brayton for use in the reciprocating oil-burning engine that he developed around 1870. Today, it is used for gas turbines only where both the compression and expansion processes take place in rotating machinery. Gas turbines usually operate on an *open cycle,* as shown in figure (a):



a. An open-cycle gas-turbine engine

The open gas-turbine cycle described above can be modelled as a *closed cycle,* as shown in figure (b), by using the air-standard assumptions. The compression & expansion processes remain the same, but combustion is replaced by a constant-pressure heat-addition from an external source, and the exhaust process is replaced by a constant pressure heat-rejection process to the ambient air.



b. A closed-cycle gas-turbine engine

Brayton Cycles

The ideal cycle that the working fluid undergoes in this closed loop is the **Brayton cycle,** which is made up of four internally reversible processes:

1-2 Isentropic compression (in a compressor)

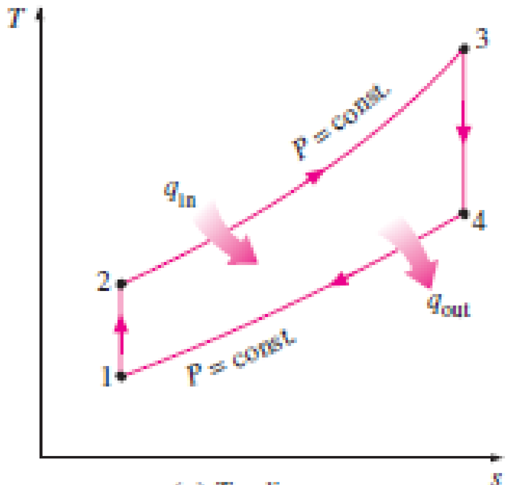
2-3 Constant-pressure heat addition

3-4 Isentropic expansion (in a turbine)

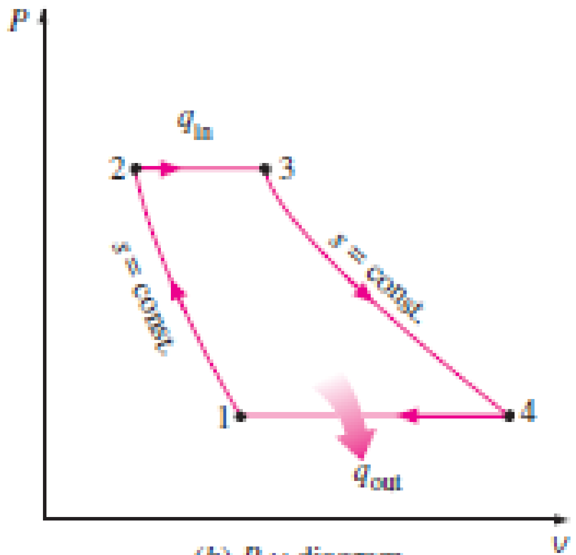
4-1 Constant-pressure heat rejection

Note that:

- All the four processes are executed in steady-flow devices
- They are analysed as steady-flow processes



(a) T-s diagram



(b) P-v diagram

Efficiency of the Brayton Cycle

If changes in kinetic and potential energies are neglected, the energy balance for a steady-flow process can be expressed as

$(qin - q_{out})$ + $(w_{in} - w_{out})$ = $h_{exit} - h_{inlet}$ … … 1

- Therefore. Heat transfer to and from the working fluid are;

- q_{in} = $h_3 - h_2$ = $c_p(T_3 - T_2)$ ……… 2

And

- Q_{out} = $h_4 - h_1$ = $c_p(T_4 - T_1)$ ………. 3

Thermal efficiency of the Brayton Cycle

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

$$\eta_{\text{th},Brayton} = \frac{W_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

Processes 1-2 and 3-4 are isentropic, and P2 = P3 and P4 = P1. Thus,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} \& \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

Substituting these in the thermal efficiency expression and simplification gives:

$$\eta_{\text{th},Brayton} = 1 - \frac{1}{r_p^{\frac{k-1}{k}}}$$

where: $r_p = \frac{P_2}{P_1}$

$$is\ the\ pressure\ ratio\ and\ k\ is\ the\ specific\ heat\ ratio$$

Note: the thermal efficiency of an ideal Brayton cycle depends on the pressure ratio of the gas turbine and the specific heat ratio of the working fluid.

Recap

The most efficient cycle operating between a heat source at TH and a sink at TL is the **Carnot cycle**, thermal efficiency:

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

In reciprocating engines, the compression ratio r and the mean effective pressure MEP are defined as;

$$r = \frac{v_{max}}{v_{min}} \text{ and } MEP = \frac{W_{net}}{V_{max} - Vmin} = \frac{w_{net}}{v_{max} - vmin} \quad (KPa)$$

Under cold-air-standard assumptions, the thermal efficiency of the ideal **Otto cycle** is where r is the compression ratio and k is the specific heat ratio cp/cv;

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

The **Diesel cycle** thermal efficiency under cold-air-standard assumptions is;

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

where r_c is the cut-off ratio, defined as the ratio of the cylinder volumes after and before the combustion process.

The thermal efficiency of the simple Brayton cycle increases with the pressure ratio;

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

Tutorial question: Ideal Otto Cycle

An ideal Otto cycle has a compression ratio of 8. At 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

(a) the maximum temperature and pressure that occur during the cycle,

(b) the net work output,

(c) the thermal efficiency, and

(d) the mean effective pressure for the cycle.

(*e*) Also, determine the power output from the cycle, in kW, for an engine speed of 4000 rpm (rev/min). Assume that this cycle is operated on an engine that has four cylinders with a total displacement volume of 1.6 L.