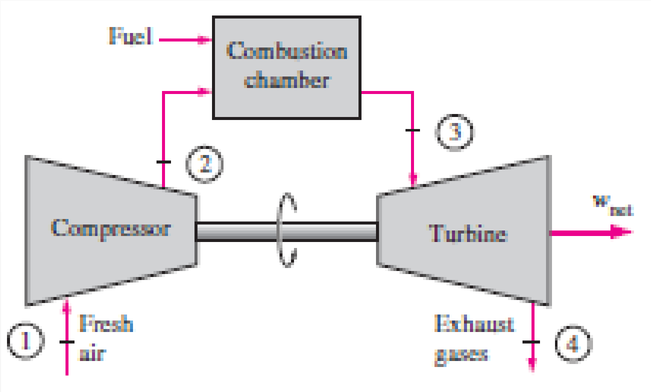
Gas Turbine Cycle

Lectures 1, 2
Simple gas cycle

Tikrit university\ engineering college\ mechanical dept.

Open cycle

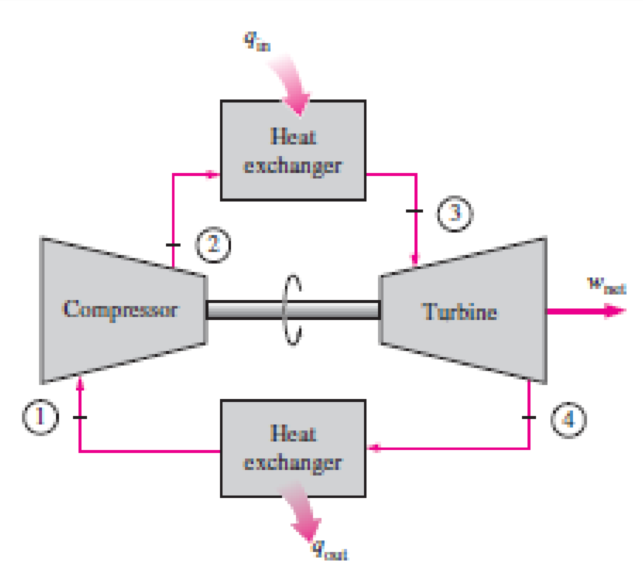
- The most basic gas turbine unit is one operating on the open cycle in which rotary compressor & turbine are mounted on a common shaft.
- Air is drawn into the compressor (C) & after that compressed air passes to a combustion chamber (C.C).



- Energy is supplied in (C.C) by spraying fuel into the air stream, the resulting hot gas expanded through the turbine (T) to the atmosphere in order to achieve net work output from the unit, the turbine must develop more output power than required to derive the compressor (C) and to overcome the mechanical losses in the cycle.
- The gas turbine have many advantages compared with steam turbine, they are small in size mass and less initial coast per unit output. They are available with relatively short delivery times and are quick to install put in use.
- The disadvantages are low efficiency and are limited life time.

closed cycle

- In the system shown in figure, the working fluid receives energy input by heat transfer from an external source, for example a gas cooled nuclear reactor. The gas exiting the turbine is passed through a heat exchanger, where it is cooled prior to re-entering the compressor.



- An idealization often used in the study of open gas turbine power pant is that of an (air standard analysis). In air standard analysis, two assumptions are made:

1. The working fluid is air , which be haves as ideal gas
2. The temp rise that would be brought about by combustion is accomplished by a heat transfer from an external source.

- .

closed cycle

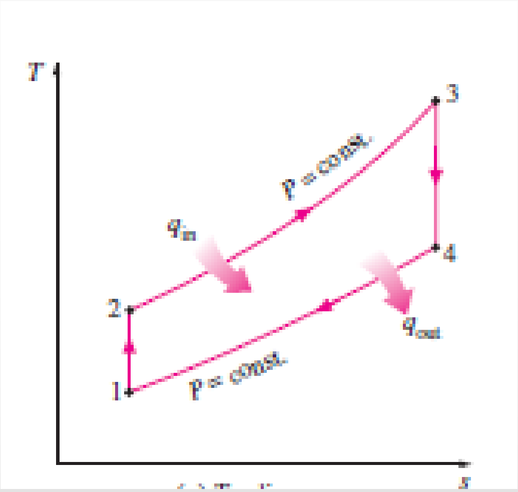
- With an air – standard analysis, we avoid dealing with the complexities of the combustion process and the change of composition during combustion.
- In general, The processes in Brayton cycle (gas turbine cycle) are:

1 ⟶ 2 : Compression

2 ⟶ 3 : Heat addition

3 ⟶ 4 : Expansion

4 ⟶ 1 : Heat reject



Cold air-standard Brayton cycle

- When an ideal Brayton cycle is analyzed on a cold air standard basis, the specific heats (C_P) are taken as constant :
- The mathematical model for the gas turbine cycle (Brayton cycle):

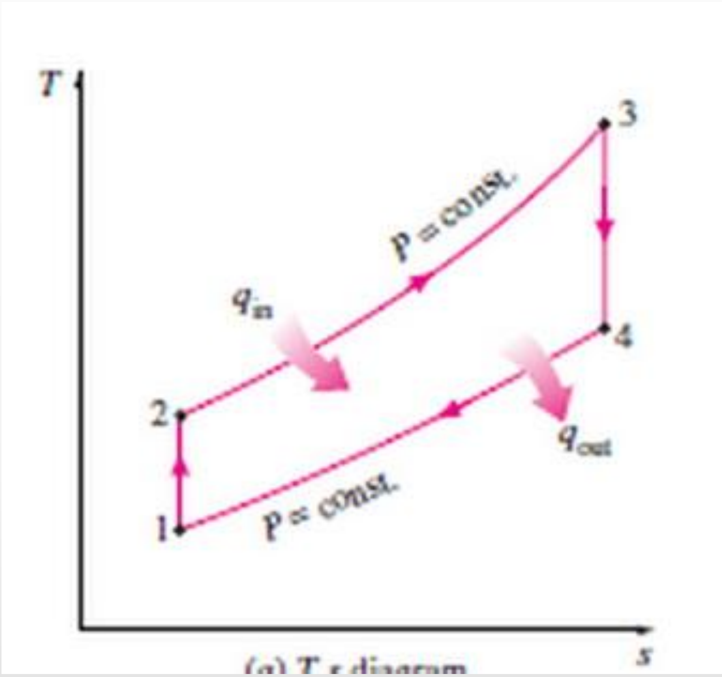
- for constant C_P:
- The compressor work input: (1 ⟶ 2)
  $= C_P\ (T_2 – T_1)$……………………………………..(1)
  where C_P = 1.005 kJ/kg.K

- Combustion chamber (heat added):)
  $= C_P\ (T_3 – T_2)$……………………………………..(2)
  where C_P = 1.13 kJ/kg.K

- Turbine work output: (3 ⟶ 4)
  $= C_P\ (T_3 – T_4)$……………………………………..(3)
  where C_P = 1.13 kJ/kg.K

Air standard analysis

Using the perfect gas relations, we can write equations (1 & 3) in team of pressure ratio (r_p) across the turbine:



- pressure ratio (r_p) = $\frac{p_3}{p_4} = \frac{p_2}{p_1}$

Using the isentropic relations :-

The absolute temp ratio across the compressor:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = (r_p)^{\frac{k-1}{k}} \quad \text{………………….(4.a)}$$

Where: k = $\frac{c_p}{c_v}$ = 1.4 (for cold air)

And across the turbine is give as :-

$$\frac{T_3}{T_4} = \frac{P_3}{P_4}^{\frac{k-1}{k}} = (r_p)^{\frac{k-1}{k}} \quad \text{…………………..(4.b)}$$

k = 1.33 (for hot gas)

So that the specific work of the turbine from eq.3 is given as :-

$$W_T = C_p\, T_3 \left(1 - \frac{T_4}{T_3}\right) = C_p\, T_3 \left(1 - \frac{1}{(r_p)^{\frac{k-1}{k}}}\right) \quad \text{..................................(5)}$$

Where $T_3 \neq T_2$

And the specific work of compressor from eq.1 is given as :-

$$W_c = C_p\, T_2 \left(1 - \frac{T_1}{T_2}\right) = C_p\, T_2 \left(1 - \frac{1}{(r_p)^{\frac{k-1}{k}}}\right) \quad \text{..................................(6)}$$

where $(r_p)_c = (r_p)_T = \frac{p_2}{p_1} = \frac{p_3}{p_4} = constant$.

The net specific work of the gas turbine cycle :-

$W_{net} = W_T - W_C$ ……………………………………………………………(7)

And the output power, $P = \dot{m} * W_{net}$ ………………………………………(8)

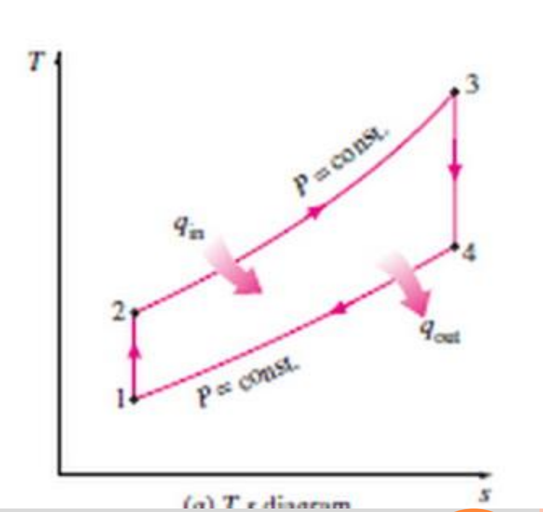
The thermal efficiency of the cycle is:

$$\eta_{th} = \frac{W_{net}}{Q_{add}} = \frac{W_T - W_C}{Q_{add}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

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

$$= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_1}{T_2}\left[\frac{\left(\left(\frac{T_4}{T_1}\right) - 1\right)}{\left(\left(\frac{T_3}{T_2}\right) - 1\right)}\right], \text{ where } \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

$$= 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\frac{T_2}{T_1}} = 1 - \frac{1}{(r_p)^{\frac{k-1}{k}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$



Cold air standard (constant specific heat) .

$W_c = C_p\,(T_2 - T_1)$

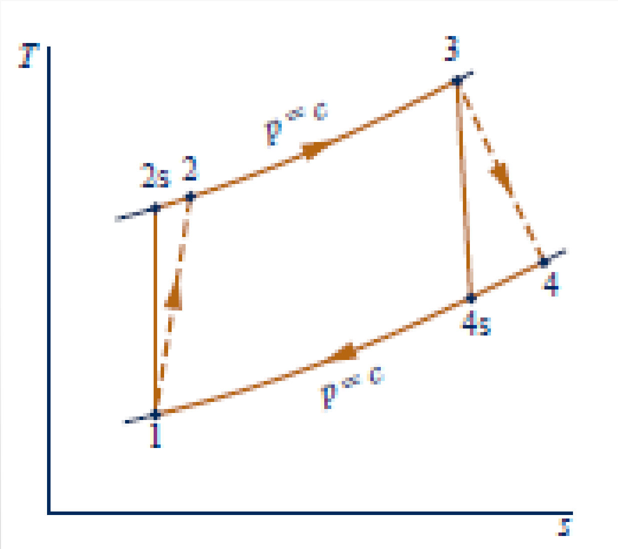
Air – standard (variable specific heat) .

$W_c = h_2 - h_1$

:Example : Gas turbine unit has pressure ratio ($r_p = \frac{6}{1}$) & max temp is 600°C. The isentropic efficiency (η_c = 0.82 , η_T = 0.85). Calculate the power output in (kW), the flow rate of the hot gasses entering the turbine at rate of 15 $\frac{kg}{s}$. The air entrance temp to the compressor is 15 °C, and find BWR.

for air : $C_p = 1.005 \frac{kJ}{kg.K}$, k = 1.4 .

For gas : $C_p = 1.13 \frac{kJ}{kg.K}$, k = 1.33 .



Solution:

For isentropic compression process (compressor):

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

$T_1 = 15+273 = 288$ K

$$\therefore T_{2s} = 288 * (6)^{\frac{1.4-1}{1.4}} = 481\ K$$

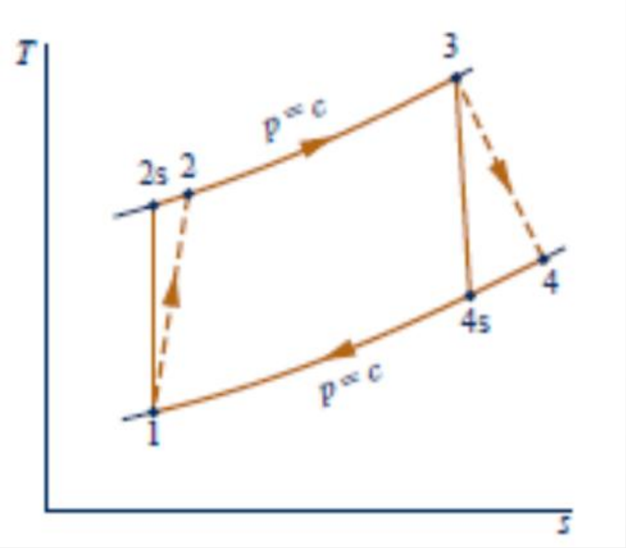
$$\eta_C = \frac{ideal\ work}{actual\ work} = \frac{T_{2s}-T_1}{T_2-T_1} = 0.82$$

$T_2 = 521$ K

- for isentropic expansion process (turbine):

$$\frac{T_3}{T_{4s}} = \left(\frac{P_3}{P_4}\right)^{\frac{k-1}{k}} = (6)^{\frac{1.33-1}{1.33}}$$, where $T_3 = 600+273 = 873$ K

$T_{4s} = 558$ K



$$\eta_T = \frac{actual\ work}{ideal\ work} = \frac{T_3 - T_4}{T_3 - T_{4s}} = 0.85$$

$T_4 = 605$ K

$w_C = C_P (T_2 - T_1) = 1.005(521-288) = 234.16$ kJ/kg

$w_T = C_P (T_3 - T_4) = 1.11(873 - 605) = 297.48$ kJ/kg

$W_{net} = w_T - w_C = 63.31$ kJ/kg

Power output = $\dot{m} * w_{net} = 15*63.31 = 949.72$ kW

$$\eta_{th} = \frac{w_{net}}{q_{add}} = \frac{63.31}{C_p(T_3 - T_2)} = \frac{63.31}{1.11(873-521)} = 15.8\ \%$$

$$\text{BWR} = \frac{W_C}{W_T} = \frac{C_p(T_2 - T_1)}{C_p\ (T_3 - T_4)} = 0.787$$