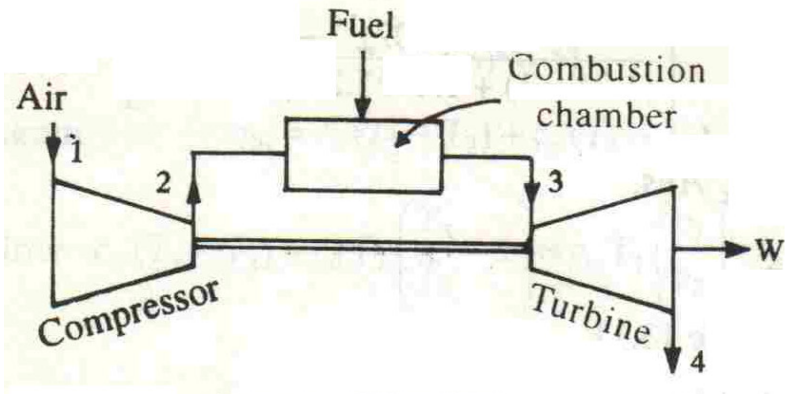
# GAS TURBINES

**Unit 3:**

**Gas Turbines and Jet Propulsion:** Classification of Gas Turbines, Analysis of open cycle gas turbine cycle. Advantages and Disadvantages of closed cycle. Methods to improve thermal efficiency. Jet propulsion and Rocket propulsion.

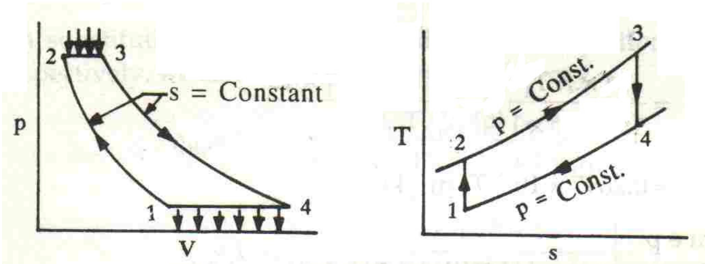
## Simple Gas Turbine Cycle




Open type gas-turbine cycle

A schematic diagram of a simple gas turbine power plant is shown in figure. Air is drawn from the atmosphere into the compressor, where it is compressed reversibly and adiabatically. The relatively high pressure is then used in burning the fuel in the combustion chamber. The air fuel ratio is quite high (about 60:1) to limit the temperature of the burnt gases entering the turbine. The gases then expand isentropically in the turbine. A portion of the work obtained from the turbine is utilized to drive the compressor and the auxiliary drive, and rest of the power output is the net power of the gas turbine plant.

A gas turbine plant works using a Brayton or joule cycle. This cycle was originated by joule, a British engineer for use in a hot air reciprocating engine and later in about 1870 an American engineer George Brayton tried this cycle in a gas turbine. This cycle consists of two constant pressures and two adiabatic processes. The P-V and T-S diagrams of the cycle are as shown in figure.




p-v and T-s diagrams of air stander gas-turbine cycle

Process 1 – 2: isentropic compression in the compressor

Process 2 – 3: constant pressure heat addition in the combustion chamber

Process 3 – 4: isentropic expansion in the turbine

Process 4 -1: constant pressure heat rejection in the atmosphere or cooling of air in the intercooler (closed cycle).

**Expression of net work output:**

We have net work output, $W_N = W_T - W_C$

Turbine work, $W_T = h_3 - h_4$

$= C_P (T_3 - T_4)$ since the working fluid is a perfect gas

Compressor work, $W_C = h_2 - h_1$

$= C_P (T_2 - T_1)$

$\therefore W_N = C_P (T_3 - T_4) - C_P (T_2 - T_1)$

Let $R = \frac{P_2}{P_1} =$ pressure ratio for compression

$t = T_3/T_1$ = Temperature ratio

$$W_N = C_P T_1 \left[ \frac{T_3}{T_1} - \frac{T_4}{T_1} - \frac{T_2}{T_1} + 1 \right]$$

We have $\frac{T_1}{P_1^{\frac{r-1}{r}}} = \frac{T_2}{P_2^{\frac{r-1}{r}}}$ $\qquad \therefore \frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{r-1}{r}} = R^{\frac{r-1}{r}}$

$$\frac{T_4}{T_1} = \frac{T_4}{T_3} \frac{T_3}{T_1}$$

$$= \left( \frac{P_4}{P_3} \right)^{\frac{r-1}{r}} t = \left( \frac{1}{R} \right)^{\frac{r-1}{r}} t \qquad \because P_1 = P_4 \quad \& \quad P_2 = P_3$$

$$\therefore W_N = C_P T_1 \left[ t - \frac{t}{R^{\frac{r-1}{r}}} - R^{\frac{r-1}{r}} + 1 \right]$$

**Expression for Thermal Efficiency:**

We have thermal efficiency, $\eta_{th} = \frac{W_N}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$

Heat added, $Q_H = h_3 - h_2 = C_P (T_3 - T_2)$
Heat rejected, $Q_L = h_4 - h_1 = C_P (T_4 - T_1)$

$$\therefore \eta_{th} = 1 - \frac{C_P(T_4 - T_1)}{C_P(T_3 - T_2)} = 1 - \frac{T_1\left[\frac{T_4}{T_1} - 1\right]}{T_2\left[\frac{T_3}{T_2} - 1\right]}$$

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

But as $P_2 = P_3$ & $P_1 = P_4$, it follows that $\frac{T_2}{T_1} = \frac{T_3}{T_4}$ *or* $\frac{T_4}{T_1} = \frac{T_3}{T_1}$

$$\therefore \eta_{th} = 1 - \frac{T_1}{T_2} \quad i.e., \quad \eta_{th} = 1 - \frac{1}{\left(\frac{T_2}{T_1}\right)} \quad \text{or} \quad \eta_{th} = 1 - \frac{1}{R^{\frac{r-1}{r}}}$$

From the above equation, it is seen that the efficiency of the air standard gas turbine cycle increases with increase in pressure ratio (R) and the type of working fluid.

**Optimum Pressure Ratio for Specific Power Output**

In a gas turbine cycle, $T_1$ is the temperature of the atmosphere and $T_3$ is the temperature of the burnt gases entering the turbine. Temperature $T_3$ is fixed by the metallurgical consideration of the turbine and temperature $T_1$ is fixed by the atmospheric condition. Between these two extreme values of temperature, there exists an optimum pressure ratio for which the work output of the turbine is maximum.

We have, the net work output of the turbine is,

$$W_N = C_P T_1 \left[ t - \frac{t}{R^{\frac{r-1}{r}}} - R^{\frac{r-1}{r}} - 1 \right] \qquad \text{--- (1)}$$

The optimum pressure ratio is obtained by differentiating the net work output w.r.t. the pressure ratio and putting the derivative equal to zero i.e., $\frac{dW_N}{dR} = 0$

$$\text{Or } \frac{d}{dR}\left[ C_P T_1 \left\{ t - \frac{t}{R^{\frac{\gamma-1}{\gamma}}} - R^{\frac{\gamma-1}{\gamma}} - 1 \right\} \right] = 0$$

Differentiating with respect to R we get,

$$-t\frac{1-\gamma}{\gamma}R^{\frac{1-\gamma-\gamma}{\gamma}}-\frac{\gamma-1}{\gamma}R^{\frac{\gamma-1-\gamma}{\gamma}}=0$$

$$\text{i.e., } -t\left(\frac{1-\gamma}{\gamma}\right)R^{\frac{1-2\gamma}{\gamma}}=\frac{\gamma-1}{\gamma}R^{-1/\gamma}$$

$$t\left(\frac{\gamma-1}{\gamma}\right)R^{\frac{1-2\gamma}{\gamma}}=\frac{\gamma-1}{\gamma}R^{-1/\gamma}$$

$$\text{or } \frac{R^{-1/\gamma}}{R^{\frac{1-2\gamma}{\gamma}}}=t \quad or \quad R^{-\frac{1}{\gamma}-\frac{1-2\gamma}{\gamma}}=t$$

$$\text{or } R^{\frac{-1-1+2\gamma}{\gamma}}=t \quad or \quad R^{\frac{2(\gamma-1)}{\gamma}}=t$$

$$\text{or } (R)_{opt}=t^{\frac{\gamma}{2(\gamma-1)}} \qquad \text{i.e., } R_{opt}=\left[\frac{T_3}{T_1}\right]^{\frac{\gamma}{2(\gamma-1)}}$$

Substituting this value of R in the expression for $W_N$, we get

$$(W_N)_{opt}=C_PT_1\left[t-\frac{t}{\left[t^{\frac{r}{2(r-1)}}\right]^{\frac{r-1}{r}}}-\left[t^{\frac{r}{2(r-1)}}\right]^{\frac{r-1}{r}}+1\right]$$

$$=C_PT_1\left[t-\frac{t}{t^{\frac{1}{2}}}-t^{\frac{1}{2}}+1\right]$$

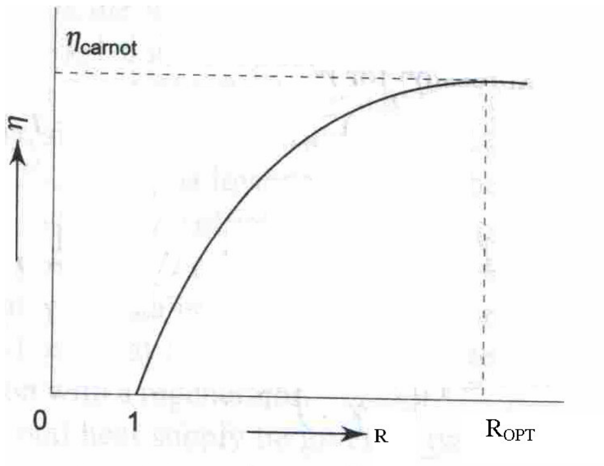
$$=C_PT_1\left[t-t^{\frac{1}{2}}-t^{\frac{1}{2}}+1\right]$$

$$=C_PT_1\left[t-2t^{\frac{1}{2}}+1\right]$$

$$(W_N)_{opt}=C_PT_1\left[t^{\frac{1}{2}}-1\right]$$

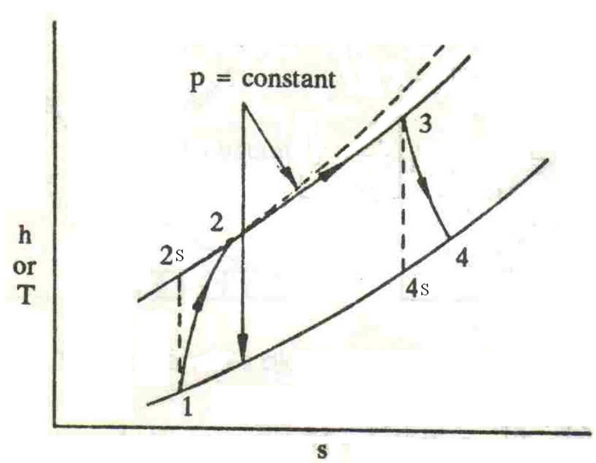
$$\eta_{th} = 1 - \frac{1}{R^{\frac{r-1}{r}}} \quad = \quad 1 - \frac{1}{\left[ t^{\frac{r}{2(r-1)}} \right]^{\frac{r-1}{r}}}$$

$$\therefore (\eta_{th})_{opt} = 1 - \frac{1}{t^{\frac{1}{2}}}$$




*Effect of pressure ratio on Brayton cycle efficiency*

In an ideal gas turbine plant, the compression and expansion processes are isentropic and there is no pressure-drop in the combustion chamber. But because of irreversibilities associated in the compressor and the turbine, and the pressure-drop in the actual flow passages and combustion chamber, an actual gas turbine plant differs from ideal one. The T-S diagram of actual plant is shown in figure.

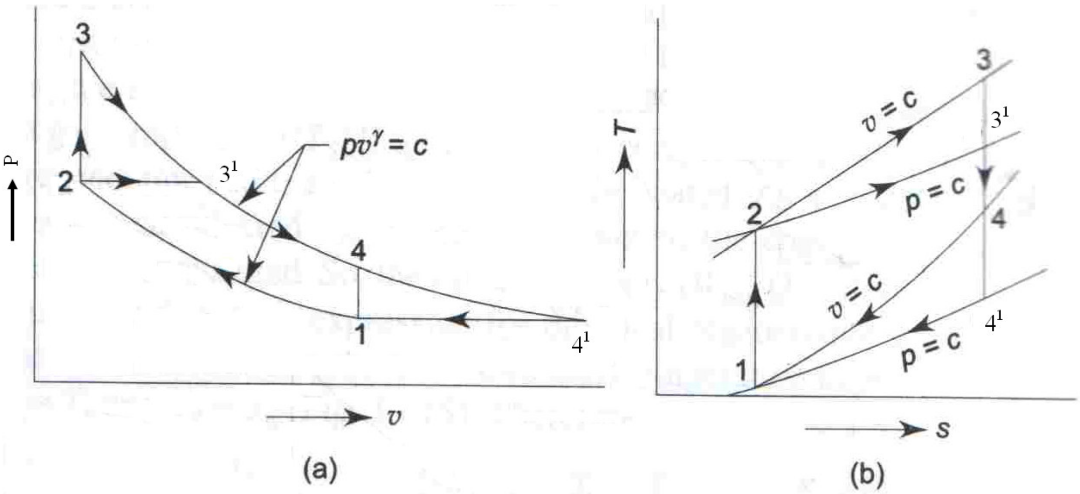



T-s diagram of the actual cycle

$$\therefore Compressor \quad efficeincy, \quad \eta_C = \frac{h_{2S} - h_1}{h_2 - h_1}$$

$$\text{and the } turbine \quad efficeincy, \quad \eta_t = \frac{h_3 - h_4}{h_3 - h_{4S}}$$

**Comparison between Brayton cycle and Otto cycle:**




*Comparison of Otto and Brayton cycles*

1-2-3-4⇒ Otto cycle
$1\text{-}2\text{-}3^1\text{-}4^1$⇒ Brayton cycle

For same comparison ratio and work capacity, the Brayton cycle handles a larger range of volume and a smaller range of pressure and temperatures than does the Otto cycle.

In the reciprocating engine field, the Brayton cycle is not suitable. A reciprocating engine cannot efficiently handle a large volume flow of low pressure gas, for which the engine size ($\pi/4\ D^2L$) becomes large, and the friction losses also become more. So the Otto cycle is suitable in the reciprocating engine field.

In turbine plants, however, the Brayton cycle, is more suitable than the Otto cycle. An I.C. engine is exposed to the highest temperature (after the combustion of fuel) only for a short while, and it gets time to become cool in the other processes of the cycle. On the other hand, a gas turbine plant, a steady flow device, is always exposed to the highest temperature used. So to protect material, the maximum temperature of gas that can be used in a gas turbine plant cannot be as high as in I.C. engine. Also, in the steady flow machinery, it is more difficult to carryout heat transfer at constant volume than at constant pressure. Also, a gas turbine can handle a large volume flow of gas quite efficiently.

**Classification:** Gas turbine are mainly divided into two group

**I Constant pressure combustion gas turbine**
i) Open cycle, ii) Closed cycle

**II Constant volume combustion gas turbine**
In almost all the field open cycle gas turbine plants are used. Closed cycle plants were introduced at one stage because of their ability to burn cheap fuel.

**Advantages and disadvantages of closed cycle over open cycle**

**Advantages of closed cycle:**

i) Higher thermal efficiency
ii) Reduced size
iii) No contamination
iv) Improved heat transmission
v) Improved part load $\eta$
vi) Lesser fluid friction
vii) No loss of working medium
viii) Greater output and
ix) Inexpensive fuel.

**Disadvantages of closed cycle:**

i) Complexity
ii) Large amount of cooling water is required. This limits its use of stationary installation or marine use
iii) Dependent system
iv) The wt of the system pre kW developed is high comparatively, $\therefore$ not economical for moving vehicles
v) Requires the use of a very large air heater.