

# MAE431-Energy System Presentation

*Topic: Introduction to Brayton Cycle*

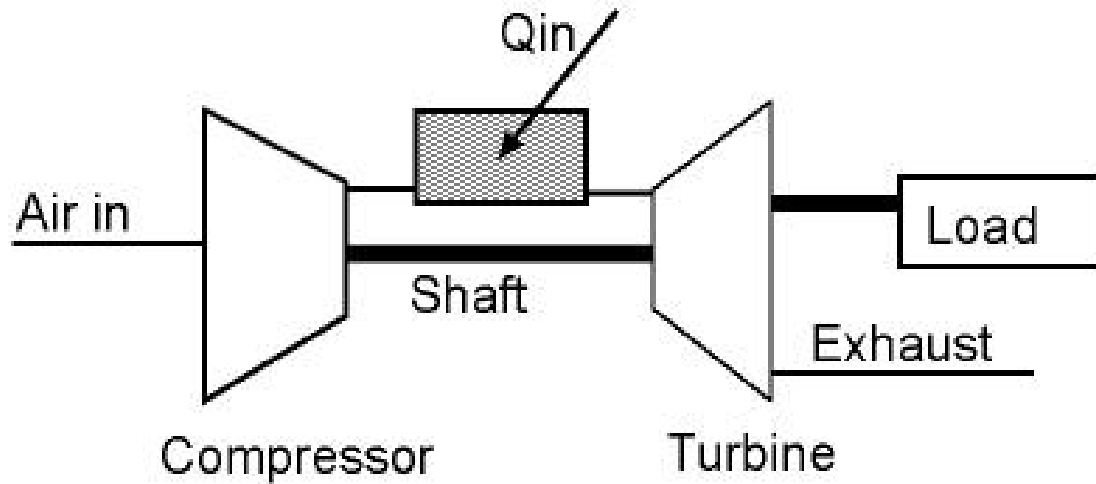
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# Topics covered:

1. Gas Turbine power Plant.
2. History of Brayton Cycle.
3. Air standard Brayton Cycle
4. Work and Heat Transfer in Brayton cycle.  
-Ideal Air-Standard Brayton Cycle.
5. Pressure Ratio effect on the efficiency of Brayton cycle.
6. Irreversibility effect on the efficiency.
7. Regenerative gas turbine.

# 1. Gas Turbine Power Plant

Introduction:



Three basic components:

1. Compressor
2. Combustor
3. Turbine

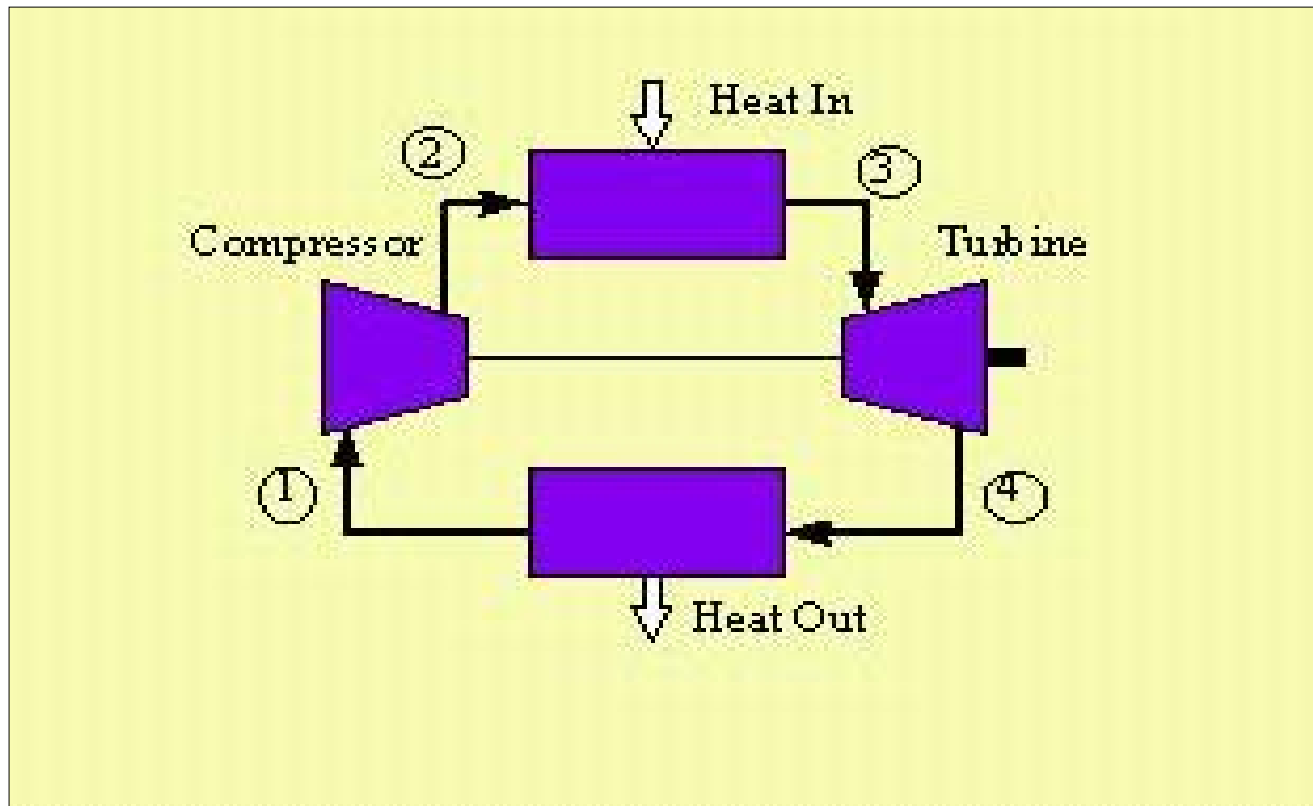
# 1. Gas Turbine Power Plant

## *-Modeling Gas Turbine Power Plant*

1. Working Fluid is air.
2. Combustion process model by a Heat Exchanger.
3. No composition change in the air.

# 1. Gas Turbine Power Plant

Model of the Gas Turbine Power Plant- Brayton Cycle

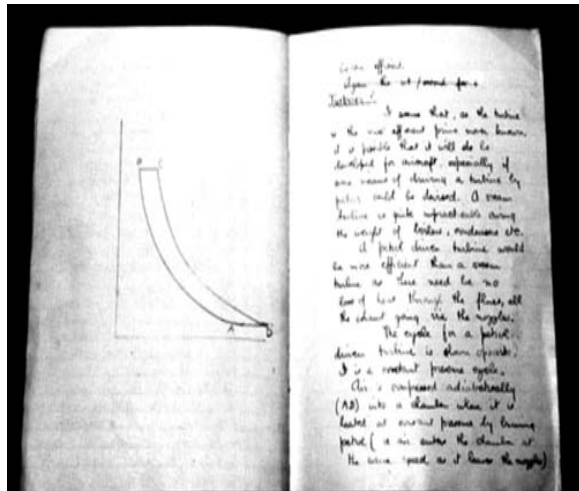


## 2. History of Brayton Cycle



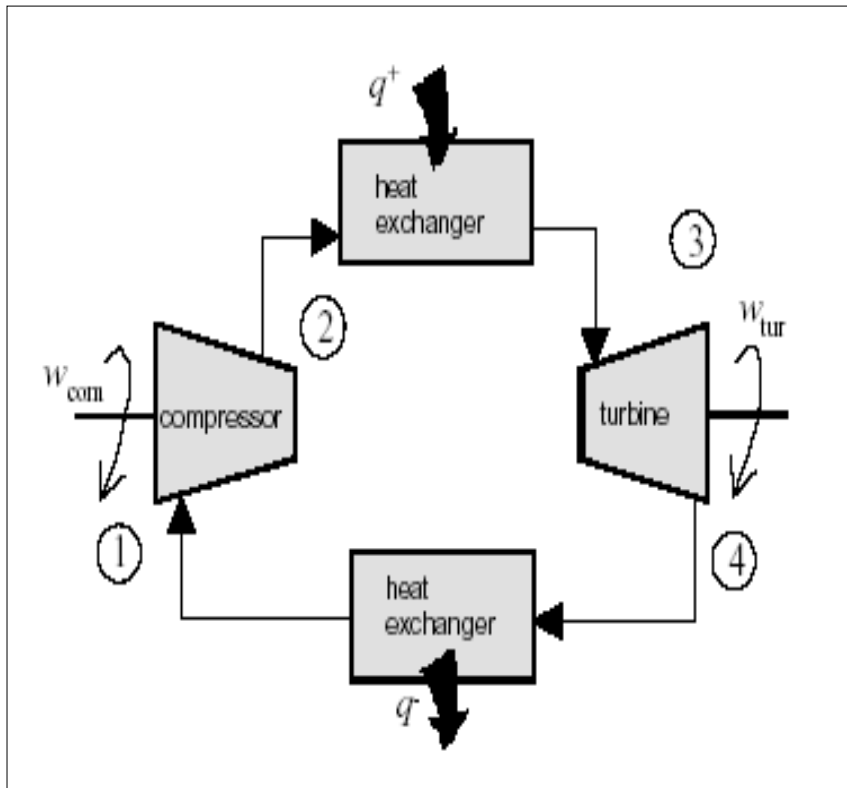
- Invented by *George Baily Brayton*.
- Not commercially successful.

Reasons: Not compact and efficient as the Otto cycle available at the same time.



- *Frank Whittle*, a young cadet shows the limitation of the piston driven engines for high speed air craft in his term paper.
- He showed that a continuous flow turbine based engine in which combustion occurred at constant pressure could overcome these limitations.
- This cycle, of course, is the Brayton cycle.

### 3. Air Standard Brayton Cycle

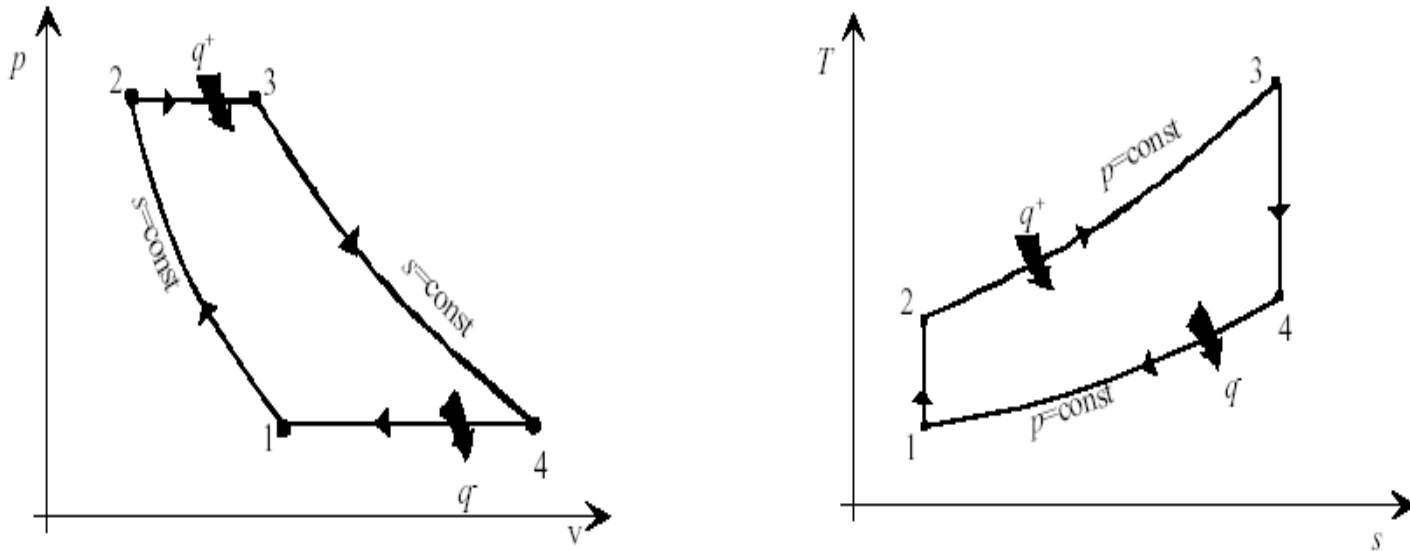


*Assumptions:*

- *Model combustion as a heat exchanger.*
- *Air is an Ideal Gas*
- *Model as a close system.*
- *Undergoes a thermo-dynamic Cycle.*

# 3. Air Standard Brayton Cycle

## *P-v Diagram and T-s Diagram of Brayton Cycle*



- *Process 1-2: Isentropic compression in the compressor*
- *Process 2-3: Heat Addition at a constant pressure*
- *Process 3-4: Isentropic expansion in a turbine*
- *Process 4-1: Heat Rejection at a constant pressure.*

## 4. Work and Heat Transfer in Brayton Cycle

*Analysis Tools:*

1. Mass Rate Balance Equation.

$$\sum_{in} \dot{m}_{in} = \sum_{out} \dot{m}_{out}$$

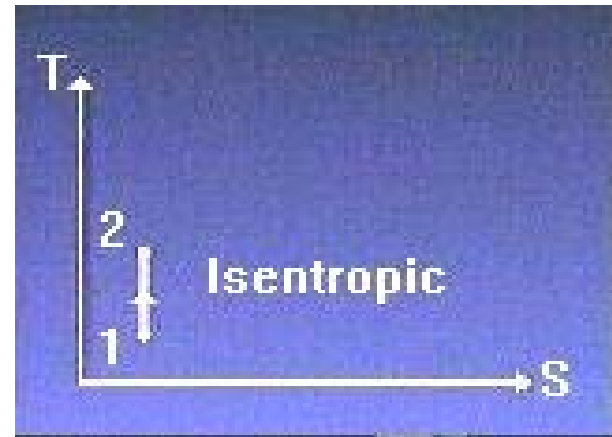
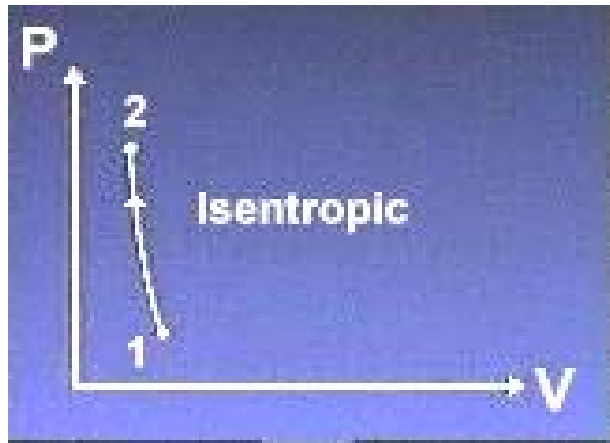
2. Energy Rate Balance Equation.

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W} + \sum_{in} \dot{m}_{in} \left( h_{in} + \frac{V_{in}^2}{2} + gz_{in} \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right)$$

# 4. Work and Heat Transfer in Brayton Cycle

*State 1 to State 2:*

*Isentropic Compression Process in the Compressor.*



*Assumptions:*

- Steady State Exists.
- Kinetic and Potential Energy are negligible in the process
- No Heat Transfer in the compression process.

# 4. Work and Heat Transfer in Brayton Cycle

*Mathematical model:*

*State 1 to State 2-*

1. Apply Mass Balance Equation,

$$\sum_{in} \dot{m}_{in} = \sum_{out} \dot{m}_{out}$$
$$\Rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}$$

2. Apply Energy Rate Balance Equation,

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W} + \sum_{in} \dot{m}_{in} \left( h_{in} + \frac{V_{in}^2}{2} + gz_{in} \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right)$$

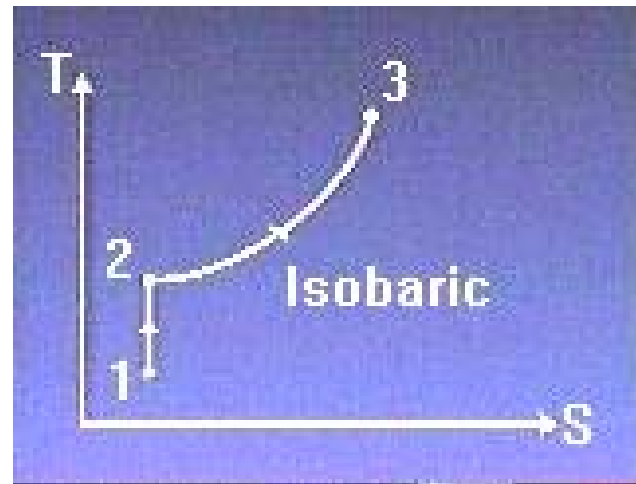
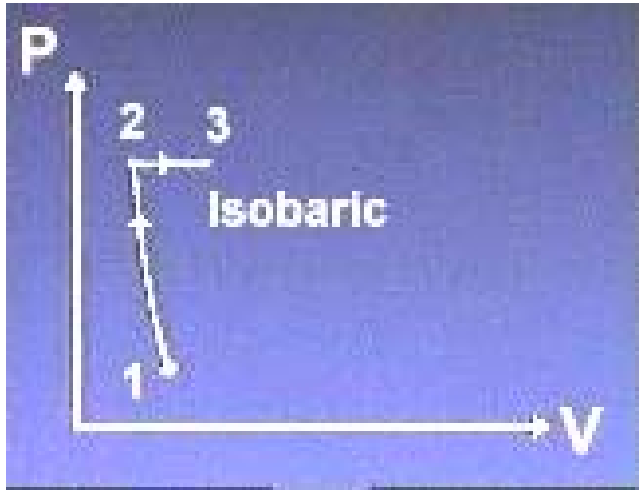
With the given assumptions, we have:

$$\dot{W}_{compressor} = \dot{m}(h_1 - h_2)$$

## 4. Work and Heat Transfer in Brayton Cycle

*State 2 to state 3:*

*-Isobaric Expansion Process in the Heat Exchanger.*



Assumptions:

- Steady State Conditions exists.
- Kinetic energy and potential energy is negligible
- No work is being done during this process.

# 4. Work and Heat Transfer in Brayton Cycle

*Mathematical model:*

*State 2 to State 3-*

1. Apply Mass Balance Equation,

$$\sum_{in} \dot{m}_{in} = \sum_{out} \dot{m}_{out}$$

$$\Rightarrow \dot{m}_2 = \dot{m}_3 = \dot{m}$$

2. Apply Energy Rate Balance Equation,

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W} + \sum_{in} \dot{m}_{in} \left( h_{in} + \frac{V_{in}^2}{2} + gz_{in} \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right)$$

With the given assumptions, we have:

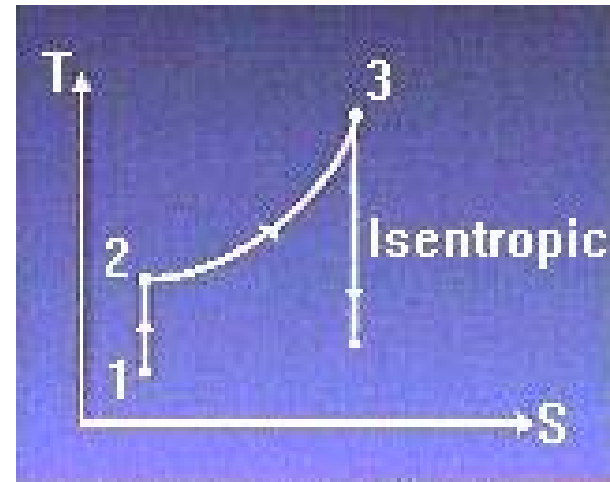
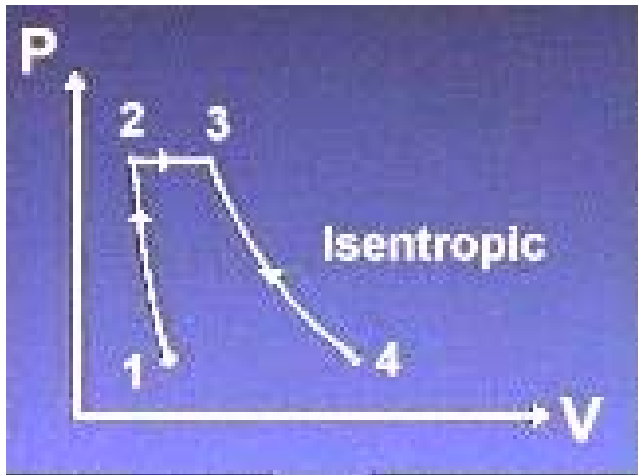
$$\Rightarrow \dot{Q}_{in} = \dot{m}h_3 - \dot{m}h_2$$

$$\Rightarrow \frac{\dot{Q}_{in}}{\dot{m}} = h_3 - h_2$$

## 4. Work and Heat Transfer in Brayton Cycle

*State 3 to State 4:*

*Isentropic Expansion Process in the Turbine*



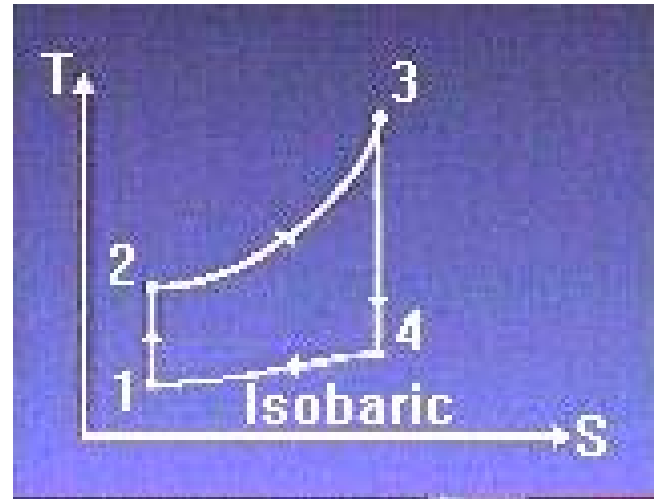
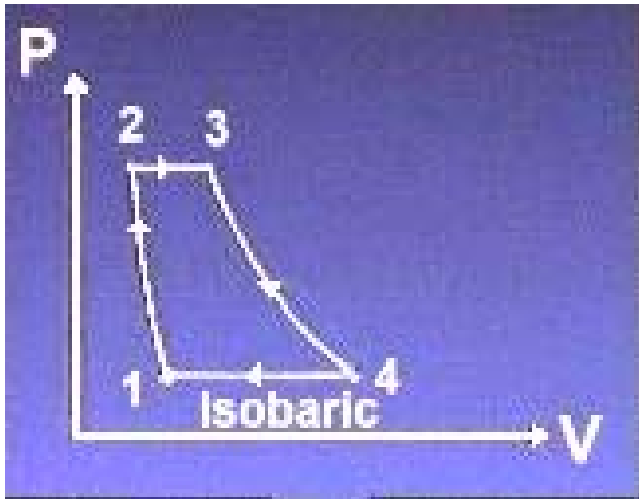
Similar to the process from State 1 to State 2, the Work output is:

$$\frac{\dot{W}_{turbine}}{\dot{m}} = (h_3 - h_4)$$

## 4. Work and Heat Transfer in Brayton Cycle

*State 4 to State 1:*

*-Isobaric Heat Transfer Process in the Heat Exchanger*



Similar to the process from State 2 to State 3, the Heat Transfer is:

$$\frac{\dot{Q}_{out}}{\dot{m}} = (h_4 - h_1)$$

## 4. Work and Heat Transfer in Brayton Cycle

*Thermal Efficiency of Brayton Cycle:*

$$\text{Thermal Efficiency, } \eta = \frac{\text{desired} - \text{work} - \text{output}}{\text{required} - \text{heat} - \text{input}}$$

$$\Rightarrow \eta = \frac{\dot{W}_{\text{turbine}}/\dot{m} - \dot{W}_{\text{compressor}}/\dot{m}}{\dot{Q}_{\text{in}}/\dot{m}}$$

(Part of the work Output was used to drive the compressor.)

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

# 4. Work and Heat Transfer in Brayton Cycle

-Ideal Air-Standard Brayton Cycle.

*Using Ideal Gas Equation to further idealize the Brayton Cycle*

## **Advantages:**

1. We can avoid using Air table to find the respective enthalpy.
2. Can provide an upper limit to the performance of Brayton Cycle

## **Assumptions:**

1. There is no frictional pressure drop in the in the cycle.
2. There is no irreversibility in the cycle.
3. Heat Transfer to the surrounding is also ignored.

**Basic Equations:** Ideal gas Equation for Isentropic Process:

$$P_1 V_1^k = P_2 V_2^k \quad \text{or} \quad T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{(k-1)}{k}}$$

## 4. Work and Heat Transfer in Brayton Cycle

-Ideal Air-Standard Brayton Cycle.

We will get the following relations for Brayton Cycle:

$$\frac{V_1}{V_4} = \frac{V_2}{V_3} \quad \text{and} \quad \frac{P_1}{P_2} = \frac{P_4}{P_3} \quad \text{and} \quad \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

## 5. Pressure Ratio Effect on the Efficiency of Brayton cycle.

*Using Specific Heat Equation for Ideal Gas,*

$$dh = C_p (T) dT$$

*The Thermal Efficiency of the Brayton Cycle can now be calculated in terms of temperature:*

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

We have,

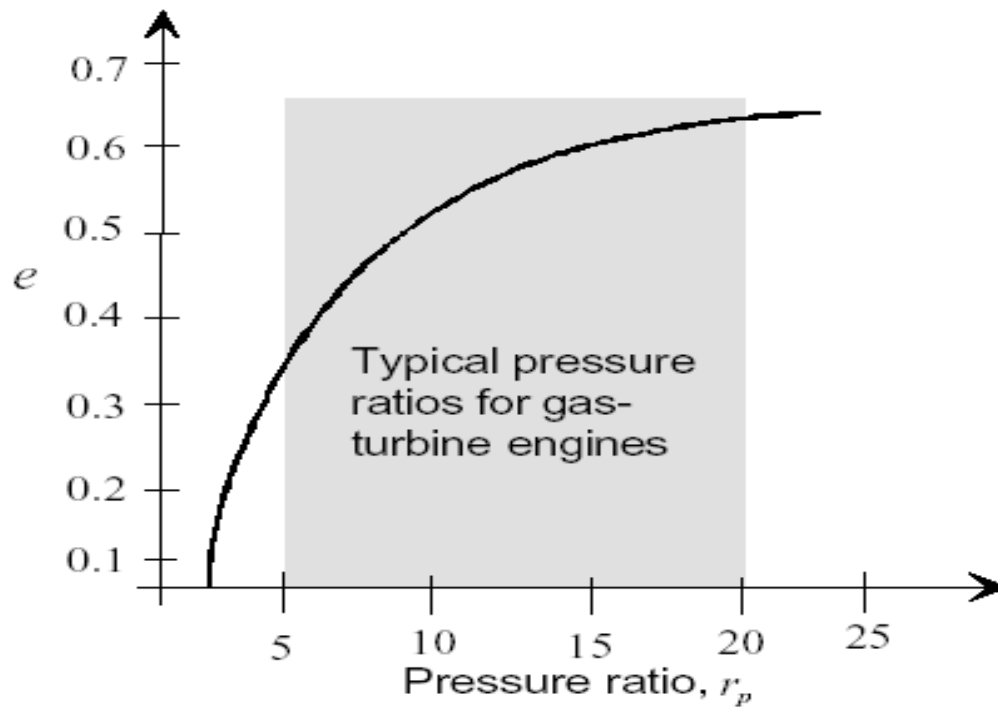
$$\eta = \frac{C_p(T_3 - T_4) - C_p(T_2 - T_1)}{C_p(T_3 - T_2)}$$

And Finally,

$$\Rightarrow \eta = 1 - \frac{1}{\left(P_2 / P_1\right)^{\frac{(k-1)}{k}}}$$

-Relation between pressure ratio and thermal efficiency.

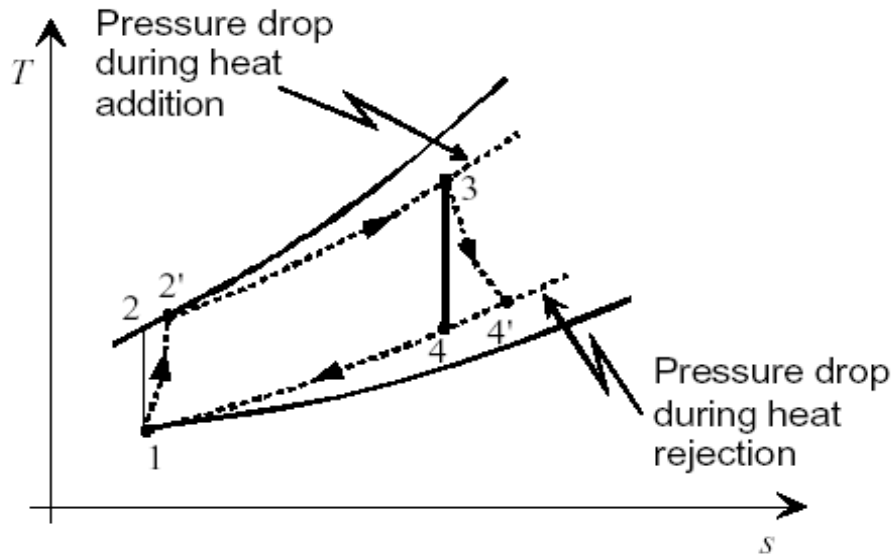
## 5. Pressure Ratio Effect on the Efficiency of Brayton cycle.



*Restrictions on the pressure ratio:*

1. Metallurgical consideration at the Turbine Inlet.
2. Size of the Gas Turbine.

# 6. Effect of Irreversibility on Efficiency



-Increase of entropy in compressor and Turbine due to frictional effect.

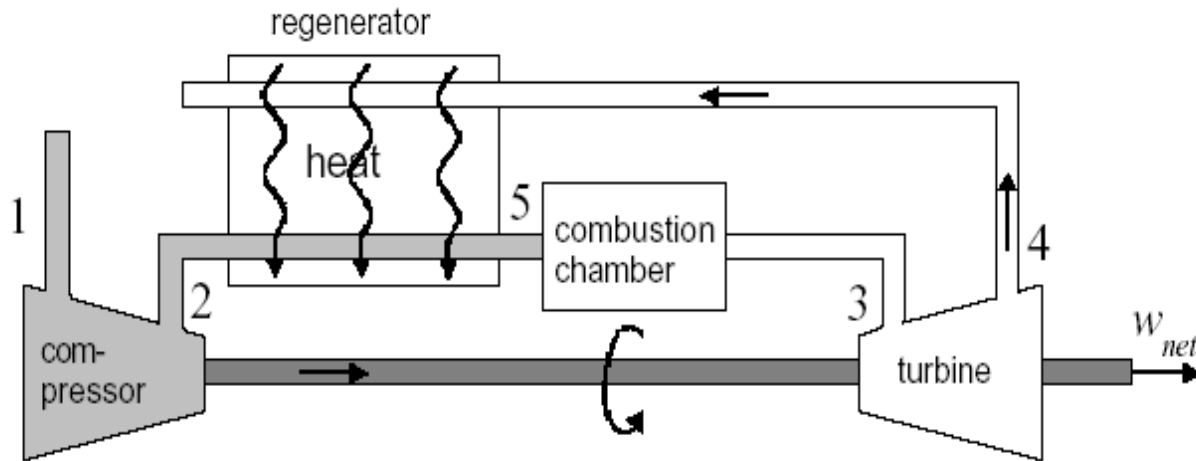
-Experience pressure drop in Heat Exchanger due to Friction.

*Thus, Isentropic Efficiency of the Turbine and Heat Exchanger become:*

$$\eta_{\text{turbine}} = \frac{(\dot{W}_{\text{turbine}} / \dot{m})}{(\dot{W}_{\text{turbine}} / \dot{m})_s} = \frac{h_3 - h_4}{h_3 - h_{4,s}}$$

$$\eta_{\text{compressor}} = \frac{(\dot{W}_{\text{compressor}} / \dot{m})}{(\dot{W}_{\text{compressor}} / \dot{m})_s} = \frac{h_{2,s} - h_1}{h_2 - h_1}$$

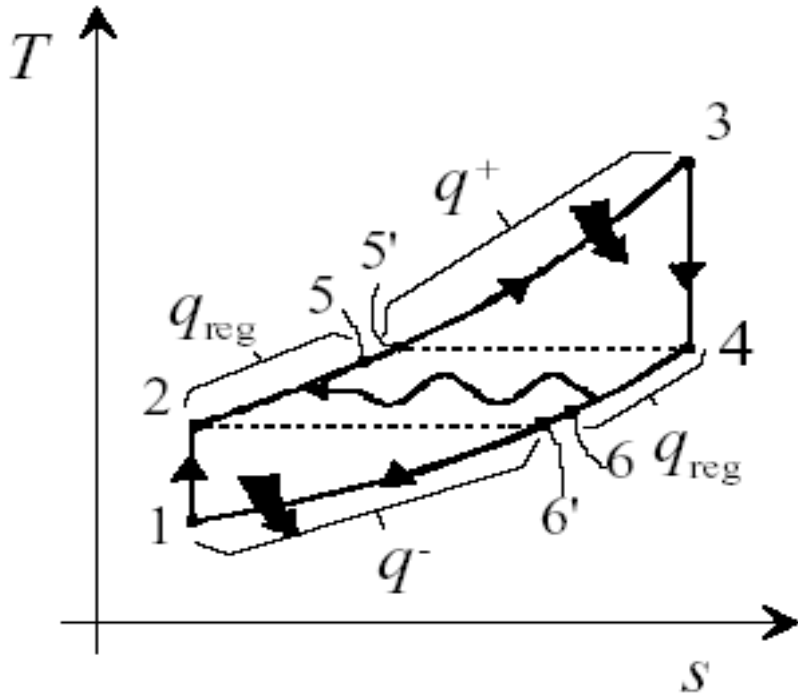
# 7. Regenerative Gas Turbine



- Use of Energy of the air exhausted from the Turbine to partly heat the air from the compressor.
- The heat exchange between the Exhaust air and the air from the compressor occurs in the “Regenerator”.

# 7. Regenerative Gas Turbine

*T-s diagram of a Regenerative Gas Turbine.*



-The exhaust gas is cooled from state 4 to state 6 in the regenerator.

-Air exiting the compressor is heated from state 2 to state 5 in the regenerator.

-The extra heat from the exhausted air will eventually go to state 1.

-Air exiting the compressor was heated from state 5' to state 3

*Now, the efficiency of the Brayton Cycle becomes:*

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_{5'}}$$

# Summary

- ***Gas Turbine Power Plant***

*Open mode, Close mode.*

- ***History of Brayton Cycle***

- ***Air Standard Brayton Cycle***

*Assumptions, Model as Two Isentropic Processes and two Isobaric Processes.*

- ***Work and Heat Transfer in Brayton Cycle***

Work: 
$$\frac{\dot{W}_{compressor}}{\dot{m}} = (h_1 - h_2) \quad \frac{\dot{W}_{turbine}}{\dot{m}} = (h_3 - h_4)$$

Heat: 
$$\frac{\dot{Q}_{in}}{\dot{m}} = (h_3 - h_2) \quad \frac{\dot{Q}_{out}}{\dot{m}} = (h_4 - h_1)$$

*Thermal Efficiency:*

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

# Summary (continue)

- *Pressure Effect on the Efficiency of the Brayton Cycle*

$$\eta = 1 - \frac{1}{(P_2 / P_1)^{\frac{(k-1)}{k}}}$$

- *Effect of Irreversibility on Efficiency*

*Isentropic efficiency:*

$$\eta_{turbine} = \frac{(\dot{W}_{turbine} / \dot{m})}{(\dot{W}_{turbine} / \dot{m})_s} = \frac{h_3 - h_4}{h_3 - h_{4,s}}$$

$$\eta_{compressor} = \frac{(\dot{W}_{compressor} / \dot{m})_s}{(\dot{W}_{compressor} / \dot{m})} = \frac{h_{2,s} - h_1}{h_2 - h_1}$$

- *Regenerative Gas Turbine*

*Increase in Efficiency:*

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_5}$$

End- Thank you.