MAE431-Energy System Presentation

Topic: Introduction to Brayton Cycle

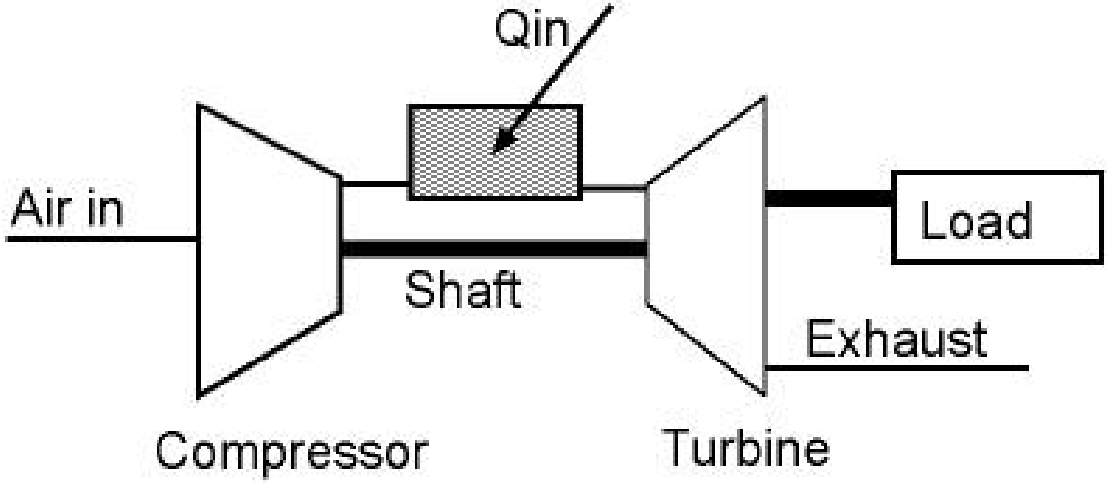
Prepared by: Lee Leng Feng

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

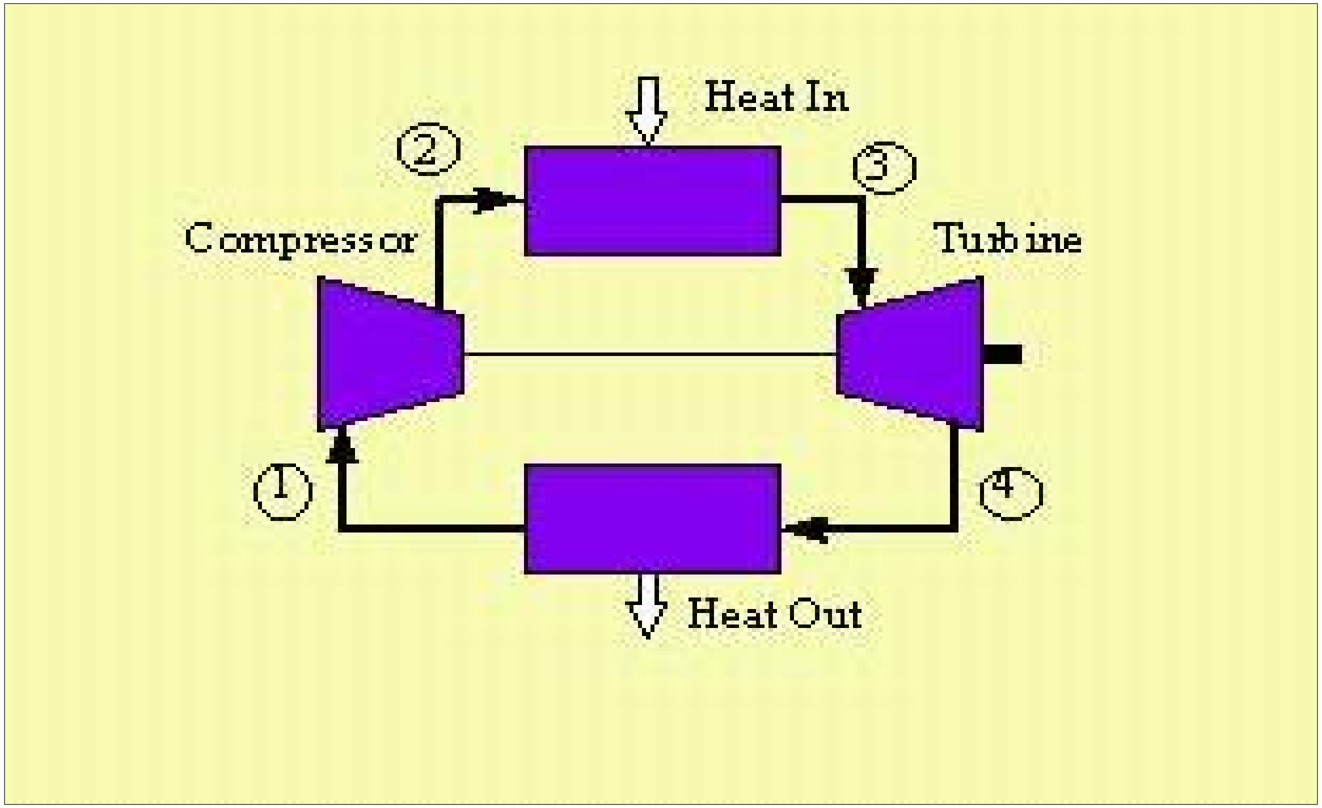
1. Gas Turbine Power Plant

-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

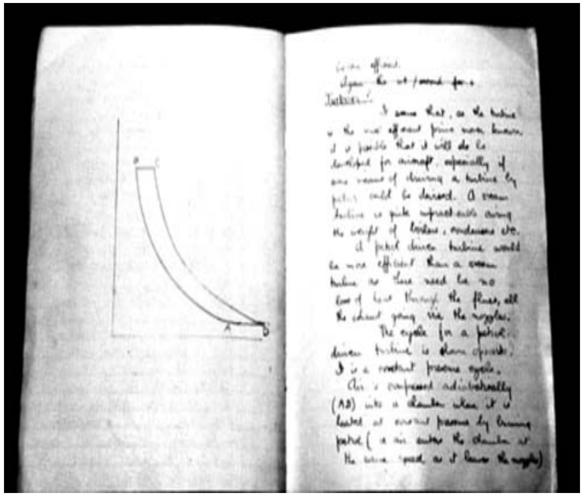
Model of the Gas Turbine Power Plant- Brayton Cycle



2. History of Brayton Cycle

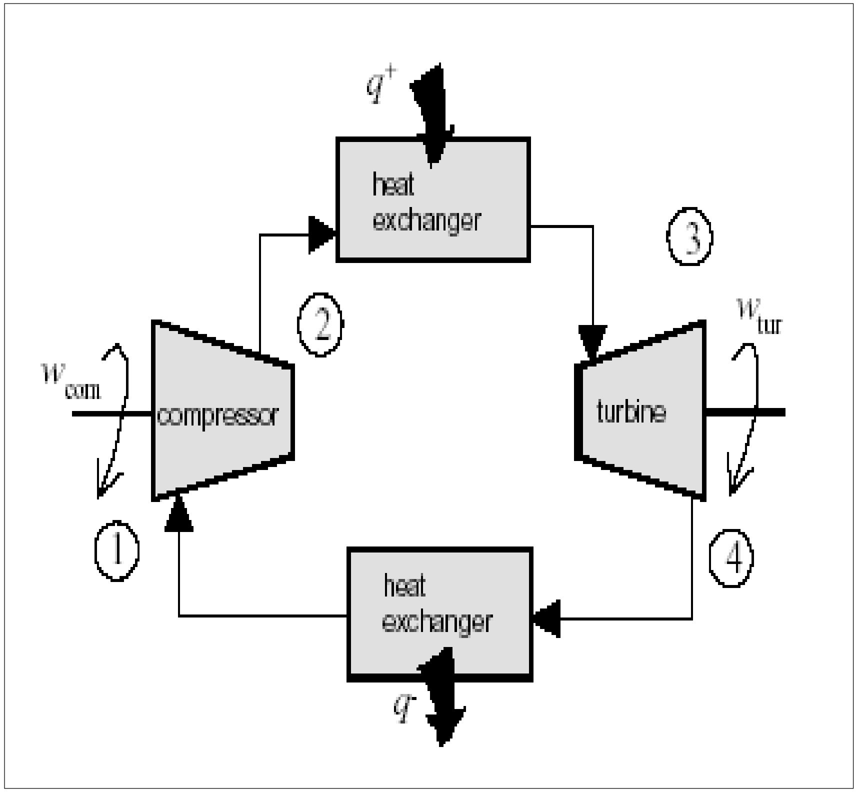
- Invented by *George Baily Brayton*.
- Not commercially successful.

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

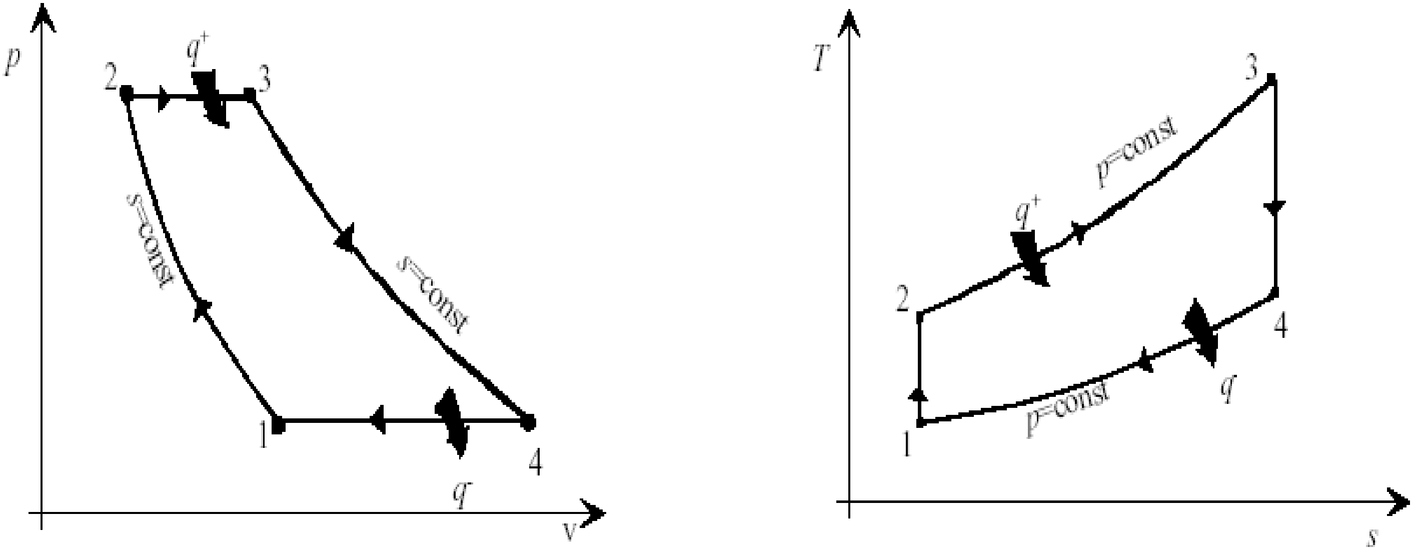


Assumptions:

- *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.

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

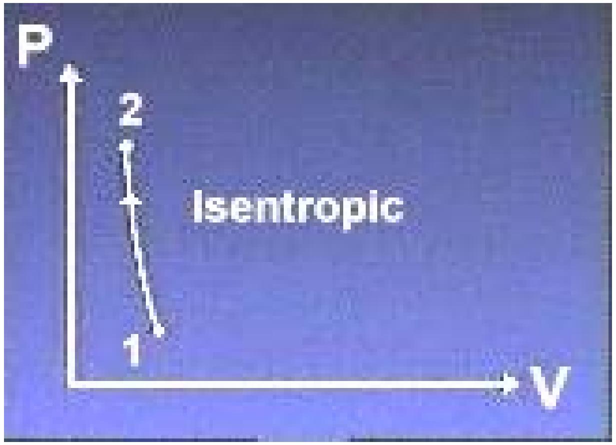
2. Energy Rate Balance Equation.

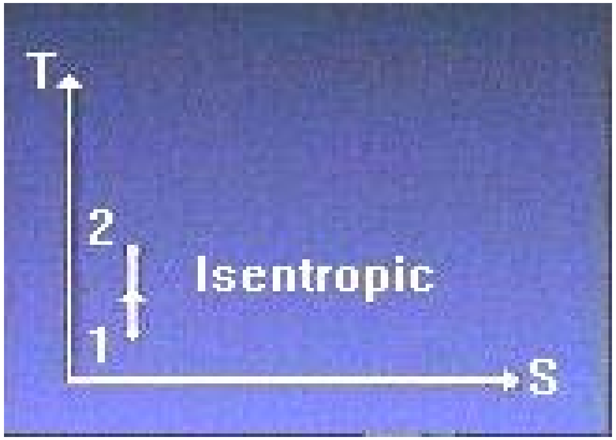
$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W} + \sum_{in} m_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gz_{in}\right) - \sum_{e} m_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

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,

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

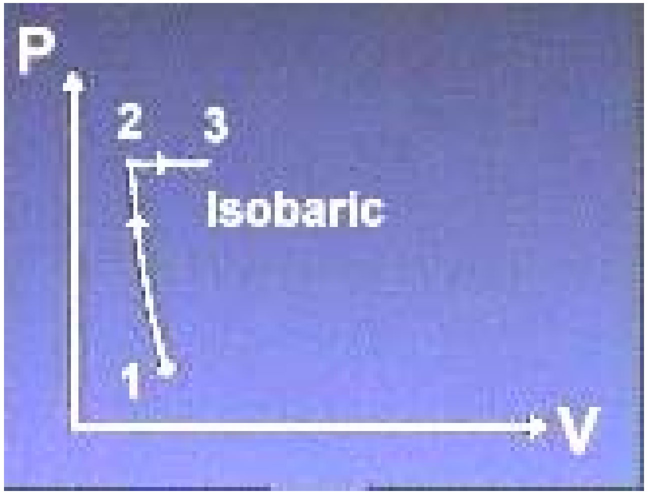
With the given assumptions, we have:

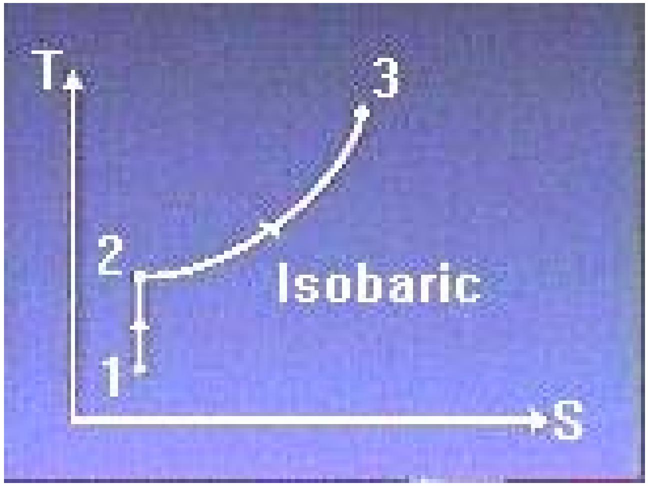
$$\dot{W}_{compressor} = \dot{m}(h_1 - h_2)$$

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,

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

With the given assumptions, we have:

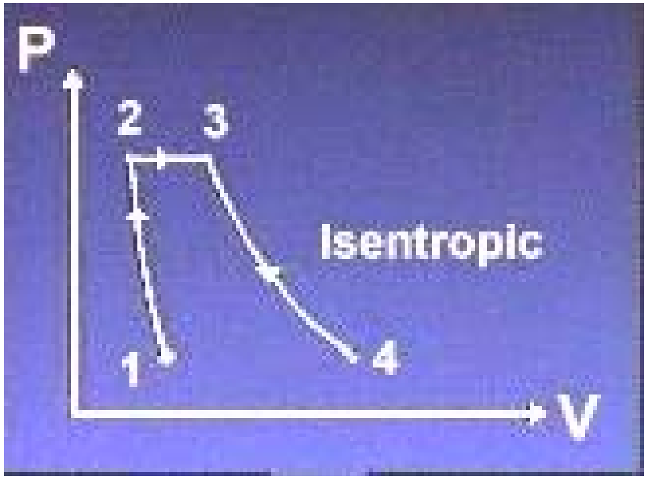
$$\Rightarrow \dot{Q}_{in} = \dot{m}h_3 - \dot{m}h_2$$

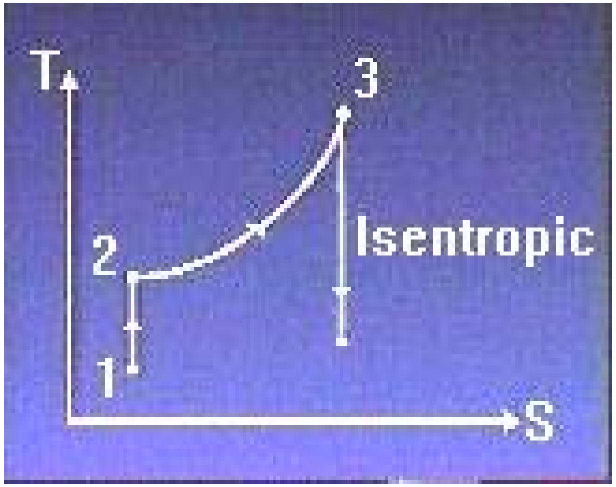
$$\Rightarrow \frac{\dot{Q}_{in}}{\dot{m}} = h_3 - h_2$$

4. Work and Heat Transfer in Brayton Cycle

State 3 to State 4:

Isentropic Expansion Process in the Turbine





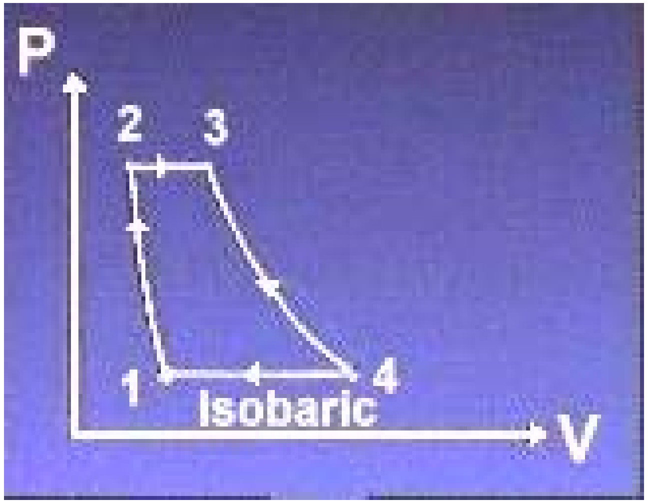
Similar to the process from State 1 to State 2, the Work output is:

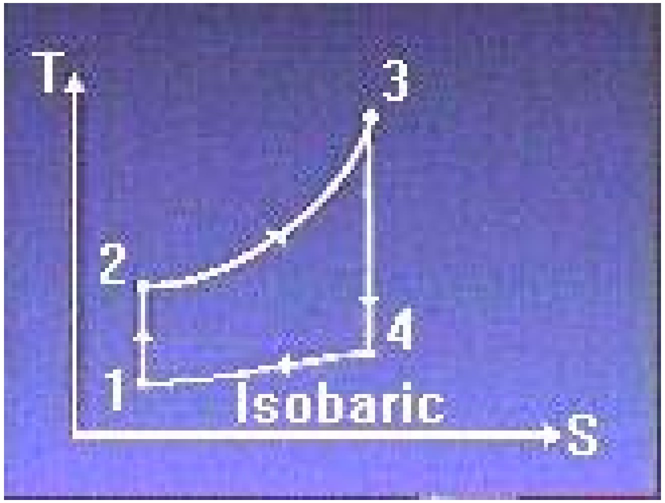
$$\frac{\dot{W}_{turbine}}{\dot{m}} = (h_3 - h_4)$$

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:

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

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

(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:

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

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,

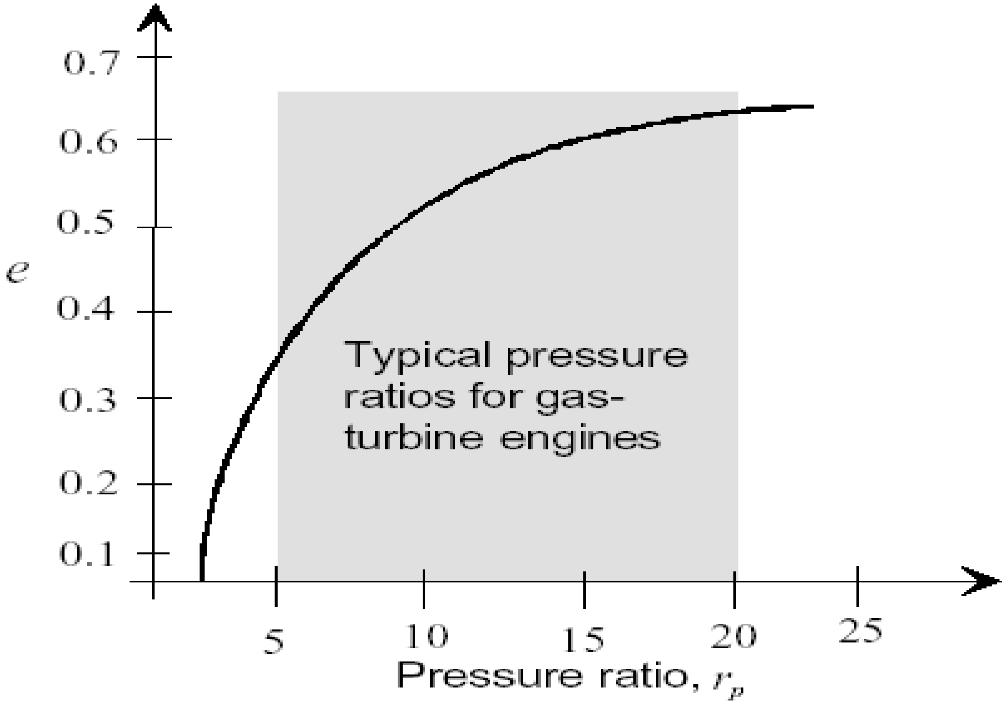
$$\eta = \frac{C_p(T_3 - T_4) - C_p(T_2 - T_1)}{C_p(T_3 - T_2)}$$

And Finally,

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

-Relation between pressure ratio and thermal efficiency.

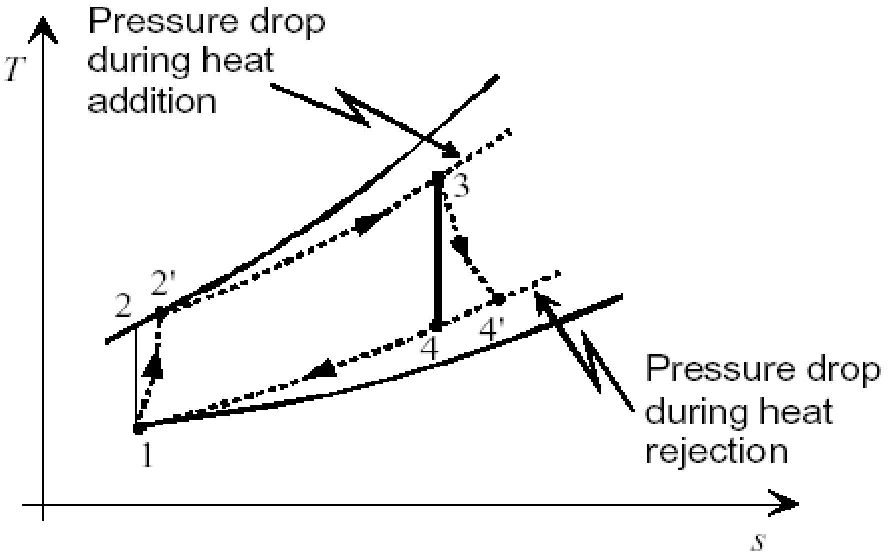
5. Pressure Ratio Effect on the Efficiency of Brayton cycle.



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.

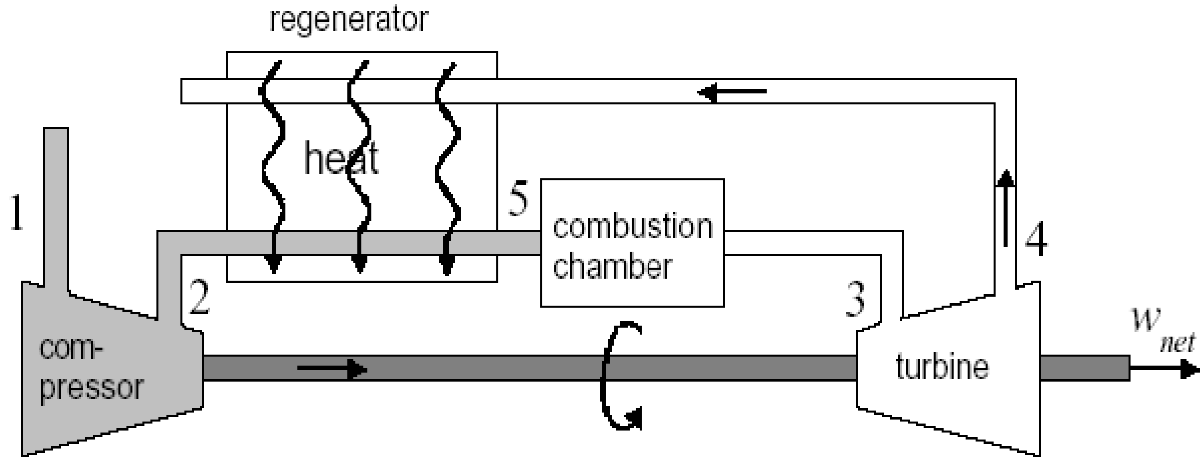
-Experience pressure drop in Heat Exchanger due to Friction.

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

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

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

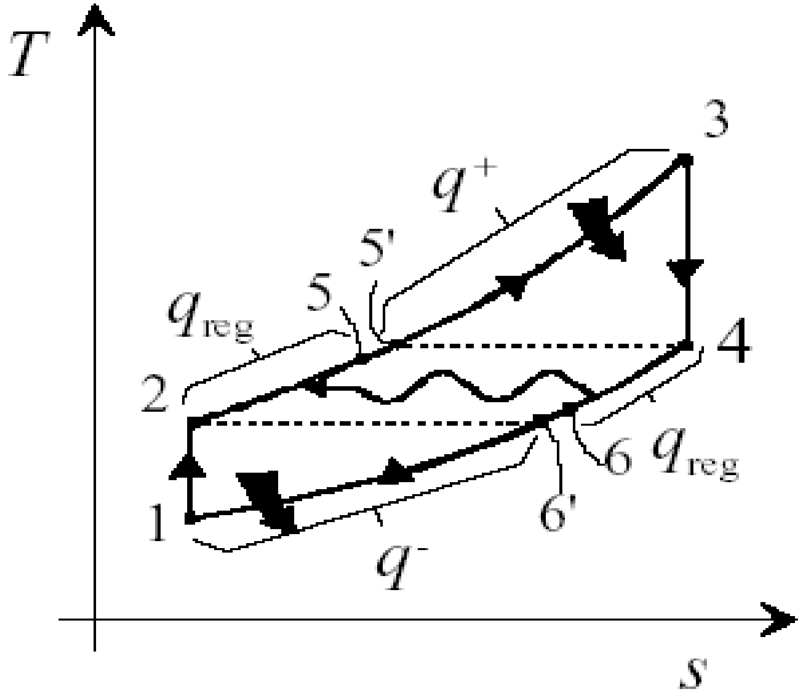
7. Regenerative Gas Turbine



- -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 existing 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 Clcle***

- ***Air Standard Brayton Cycle***

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

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

Work:

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

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

Heat:

$$\boxed{\frac{\dot{Q}_{in}}{\dot{m}} = (h_3 - h_2)}$$

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

Thermal Efficiency:

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

Summary (continue)

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

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

- *Effect of Irreversibility on Efficiency*

Isentropic efficiency:

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

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

- *Regenerative Gas Turbine*

Increase in Efficiency:

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

End- Thank you.