Chapter Six

Gas Turbine & Combined Cycles

1-Defintions of Gas Turbine:

A gas turbine is a machine delivering mechanical power or thrust. It does this using a gaseous working fluid. The mechanical power generated can be used by, for example, an industrial device. The outgoing gaseous fluid can be used to generate thrust.

In the gas turbine, there is a continuous flow of the working fluid. This working fluid is initially compressed in the compressor. It is then heated in the combustion chamber. Finally, it goes through the turbine.

The turbine converts the energy of the gas into mechanical work. Part of this work is used to drive the compressor. The remaining part is known as the network of the gas turbine.

Fig. 1 : Gas Turbine

Fig. 2 : Gas Turbine

2- The ideal gas turbine cycle:

The cycle that is present is known as the **Joule-Brayton** cycle. This cycle consists of five important points.

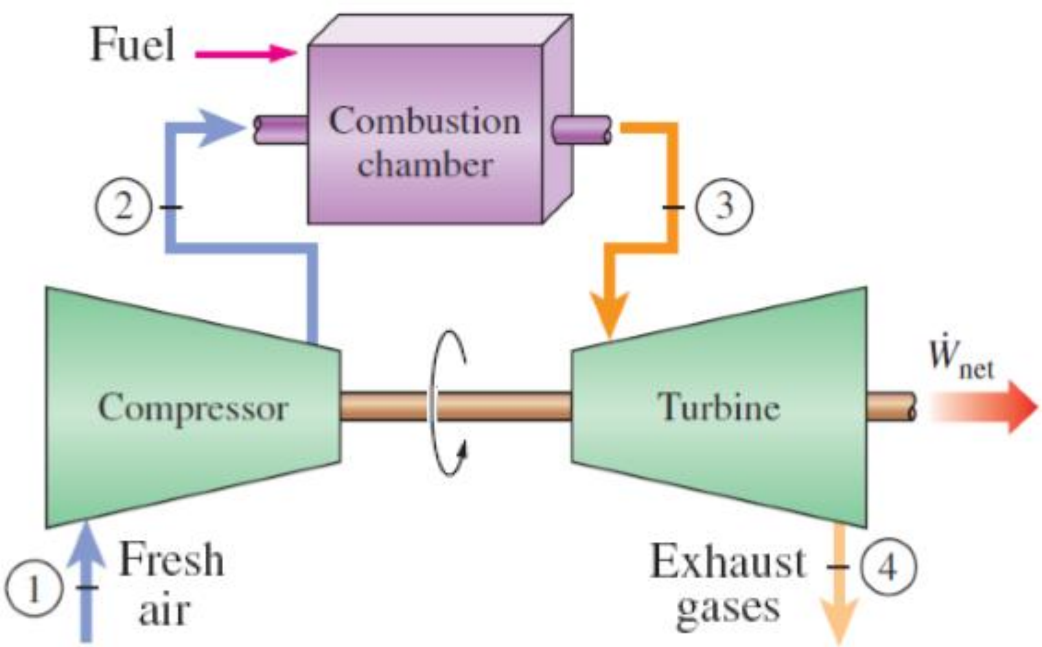


Fig. 3 : Gas Turbine Cycle

2.1 COMPONENTS OF GAS TURBINE PLANT

The gas turbine plant comprises of three important components.

(i) A compressor

(ii) Combustion chamber

(iii) Turbine

The fresh air is compressed isentropically in the compressor, then mixed with fuel and burned by combustor under constant pressure condition in the combustion chamber. This process is said to be constant pressure heat addition. The obtained hot flue gas expands through the turbine isentropically. Maximum amount of power obtained from the turbine is used to run the compressor and the remaining power is used for useful work.

2.2 CLASSIFICATION OF GAS TURBINE PLANTS

Gas turbine plants are classified as:

Based on operation

(a) Open cycle

(b) Closed cycle

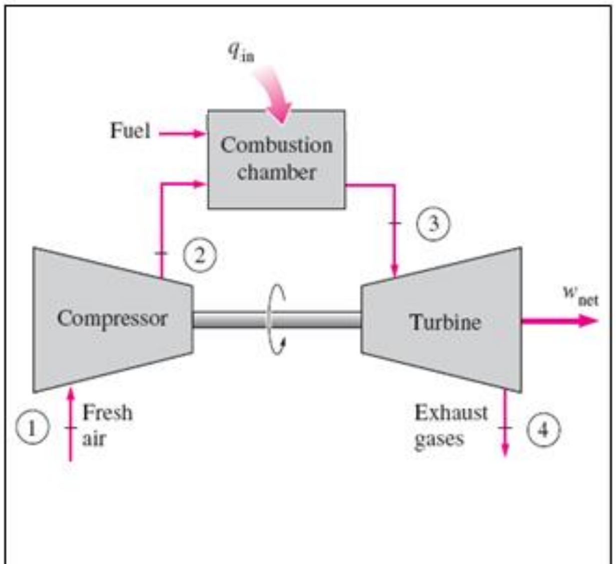
(c) Semi closed cycle

2.2.1 *Open gas turbine cycle:*

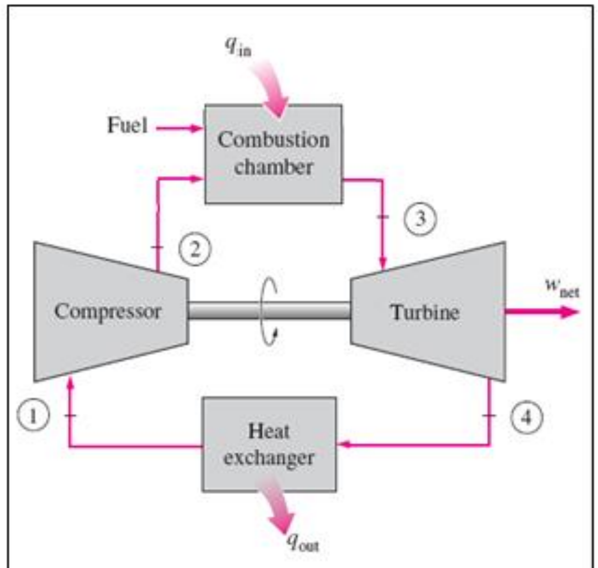
In the open cycle, fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised. The high pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure. The resulting high-temperature gases then enter the turbine, where they expand to the atmospheric pressure while producing power.

2.2.2 *Closed gas turbine cycle:*

In the closed cycle, compression and expansion processes remain the same, but the combustion process is replaced by a constant-pressure heat-addition process from an external source, and the exhaust process is replaced by a constant pressure heat-rejection process to the ambient air.



An open-cycle gas-turbine engine.



A closed-cycle gas-turbine engine.

3. *Applications of gas turbine engine:*

The two major application areas of gas-turbine engines are aircraft propulsion and electric power generation. When it is used for aircraft propulsion, the gas turbine produces just enough power to drive the compressor and a small generator to power the auxiliary equipment. The high-velocity exhaust gases are responsible for producing the necessary thrust to propel the aircraft. Gas turbines are also used as stationary power plants to generate electricity as stand-alone units or in conjunction with steam power plants on the high-temperature side. In these plants, the exhaust gases of the gas turbine serve as the heat source for the steam. The gas-turbine cycle can also be executed as a closed cycle for use in nuclear power plants. This time the working fluid is not limited to air, and a gas with more desirable characteristics (such as helium) can be used.

4. Advantages and Disadvantages Of The Gas Turbine

Advantages:

1. It is capable of producing large amount of useful power for a small size and weight.
2. it has quick starting time ,it can be brought up to full –load (peak out put)condition in minutes compared to a steam turbine plant whose start up time is measured in hours.
3. A wide variety of fuels can be utilized. Natural gas is commonly used in land based gas turbine.
4. Less installation cost.
5. The usual working fluid is atmospheric air .As basic power supply ,the gas turbine requires no coolant (e.g.. water)

Disadvantages:

1. It has lower thermal efficiency compared with other types of engines. This problem can be solved using advanced cycles techniques like reheating, regeneration, or inter cooling. Beside that, the combined cycle has the ultimate thermal efficiency.
2. Because they spin at high speeds and because of the high operating temperatures, designing and manufacturing as well as the maintenance of gas turbines is a tough problem from both the engineering and materials standpoint
3. Gas turbines tend to use more fuel when they are idling, so they prefer a constant rather than a fluctuating load.

5. Analysis of ideal gas turbine cycle:

The ideal cycle of the gas turbine (Joule-Brayton Cycle) is made up of four internally reversible processes:

1-2 isentropic compression (in a compressor)

2-3 Constant-pressure heat addition (in the combustion chamber)

3-4 isentropic expansion (in a turbine)

4-1 Constant-pressure heat rejection (in the atmosphere)

Assuming air as a working fluid with constant properties, we can analyze the cycle using the steady flow energy equation neglecting potential and kinetic terms.

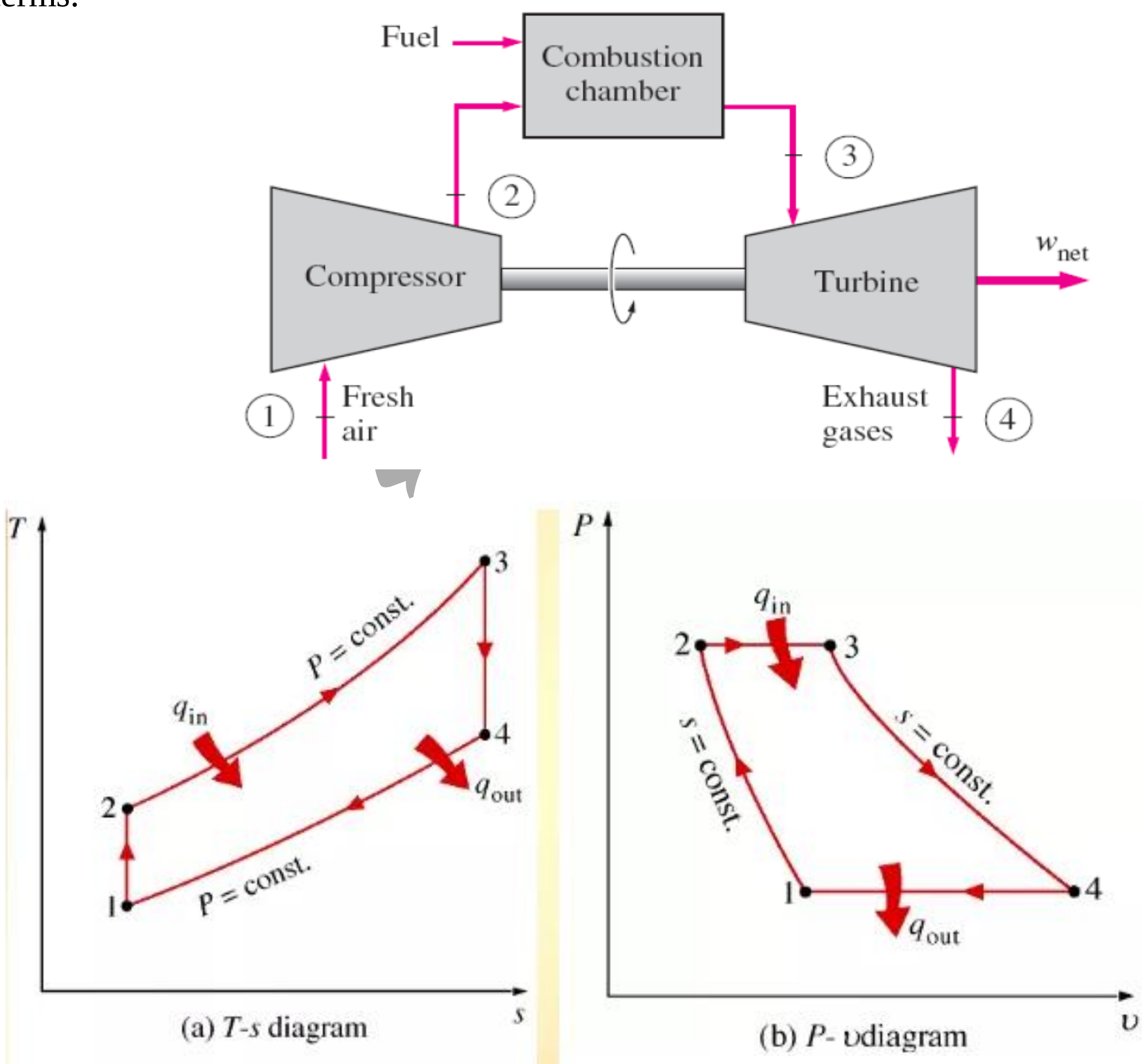


Fig. 4 : Gas Turbine Cycle

$$Q_{in} = (h_3 - h_2) = Cp_a(T_3 - T_2) = \frac{\dot{m}_{fuel}}{\dot{m}_{air}} C.V * \eta_{cc}$$

$$Q_{out} = (h_4 - h_1) = Cp_a(T_4 - T_1)$$

$$W_c = (h_2 - h_1) = Cp_a(T_2 - T_1)$$

$$W_t = (h_3 - h_4) = Cp_a(T_3 - T_4)$$

for the isentropic compression and expansion we use the thermodynamic relations:

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \quad \text{and} \quad \left(\frac{T_3}{T_4}\right) = \left(\frac{p_3}{p_4}\right)^{\frac{k-1}{k}}$$

given that $p_1 = p_4$ *and* $p_2 = p_3$ then

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{T_3}{T_4}\right) = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (PR)^{\frac{k-1}{k}}$$ where PR is pressure ratio.

The gas turbine thermal efficiency is:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = 1 - \frac{1}{PR^{\frac{k-1}{k}}}$$

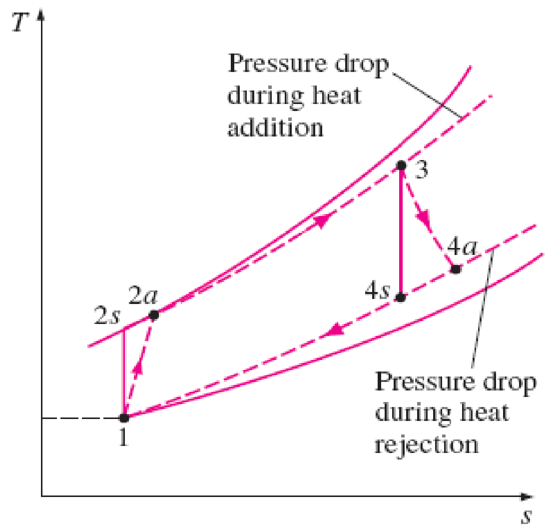
The gas turbine work ration (WR) is defined as the percent of net wok produced per turbine work:

$$WR = \frac{W_{net}}{W_{turbine}} = 1 - \frac{T_1}{T_3}(PR)^{\frac{k-1}{k}}$$

6 - Deviation of Actual Gas-Turbine Cycles from Idealized Ones:

The actual cycle deviate from the ideal cycle due to some reasons:

1. pressure drop during the heat addition and rejection process.
2. variation the working fluid across the component .
3. variation of the mass flow rate across the component.
4. the More importantly, the actual work input to the compressor is more, and the actual work output from the turbine is less because of irreversibilities



The deviation of an actual gas-turbine cycle from the ideal Brayton cycle as a result of irreversibilities.

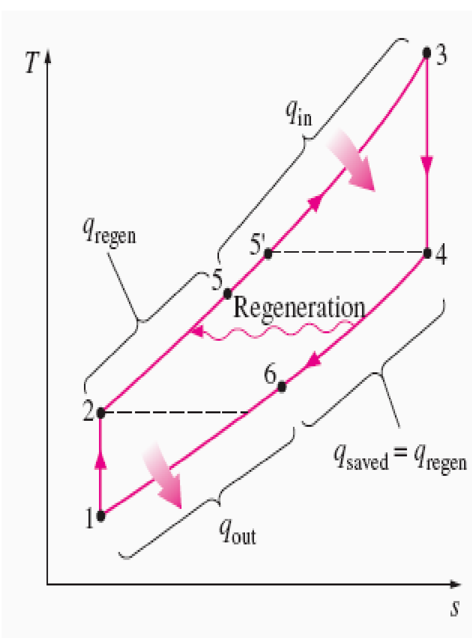
$$\eta_{c,is} = \frac{ideal\ work}{actual\ work} = \frac{h_{2s} - h_1}{h_{2a} - h_1} = \frac{T_{2s} - T_1}{T_{2a} - T_1}$$

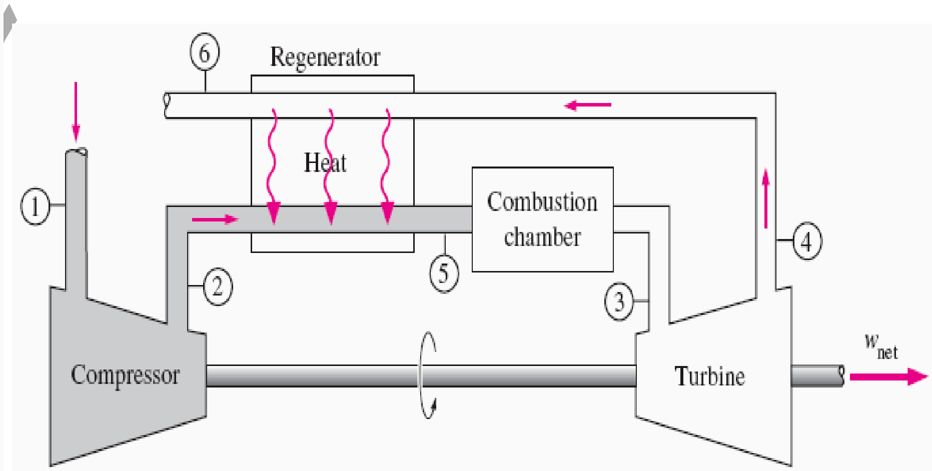
$$\eta_{t,is} = \frac{actual\ work}{ideal\ work} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} = \frac{T_3 - T_{4a}}{T_3 - T_{4s}}$$

7- Development of Gas Turbines cycles:

in order to optimize the gas turbine engine in terms of the thermal efficiency and work ratio, several modification are made for the basic cycle including:

1. Increasing the turbine inlet (or firing) temperatures: this method is restricted by the high quality metal alloys used for turbines blades. The turbine inlet temperatures have increased steadily from about 540°C (1000°F) in the 1940s to 1425°C (2600°F) .
2. Increasing pressure ratio: it is found that for a given firing temperature ,there is an optimum value for pressure ratio that gives maximum thermal efficiency. Typical pressure ratios are ranged from 5-20.
3. regenerative gas turbine cycle: in this method the high-pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a heat exchanger, which is also known as a regenerator or a recuperator.



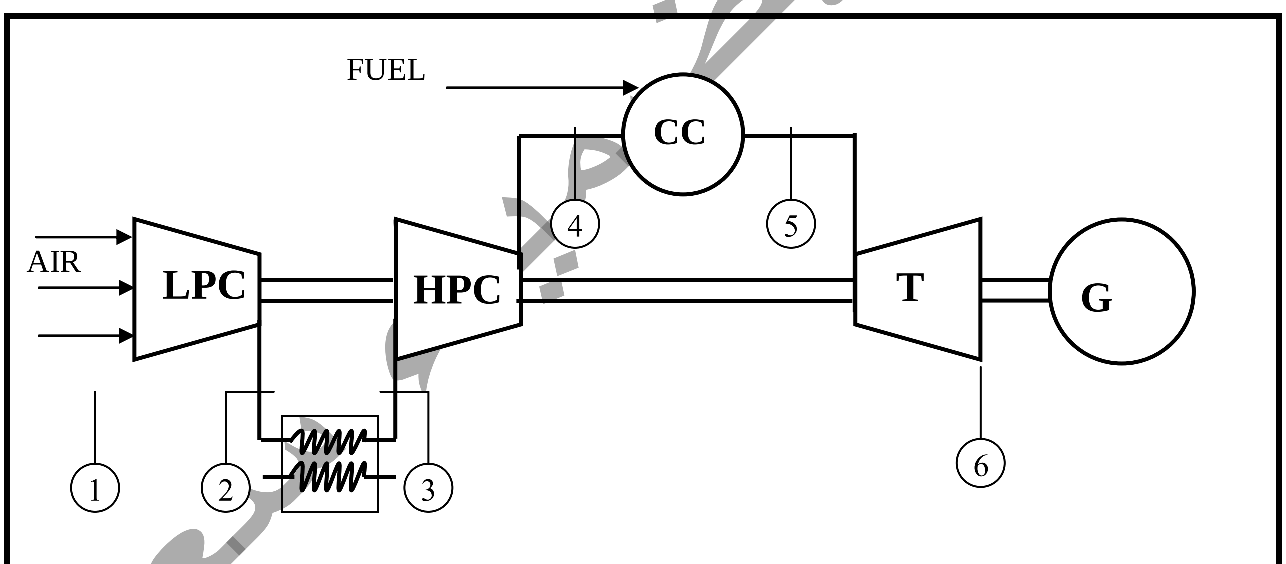


The performance of the heat exchanger (HX) affects the regeneration process. We use the effectiveness (ε) to describe how efficient is the HX:

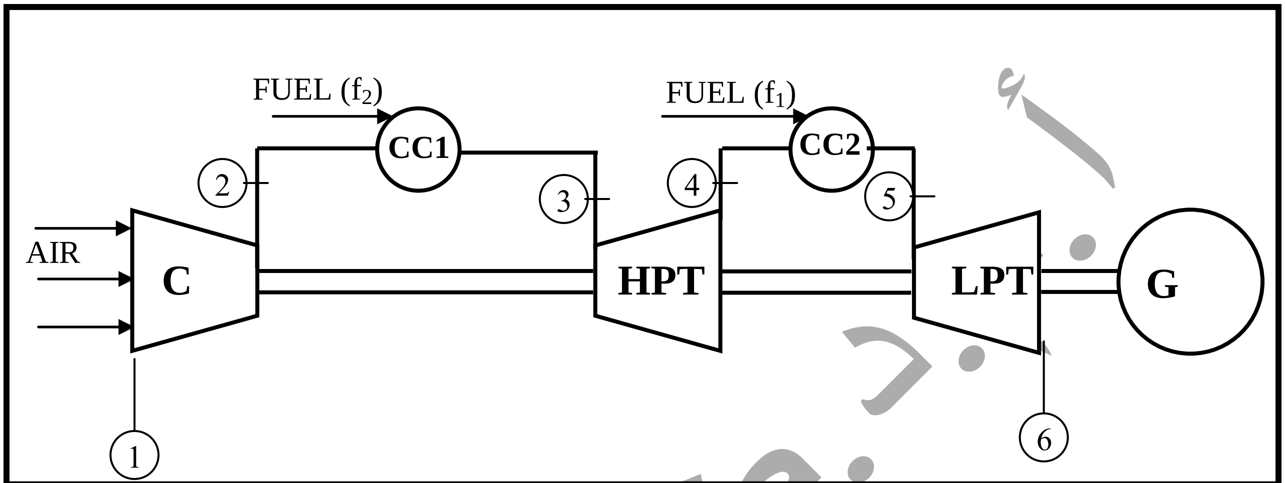
$$\varepsilon = \frac{T_5 - T_2}{T_4 - T_2}$$

For the air standard cycle, we can show that: $\eta_{th,reg} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{\frac{k-1}{k}}$

4. gas turbine with inter cooling(multi compressor GT): In this cycle, method of inter-cooling is added in the compression process. So ,the compression process is accomplished in two stages (LP and HP). The aim of this technique is to decrease the compressor work.



5. Gas turbine with Reheating (multi turbines GT): In this cycle, two turbines are used. One named high-pressure turbine and other named low-pressure turbine with extra heating between the two turbines. The aim of this connection is to produce extra power from the turbines.



8- Combined gas and steam turbine configuration(combined cycle):

In developing the model for the combined cycle plant, the energy and mass balance equations are used to analyses the irreversible Brayton and Rankine cycles, with air and water/steam as the working fluids respectively.

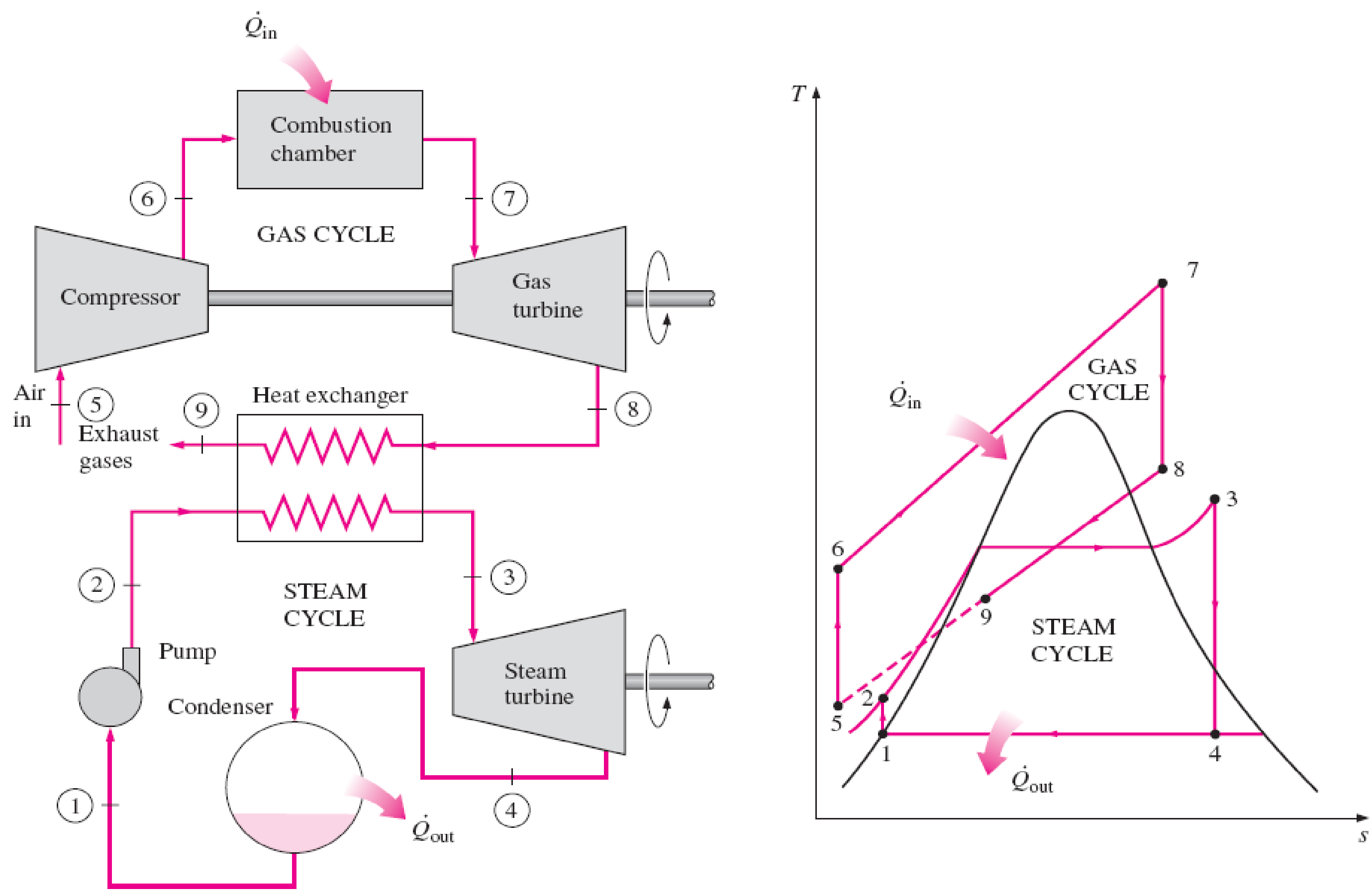


FIGURE 10–24

Combined gas–steam power plant.

Fig. 5: Combined gas – steam power plant

In Figure 5, the air compressor which is an air breathing machine takes air from the atmosphere at atmospheric conditions and compresses it thereby increasing the temperature before it is discharged into the combustion chamber. Part of this compressed air is used for cooling some critical parts of the system and also for dilution. In the combustion chamber, fuel is injected and together with air, combustion takes place. The products of the combustion are directed into the turbine after appropriate cooling has been done to meet the temperature requirement of the turbine blade material. Again, after expansion in the turbine to provide the required power, the flue gas is passed through the HRSG where it exchanges heat with water flowing through the HRSG which is supplied from the pump. The flue gas after heating the water is discharged into the atmosphere at temperatures acceptable by the Environmental Protection Agency (EPA). The steam generated in the HRSG is channelled to the steam turbine. After expansion through the steam turbine, the steam is exhausted into the condenser where cooling water from the reservoir is used to condense the steam to water for re-circulation through the HRSG by the pump. Cooling water from the reservoir is circulated through the tubes of the condenser to aid in proper cooling of the exhaust steam from the steam turbine. The temperature-entropy diagram depicting the processes described above is also shown in Figure 5.

9- Gas Turbine Blade cooling

Because of their superior high-temperature strength and durability, ceramics can be used as structural materials for hot section components (blades, nozzles, combustor liners etc.).

Adequate reliability and life are difficult to achieve, but demonstrator engines have been run for short periods. Ceramic rotor blades have been investigated for the use in stationary gas turbines for power values up to about 5MW, and field tests were carried out in the late 1990s. About 1000 hours of endurance running were achieved, before the blade was destroyed by impact of a small object which broke loose within the combustor.

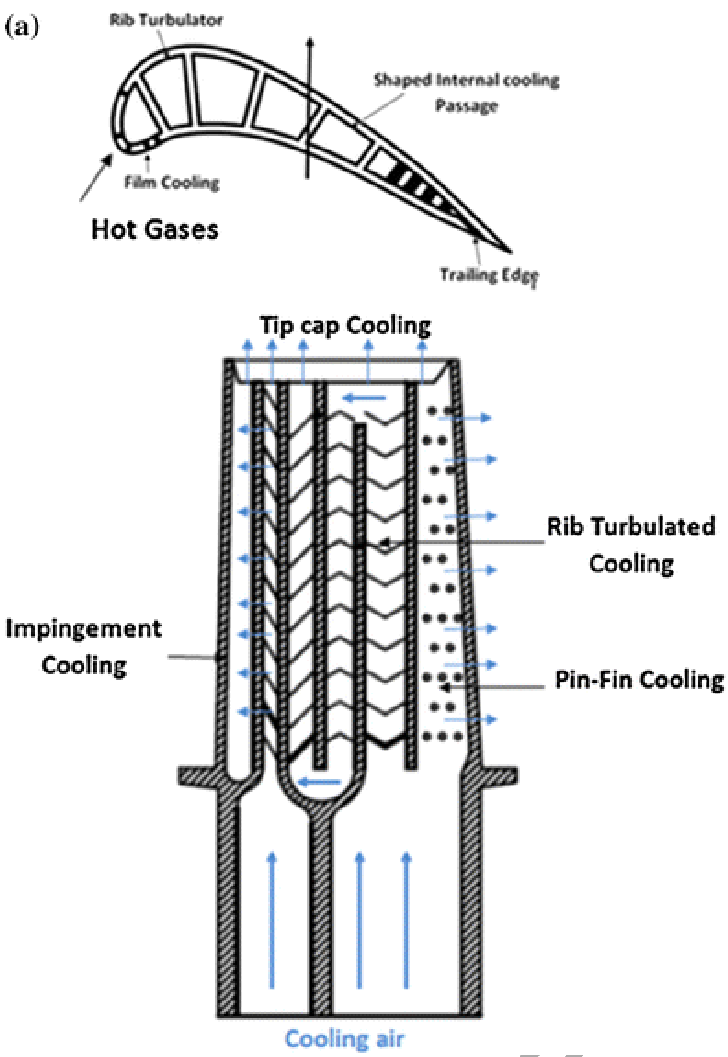
There are many types of cooling methods, which includes **internal air cooling**, **external air cooling**.

Internal Cooling of Turbine Blade

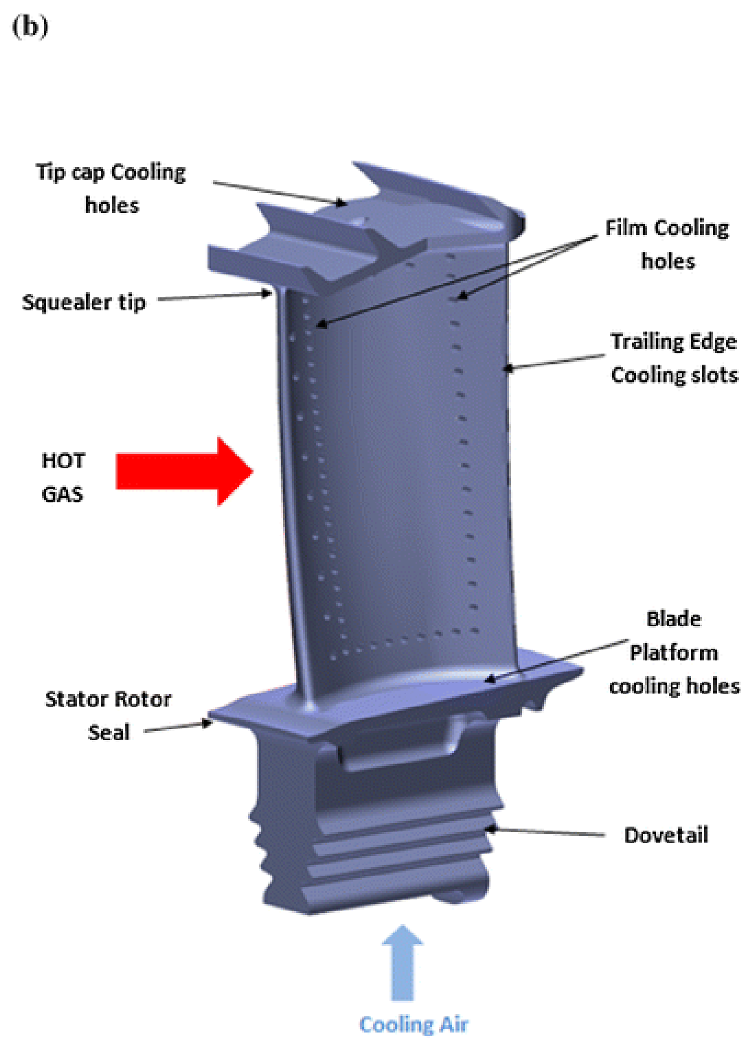
The internal cooling techniques of the gas turbine blade includes: jet impingement, rib turbulated cooling, and pin-fin cooling which have been developed to maintain the metal temperature of turbine vane and blades within acceptable limits in this harsh environment.

External cooling (film cooling):

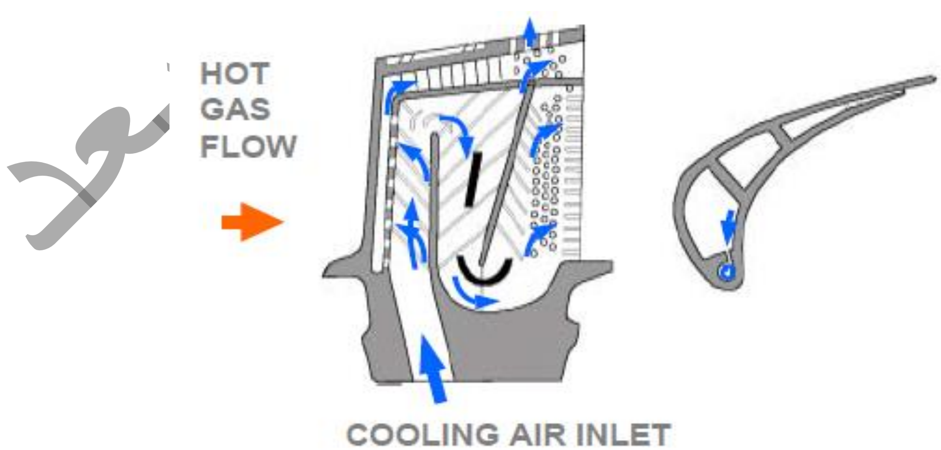
In this cooling method, air is extracted from the compressor and forced through internal cooling passages within turbine blades and vanes before being ejected through discrete cooling holes on the surfaces of these airfoils. The air leaving these cooling holes forms a film of cool air on the component surface which protects the part from hot gas exiting the combustor.



Impingement Cooling



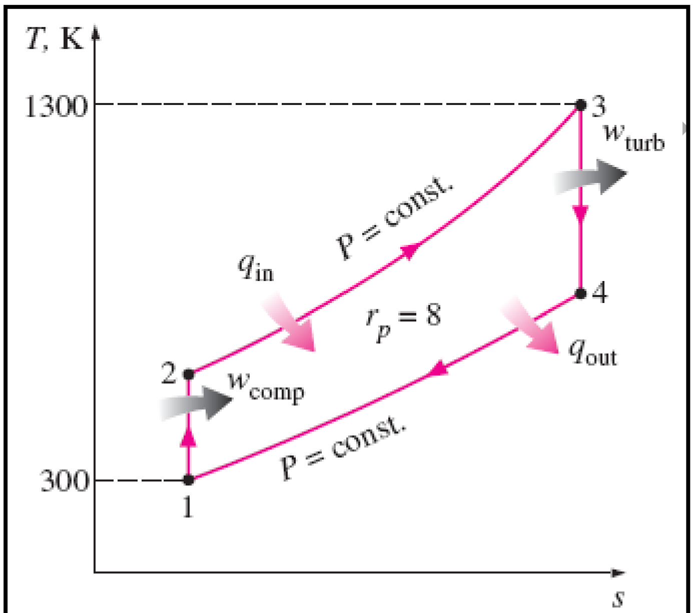
Film Cooling



Convection Cooling

Example 1: The Simple Ideal Joule-Brayton Cycle

An open cycle gas-turbine power plant operating on an ideal Brayton cycle has a pressure ratio of 8. The air temperature is $27\ ^{o}\text{C}$ at the compressor inlet (ambient temperature) and $1027\ ^{o}C$ at the turbine inlet (firing temperature). Determine (*a*) the gas temperature at the exits of the compressor and the turbine, (*b*) the work ratio, and the thermal efficiency.



Process 1-2 (isentropic compression of an ideal gas):

$$\frac{T_2}{T_1} = (PR)^{\frac{\gamma-1}{\gamma}} \quad \Rightarrow \frac{T_2}{(27+273)} = (8)^{\frac{1.4-1}{1.4}} \Rightarrow T_2 = 543.43K$$

Process 3-4 (isentropic expansion of an ideal gas):

$$\frac{T_3}{T_4} = (PR)^{\frac{\gamma-1}{\gamma}} \quad \Rightarrow \frac{1300}{T_4} = (8)^{\frac{1.4-1}{1.4}} \Rightarrow T_4 = 717.66K$$ (note the high exhaust temperature)

Performance:

$$W_c = Cp_a(T_2 - T_1) = 1.005*(543.43-300) = 244.7 kJ/kg$$

$$W_t = Cp_a(T_3 - T_4) = 1.005*(1300 - 717.66) = 585.3 kJ/kg$$

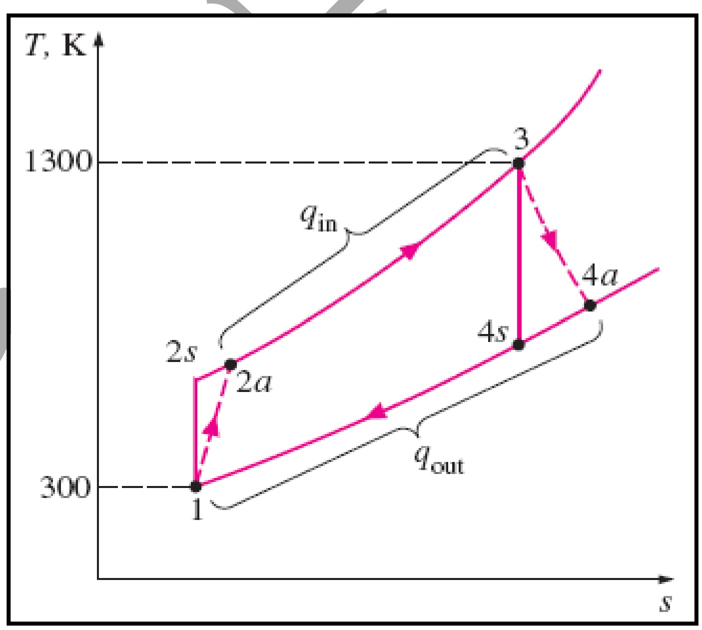
$$Q_{in} = Cp_a(T_3 - T_2) = 1.005*(1300 - 543.43) = 760.4 kJ/kg$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = 1 - \frac{1}{PR^{\frac{k-1}{k}}} = 1 - \frac{1}{8^{\frac{1.4-1}{1.4}}} = 44.79\%$$

$$WR = \frac{W_{net}}{W_{turbine}} = 1 - \frac{T_1}{T_3}(PR)^{\frac{k-1}{k}} = 1 - \frac{300}{1300}(8)^{\frac{1.4-1}{1.4}} = 58.2\%$$

Example 2: An Actual Gas-Turbine Cycle

For the last example, assuming a compressor isentropic efficiency of 80 percent and a turbine isentropic efficiency of 85 percent. Determine (*a*) the gas temperature at the exits of the compressor and the turbine, (*b*) the work ratio, and the thermal efficiency.



Process 1-2 :

$$\frac{T_{2s}}{T_1} = \left(PR\right)^{\frac{\gamma-1}{\gamma}} \quad \Rightarrow \frac{T_{2s}}{(27+273)} = (8)^{\frac{1.4-1}{1.4}} \Rightarrow T_{2s} = 543.43K$$

$$\eta_{c,is} = 0.8 = \frac{ideal\ work}{actual\ work} = \frac{h_{2s}-h_1}{h_{2a}-h_1} = \frac{T_{2s}-T_1}{T_{2a}-T_1} = \frac{543.43-300}{T_{2a}-300} \Rightarrow T_{2a} = 604.29K$$

Process 3-4

$$\frac{T_3}{T_{4s}} = \left(PR\right)^{\frac{\gamma-1}{\gamma}} \quad \Rightarrow \frac{1300}{T_{4s}} = (8)^{\frac{1.4-1}{1.4}} \Rightarrow T_{4s} = 717.66K$$

$$\eta_{t,is} = 0.85 = \frac{actual\ work}{ideal\ work} = \frac{h_3-h_{4a}}{h_3-h_{4s}} = \frac{T_3-T_{4a}}{T_3-T_{4s}} = \frac{1300-T_{4a}}{1300-717.66} \Rightarrow T_{4a} = 805.011K$$

Performance:

$$W_{c,is} = Cp_a(T_{2s}-T_1) = 1.005*(543.43 - 300) = 244.7kJ/kg$$

$$W_{c,a} = \frac{W_{c,is}}{\eta_{c,is}} = \frac{244.7}{0.8} = 305.88kJ/kg$$

$$W_{t,is} = Cp_a(T_3-T_{4s}) = 1.005*(1300-717.66) = 585.3kJ/kg$$

$$W_{t,a} = \eta_{t,is} * W_{t,is} = 0.85*585.3 = 497.5kJ/kg$$

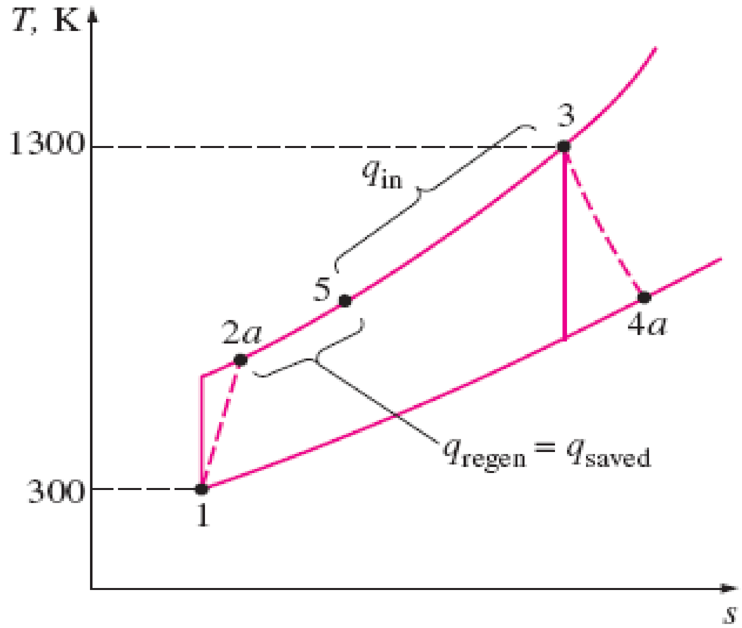
$$Q_{in} = Cp_a(T_3-T_{2a}) = 1.005*(1300-604.29) = 699.3kJ/kg$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{t,a}-W_{c.a}}{Q_{in}} = \frac{497.5-305.88}{699.3} = 27.4\%$$

$$WR = \frac{W_{net}}{W_{t,a}} = \frac{497.5-305.88}{497.5} = 38.52\%$$

EXAMPLE 3. Actual Gas-Turbine Cycle with Regeneration

Determine the thermal efficiency of the gas-turbine described in Example 2, if a regenerator having an effectiveness of 80 percent is installed.



$$\varepsilon = \frac{T_5 - T_{2a}}{T_{4a} - T_{2a}} \Rightarrow 0.8 = \frac{T_5 - 604.29K}{805.011 - 604.29} \Rightarrow T_5 = 764.86K$$

$$W_{c,a} = 305.88 kJ/kg$$

$$W_{t,a} = 497.5 kJ/kg$$

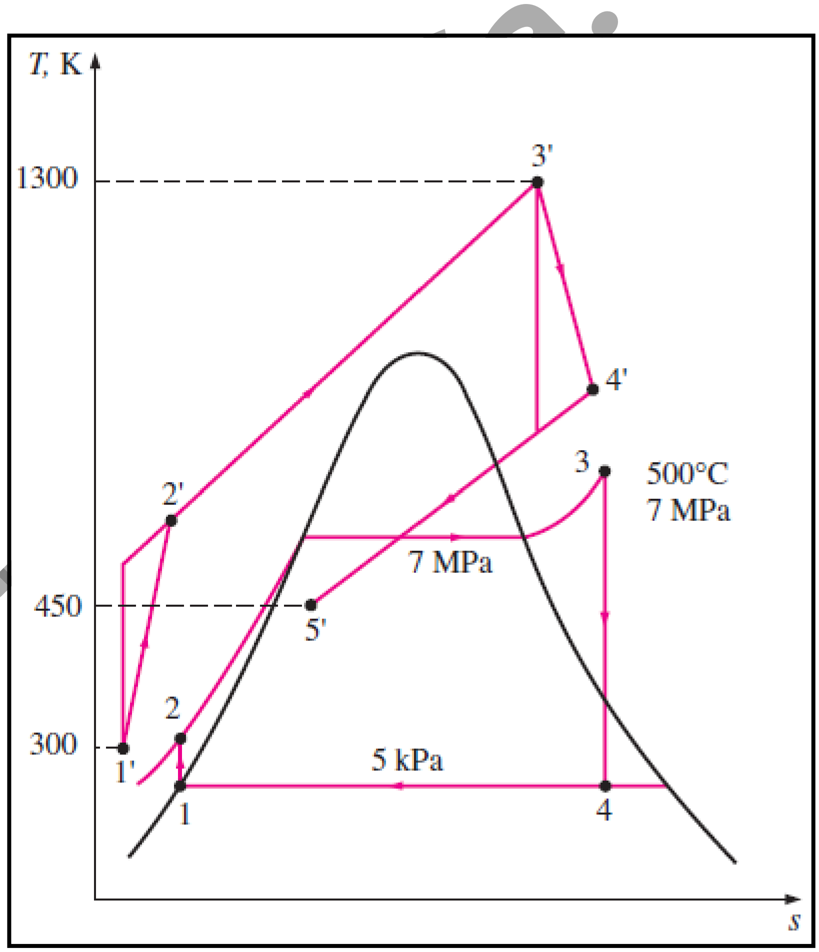
$$Q_{in} = Cp_a (T_3 - T_5) = 1.005 * (1300 - 764.86) = 537.82 kJ/kg$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{t,a} - W_{c.a}}{Q_{in}} = \frac{497.5 - 305.88}{537.82} = 35.6\%$$

$$WR = \frac{W_{net}}{W_{t,a}} = \frac{497.5 - 305.88}{497.5} = 38.52\% \text{ the same}$$

Example: Combined Cycle Power Plant.

Consider a combined gas–steam power cycle in which the gas-turbine cycle has a pressure ratio of 8. The inlet temperatures to the compressor and turbine are 300 K and 1300 K respectively. The isentropic efficiency of the compressor is 80 percent, and that of the gas turbine is 85 percent. The steam cycle is a simple ideal Rankine cycle operating between the pressure limits of 7 MPa and 5 kPa for the boiler and condenser respectively. Steam is heated in a HRB by the exhaust gases to a temperature of 500°C. The exhaust gases leave the heat exchanger at 450 K. Determine (*a*) the ratio of the mass flow rates of the steam and the combustion gases and (*b*) the thermal efficiency of the combined cycle.(Neglect pump work)



Process 1-2 :

$$\frac{T_{2s}}{T_1} = (PR)^{\frac{\gamma-1}{\gamma}} \quad \Rightarrow \frac{T_{2s}}{(27+273)} = (8)^{\frac{1.4-1}{1.4}} \Rightarrow T_{2s} = 543.43K$$

$$\eta_{c,is} = 0.8 = \frac{ideal\ work}{actual\ work} = \frac{h_{2s}-h_1}{h_{2a}-h_1} = \frac{T_{2s}-T_1}{T_{2a}-T_1} = \frac{543.43-300}{T_{2a}-300} \Rightarrow T_{2a} = 604.29K$$

$$\frac{T_3}{T_{4s}} = (PR)^{\frac{\gamma-1}{\gamma}} \quad \Rightarrow \frac{1300}{T_{4s}} = (8)^{\frac{1.4-1}{1.4}} \Rightarrow T_{4s} = 717.66K$$

$$\eta_{t,is} = 0.85 = \frac{actual\ work}{ideal\ work} = \frac{h_3-h_{4a}}{h_3-h_{4s}} = \frac{T_3-T_{4a}}{T_3-T_{4s}} = \frac{1300-T_{4a}}{1300-717.66} \Rightarrow T_{4a} = 805.011K$$

Performance:

$$W_{c,is} = Cp_a(T_{2s}-T_1) = 1.005*(543.43-300) = 244.7kJ/kg$$

$$W_{c,a} = \frac{W_{c,is}}{\eta_{c,is}} = \frac{244.7}{0.8} = 305.88kJ/kg$$

$$W_{t,is} = Cp_a(T_3-T_{4s}) = 1.005*(1300-717.66) = 585.3kJ/kg$$

$$W_{t,a} = \eta_{t,is} * W_{t,is} = 0.85*585.3 = 497.5kJ/kg$$

$$Q_{in} = Cp_a(T_3-T_{2a}) = 1.005*(1300-604.29) = 699.3kJ/kg$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{t,a}-W_{c.a}}{Q_{in}} = \frac{497.5-305.88}{699.3} = 27.4\%$$

$$WR = \frac{W_{net}}{W_{t,a}} = \frac{497.5-305.88}{497.5} = 38.52\%$$

Steam Cycle

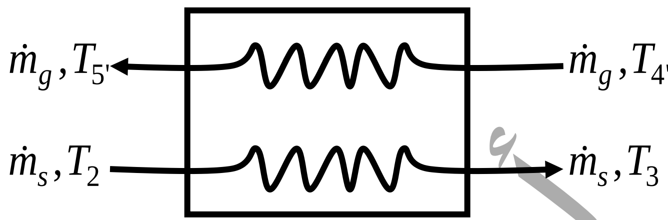
$h_1 = 138 kJ/kg$

$h_2 = 138 kJ/kg$

$h_3 = 3411. kJ/kg$

$h_4 = 2080 kJ/kg$

$W_{net} = 1338 kJ/kg$



The combined cycle:

a-The ratio of mass flow rates is determined from an energy balance on the heat exchanger:

$$\dot{m}_g h'_5 + \dot{m}_s h_3 = \dot{m}_g h'_4 + \dot{m}_s h_2$$
$$\dot{m}_s (h_3 - h_2) = \dot{m}_g (h'_4 - h'_5)$$

$$\dot{m}_s.(h_3 - h_2) = \dot{m}_g.Cp_a.(T_{4'} - T_{5'})$$

$$\therefore \frac{\dot{m}_s}{\dot{m}_g} = \frac{1.005(805.011 - 450)}{(3411 - 138)} = 0.109 kg_{steam} / kg_{gas}$$

That is, 1 kg of exhaust gases can heat only 0.109 kg of steam from 33 to 500°C as they are cooled from 805.011 to 450 K. Then the total net work output per kilogram of combustion gases becomes:

$$W_{net,total} = W_{net,GT} + \frac{\dot{m}_s}{\dot{m}_g} W_{net,ST} = 191.62 + 0.109 * (1338.) = 337.5 kJ / kg_{gas}$$

(b) The thermal efficiency of the combined cycle is determined from:

$$\eta_{th} = \frac{W_{net,total}}{Q_{in,GT}} = \frac{337.5}{699.3} = 48.3\%$$

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Gas Turbine قسم الهندسه الميكانيكيه

The Simple Ideal Joule-Brayton Cycle

1- *In an air standard Brayton cycle air at 1 bar,*20°*C is supplied to a compressor where pressure ratio is 4.5. The maximum temperature is 1000 K. Determine. (a)* thermal efficiency *(b) net work (c) work ratio*

Answers: [(a) 0.35 , (b) W_{net} = 192886.3705 J/kg, (c) Work ratio = 0.54956]

2- *In an air standard Brayton cycle air at 300 K is supplied to a compressor whose pressure ratio is 5. Mass rate of flow of air is 3 Kg/sec, air fuel ratio is 80 : 1. CV of fuel is 42 MJ/kg. Determine (a) network, net power; (b) work ratio; (c) max. temperature; (d)* η thermal

Answers: [(a) W_{net} = 580568.58 Watts, (b) Work ratio = 0.5238, (c) 997.79 K, (d) η thermal = 36.8614%]

3- *In an air standard Brayton cycle, the pressure ratio is 6. The condition of air at the beginning of compressionis 1 bar, 300 K. Air fuel ratio is 60 : 1. The calorific value of fuel is 42 kJ/kg. Determine (a) Maximum temperature; (b)Work ratio; (c) Net work; (d)* η_{th}

Answers: [(a) 1197.41 K, (b) Work ratio = 0.58197, (d) η_{th} = 0.40066]

An Actual Gas-Turbine Cycle

4- A gas turbine unit receives air at 100 kPa and 300 K and compresses it adiabatically to 600 kPa with the efficiency of the compressor 88%. The fuel has a heating value of 44180 kJ/kg and the air fuel ratio is 0.017 kg fuel/kg air. The turbine internal efficiency is 90%. Calculate the compressor work, turbine work and thermal efficiency.

Take Cp = 1.005 kJ/kgK, $\gamma = 1.4$ for air

and Cp = 1.147 kJ/kg, $\gamma = 1.3$ for products of combustion.

Answers: [(a) W_c= 234.42 kJ/kg of air, W_T = 414.7 kJ/kg of air, η_{th} = 24%]

Actual Gas-Turbine Cycle with Regeneration

5- In air-standard regenerative gas turbine cycle the pressure ratio is 5. Air enters the compressor at 1 bar, 300 K and leaves at 490 K. The maximum temperature in the adiabatic cycle is 1000 K. Calculate the cycle efficiency, given that the efficiency of the generator and the adiabatic efficiency of the turbine are each 80%. Assume for air, the ratio of specific heats is 1.4. Also shown on T - S diagram.

Answers: [η_{th} = 31%]

Combined Cycle Power Plant

6- The gas-turbine portion of a combined gas–steam power plant has a pressure ratio of 16. Air enters the compressor at 300 K at a rate of 14 kg/s and is heated to 1500 K in the combustion chamber. The combustion gases leaving the gas turbine are used to heat the steam to 400°C at 10 MPa in a heat exchanger. The combustion gases leave the heat exchanger at 420 K. The steam leaving the turbine is condensed at 15 kPa. Assuming all the compression and expansion processes to be isentropic, determine (*a*) the mass flow rate of the steam, (*b*) the net power output, and (*c*) the thermal efficiency of the combined cycle. For air, assume constant specific heats at room temperature.

Answers: [(*a*) 1.275 kg/s, (*b*) 7819 kW, (*c*) 66.4 percent]

7- The gas-turbine cycle of a combined gas–steam power plant has a pressure ratio of 8. Air enters the compressor at 290 K and the turbine at 1400 K. The combustion gases leaving the gas turbine are used to heat the steam at 15 MPa to 450°C in a heat exchanger. The combustion gases leave the heat exchanger at 247°C. Steam expands in a highpressure turbine to a pressure of 3 MPa and is reheated in the combustion chamber to 500°C before it expands in a lowpressure turbine to 10 kPa. The mass flow rate of steam is 30 kg/s. Assuming all the compression and expansion processes to be isentropic, determine (*a*) the mass flow rate of air in the gas-turbine cycle, (*b*) the rate of total heat input, and (*c*) the thermal efficiency of the combined cycle.

Answers: [(*a*) 263 kg/s, (*b*) 2.80 _ 105 kJ/s, (*c*) 55.6 percent]