TOPIC 3

GAS TURBINE CYCLES

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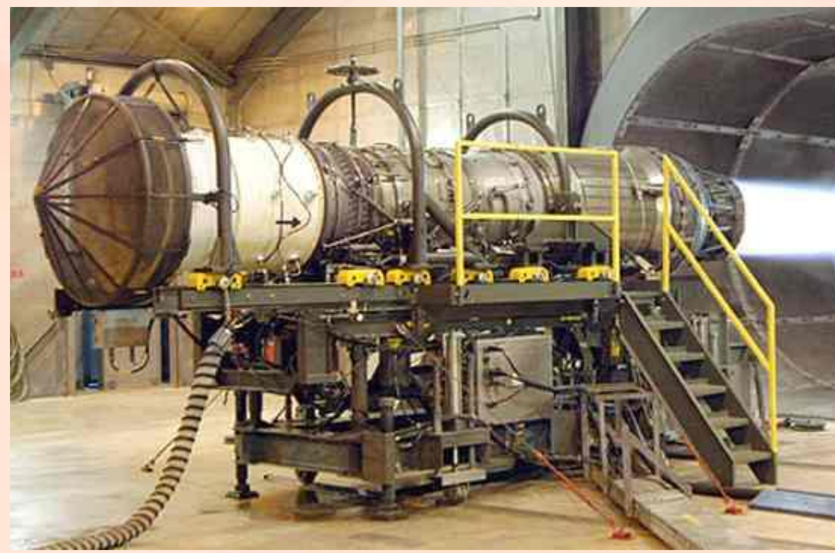
INTRODUCTION

A **gas turbine** is an engine that discharges a fast moving jet of fluid to generate thrust in accordance with Newton's third law of motion. This broad definition of jet engines includes turbojets, turbofans, rockets and ramjets and water jets, but in common usage, the term generally refers to a gas turbine used to produce a jet of high speed exhaust gases for special propulsive purposes.

F-15 Eagle is powered by two Pratt & Whitney F100 axial-flow turbofan engines



F-15 Eagle engine is tested at Robins Air Force Base, Georgia, USA

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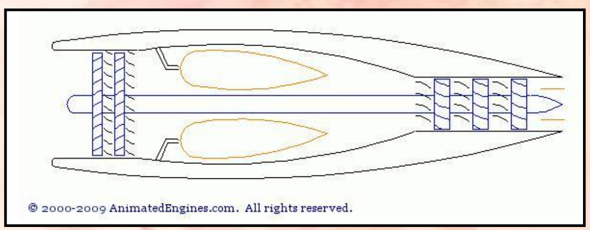
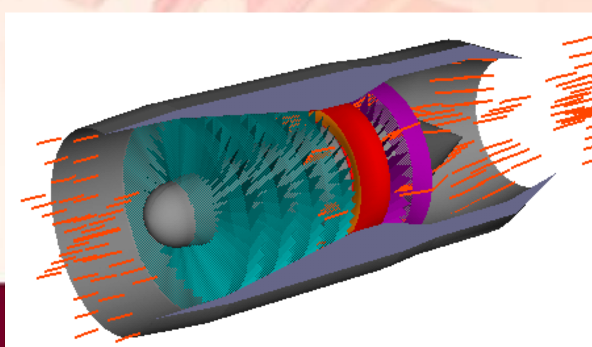
TYPES OF GAS TURBINE

Gas Turbine

Turbojet

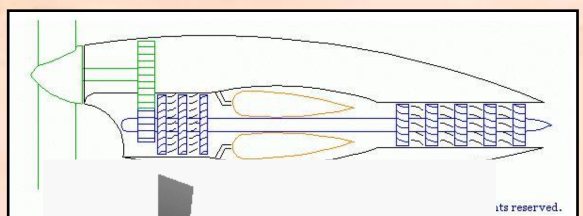
The combustion gasses flow through the nozzle generating 100% thrust and drive a turbine shaft.

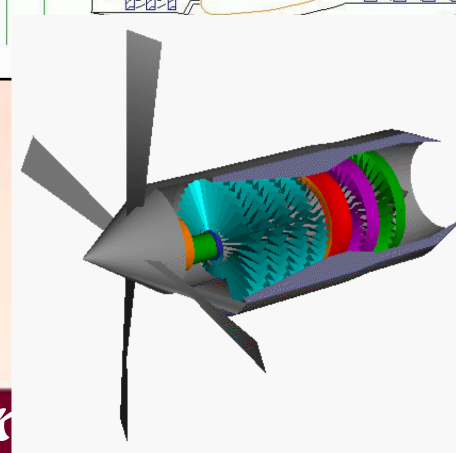




Turboprop

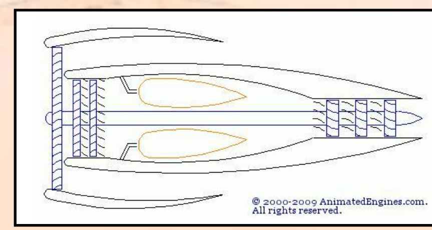
Most of the gas pressure drives the turbine. Shaft drives a propeller that creates the majority of the thrust

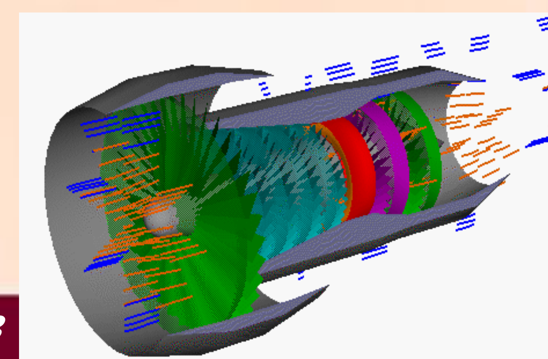




Turbofan

The gas pressure drives the turbine. Turbine shaft drives an external fan. Both gasses and fan create the thrust





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INTRODUCTION

So why does the M-1 tank use a 1,500 horsepower gas turbine engine instead of a diesel engine?

Advantages of Gas Turbines

- Great **power-to-weight ratio** compared to reciprocating engines. i.e. the amount of power you get out of the engine compared to the weight of the engine itself is very good.
- **Smaller** than their reciprocating counterparts of the same power

Disadvantages of Gas Turbines

- Compared to a reciprocating engine of the same size, gas turbines are **expensive** - because of the high spin and operating temperatures, designing and manufacturing gas turbines is a tough problem
- Gas turbines use more fuel when they are idling, and they prefer a constant rather than a fluctuating load.

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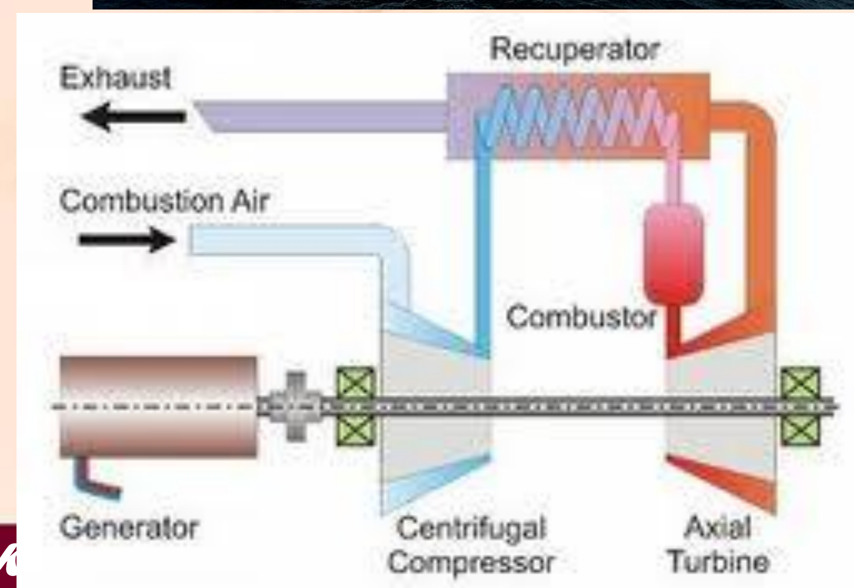
THE USE OF GAS TURBINE

***Naval Vessel - Iroquois*-class destroy**

- **Aircraft propulsion system**
- **Electric power generation**
- **Marine vehicle propulsion**
- **Combined-cycle power plant (with steam power plant)**
- **Tanks**

MiG-29



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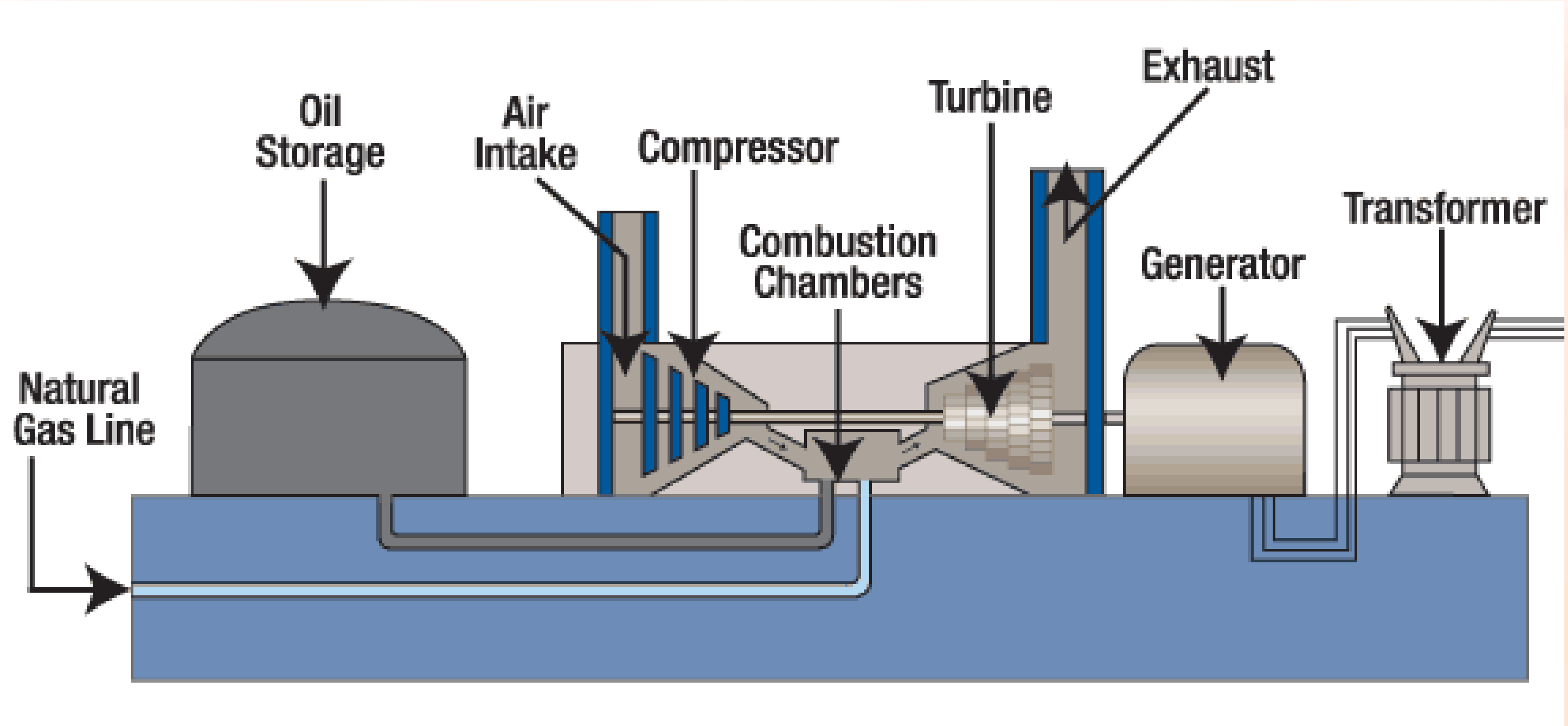
GAS TURBINE POWER PLANT



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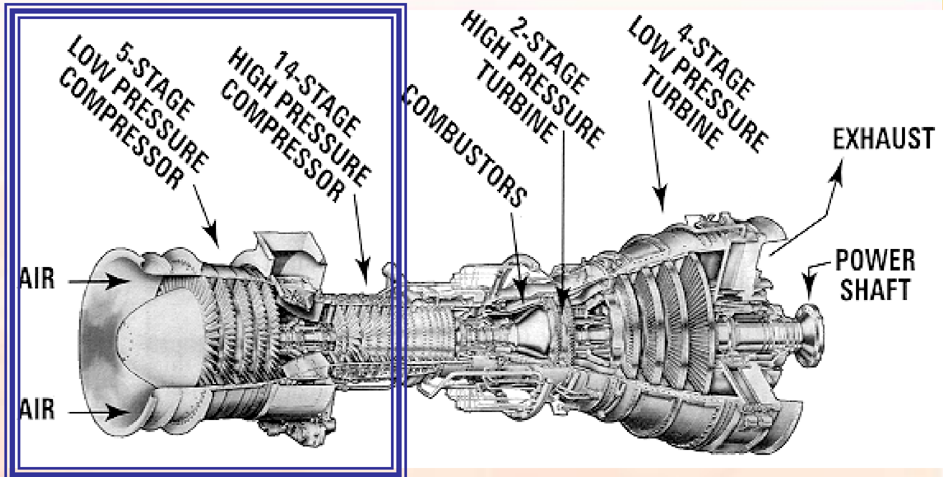
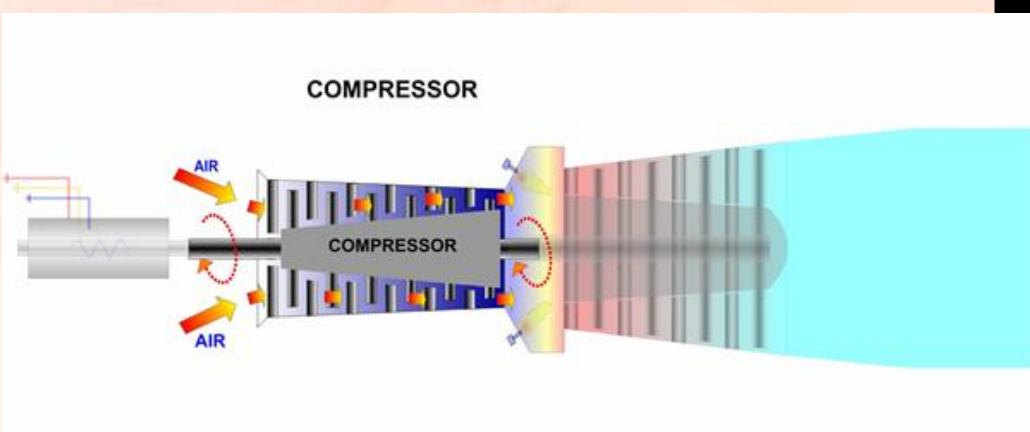
Main Components of Gas Turbine Power Plant



1. Compressor

- The compressor sucks in air form the atmosphere and compresses it to pressures in the range of 15 to 20 bar.
- The compressor consists of a number of rows of blades mounted on a shaft.
- The shaft is connected and rotates along with the main gas turbine.



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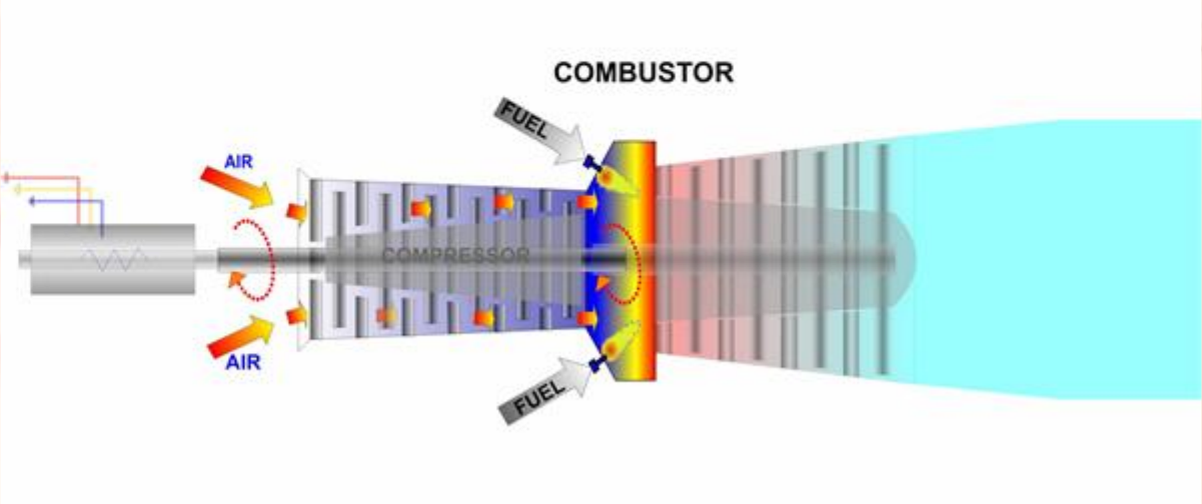
Main Components of Gas Turbine Power Plant

2. Combustor

- This is an annular chamber where the fuel burns and is similar to the furnace in a boiler.
- The hot gases in the range of 1400 to 1500 ° C leave the chamber with high energy levels.
- The chamber and the subsequent sections are made of special alloys and designs that can withstand this high temperature



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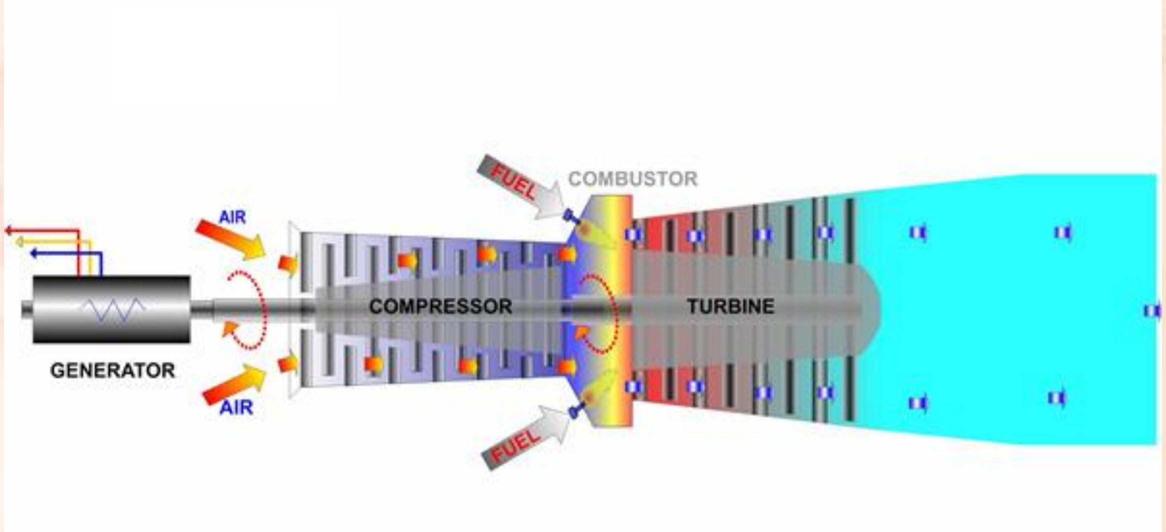
Main Components of Gas Turbine Power Plant

3. Turbine

- The turbine does the main work of energy conversion.
- The turbine portion also consists of rows of blades fixed to the shaft. The kinetic energy of the hot gases impacting on the blades rotates the blades and the shaft.
- The gas temperature leaving the Turbine is in the range of **500 to 550 ^{o}C**.
- The gas turbine shaft connects to the generator to produce electric power.



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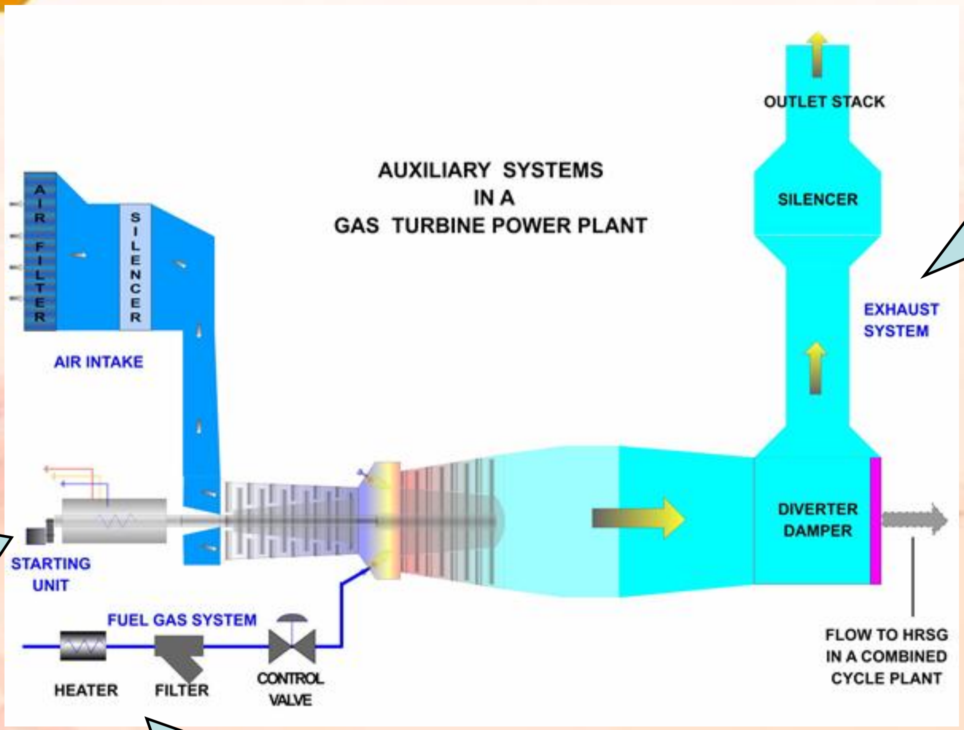
Auxiliary Components of Gas Turbine Power Plant

Air Intake System provides clean air into the compressor

Starting system provides the initial momentum for the Gas Turbine to reach the operating speed. This is similar to the starter motor of your car



Exhaust system discharges the hot gases to a level which is safe for the people and the environment

The Fuel system prepares a clean fuel for burning in the combustor. Gas Turbines normally burn Natural gas but can also fire diesel or distillate fuels

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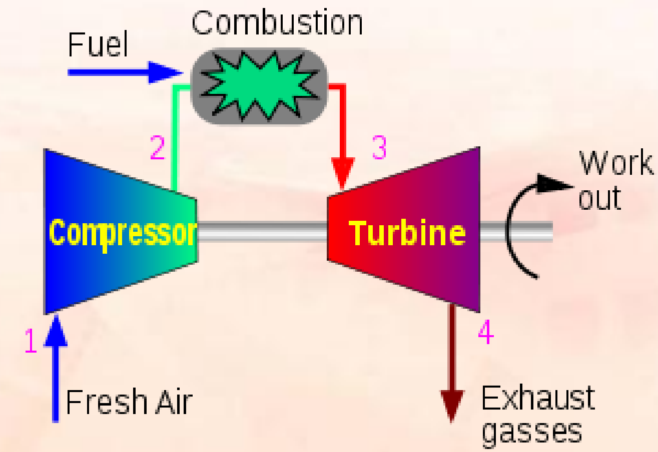
The Practical Gas Turbine Cycle

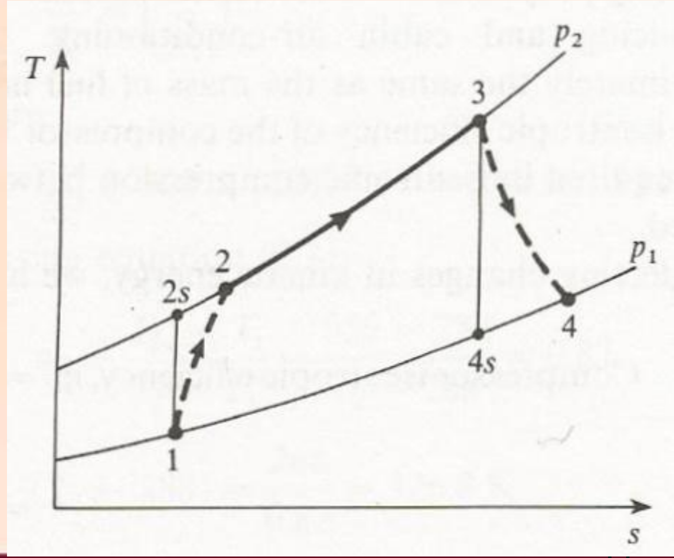
1-2 : Fresh air at ambient conditions is drawn into the compressor, its temperature and pressure are raised.

2-3 : The high-pressure air enters the combustion chamber, the fuel is burned at constant pressure (Heat is supplied)

3-4 : The high temperature and pressure gases enter the turbine and expand to the atmospheric pressure while producing power.

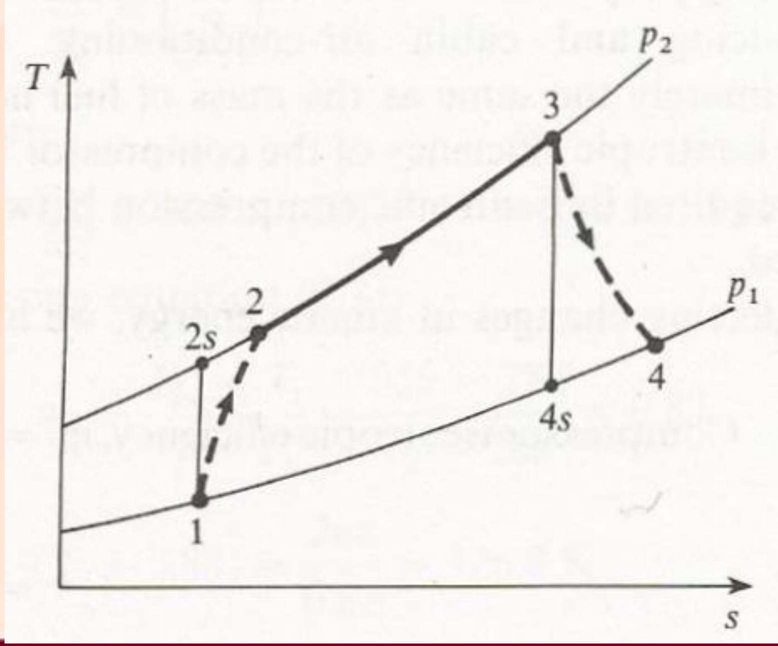
The exhaust gases leaving the turbine are thrown out (not re-circulated), causing the cycle to be classified as an open cycle.





The Practical Gas Turbine Cycle

Line 1 – 2s represents the ideal isentropic compression
Line 1 – 2 represents the irreversible (actual) compression
Line 3 – 4s represents the ideal isentropic expansion
Line 3 – 4 represents the irreversible (actual) expansion



The Practical Gas Turbine Cycle

Ideal gas equations :

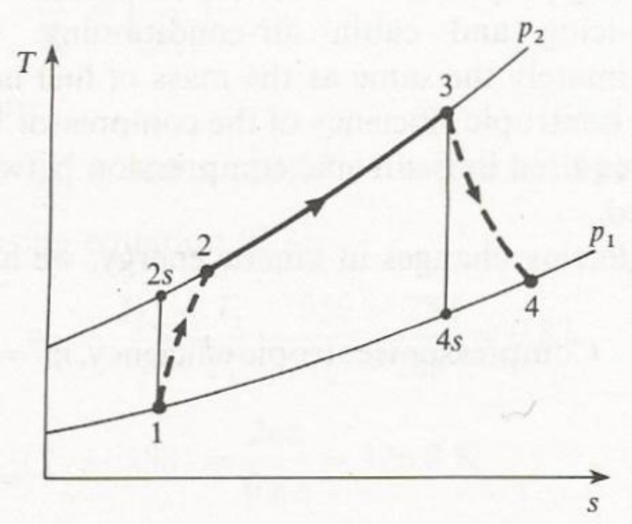
1. pV = mRT (kJ) or pv = RT (kJ/kg) where R is specific gas constant

2. $\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$ (p in kPa, V in m^3 and T in K)

3. $c_p - c_v = R$

Where c_p is specific heat at constant pressure and c_v is specific heat at constant volume

4. $h_2 - h_1 = c_p\left(T_2 - T_1\right)$



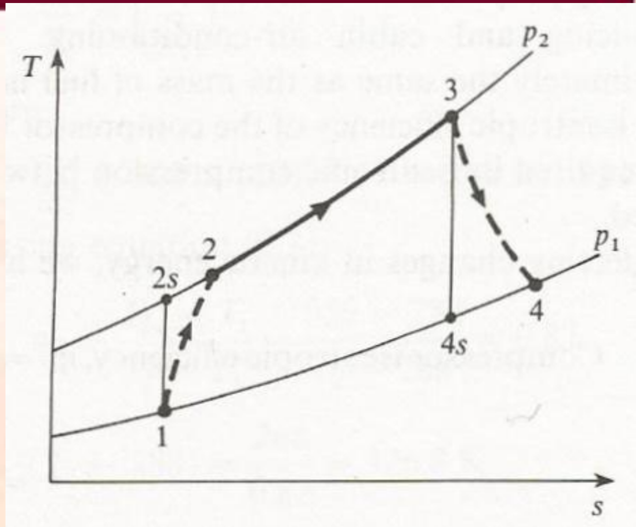
p-v-T relationships for isentropic process:

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} \qquad \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} \qquad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Where γ is specific heat ration, $\gamma = \frac{c_p}{c_v}$

The Practical Gas Turbine Cycle

Energy Analysis



Work input = $w_c = w_{12} = h_2 - h_1 = c_{pa}\left(T_2 - T_1\right)$

Heat supplied = $q_{cc} = q_{23} = h_3 - h_2 = c_{pg}\left(T_3 - T_{21}\right)$

Work output = $w_T = w_{34} = h_3 - h_4 = c_{pg}\left(T_3 - T_4\right)$

Net Work output = $w_T - w_C = w_{34} - w_{12}$

$$= c_{pg}\left(T_3 - T_4\right) - c_{pa}\left(T_2 - T_1\right)$$

Thermal Efficiency, $\eta_{th} = \dfrac{\text{Net work output}}{\text{Heat supplied}} = \dfrac{c_{pg}\left(T_3 - T_4\right) - c_{pa}\left(T_2 - T_1\right)}{c_{pg}\left(T_3 - T_2\right)}$

The Practical Gas Turbine Cycle

Energy Analysis

Compressor Isentropic Efficiency, $\eta_C = \dfrac{w_{12s}}{w_{12}} = \dfrac{c_{pa}\left(T_{2s}-T_1\right)}{c_{pa}\left(T_2-T_1\right)} = \dfrac{\left(T_{2s}-T_1\right)}{\left(T_2-T_1\right)}$

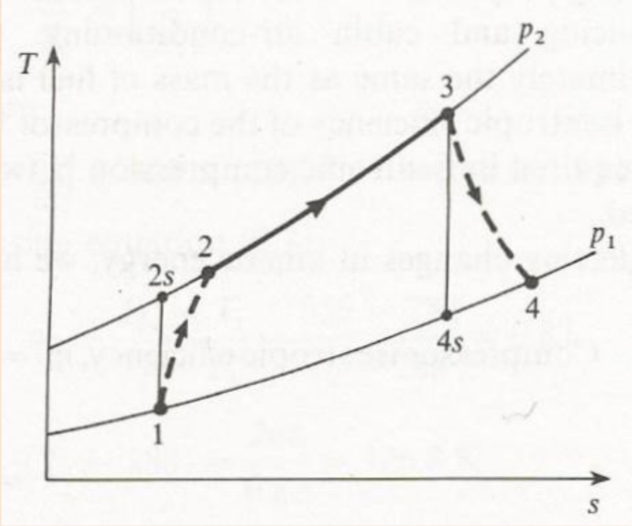
Turbine Isentropic Efficiency, $\eta_T = \dfrac{w_{34}}{w_{34s}} = \dfrac{c_{pg}\left(T_3-T_4\right)}{c_{pg}\left(T_3-T_{4s}\right)} = \dfrac{\left(T_3-T_4\right)}{\left(T_3-T_{4s}\right)}$

Work ratio,

$$r_w = \frac{\text{Net work output}}{\text{Gross work output}} = \frac{w_{net}}{w_T}$$

$$= \frac{w_T - w_C}{w_T}$$

$$= \frac{c_{pg}\left(T_3-T_4\right) - c_{pa}\left(T_2-T_1\right)}{c_{pg}\left(T_3-T_4\right)}$$



Example 9.1

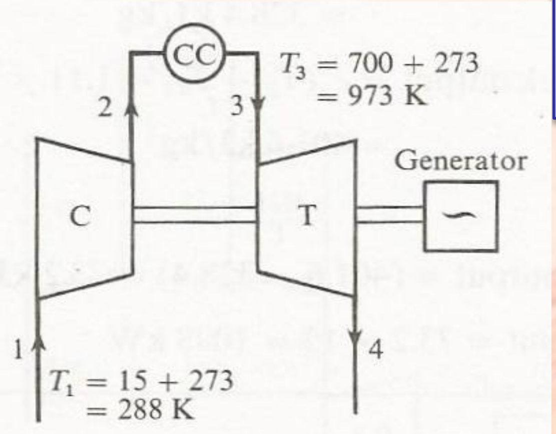
A gas turbine unit has a pressure ratio of 10/1 and a maximum cycle temperature of 700 ^{o}C. The isentropic efficiencies of the compressor and turbine are 0.82 and 0.85 respectively. Calculate the power output of an electric generator geared to the turbine when the air enters the compressor at 15 ^{o}C at the rate of 15 kg/s. Take c_p = 1.005 kJ/kgK and γ = 1.4 for the compression process and c_p = 1.11 kJ/kgK and γ = 1.333 for the expansion process.

Solution :

In order to evaluate the net work output, it is necessary to determine the T_2, T_{2S} and T_4.

Example 9.1

A gas turbine unit has a pressure ratio of 10/1 and a maximum cycle temperature of 700 °C. The isentropic efficiencies of the compressor and turbine are 0.82 and 0.85 respectively. Calculate the power output of an electric generator geared to the turbine when the air enters the compressor at 15 °C at the rate of 15 kg/s. Take c_p = 1.005 kJ/kgK and γ = 1.4 for the compression process and c_p = 1.11 kJ/kgK and γ = 1.333 for the expansion process.



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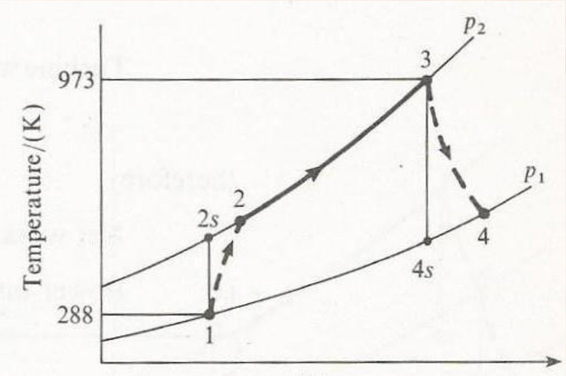
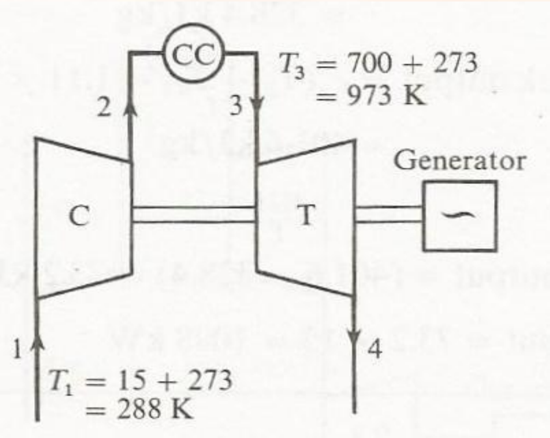


(b)

Example 9.2

Calculate the cycle efficiency and the work ratio of the plant in Example 9.1, assuming that c_p for the combustion process is 1.11 kJ/kgK.



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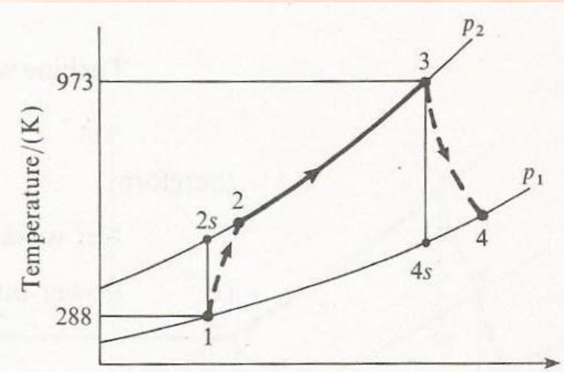


(b)

USE OF POWER TURBINE

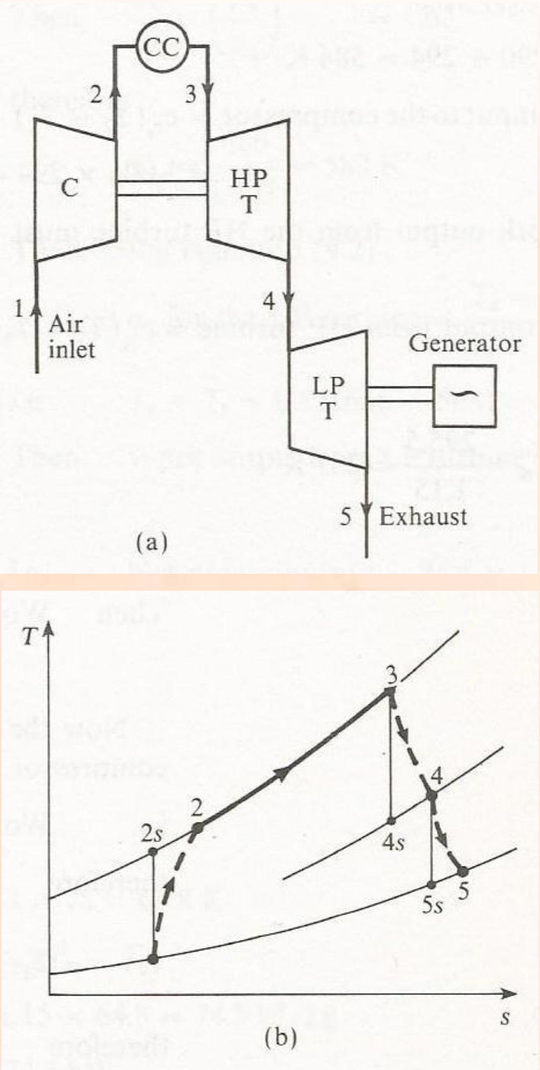
- It is more convenient to use two separate turbine, one drives the compressor and while the other provides the power output.
- High pressure turbine drives the compressor and low pressure turbine provide the power output
- If the HP turbine and LP turbine are attached on a different shaft, then

$$w_{T,HP} = w_{T,LP}$$

$$\Rightarrow \quad c_{pg}\left(T_3 - T_4\right) = c_{pa}\left(T_2 - T_1\right)$$

- The net work output,

$$w_{net} = w_{T,LP} = c_{pg}\left(T_4 - T_5\right)$$



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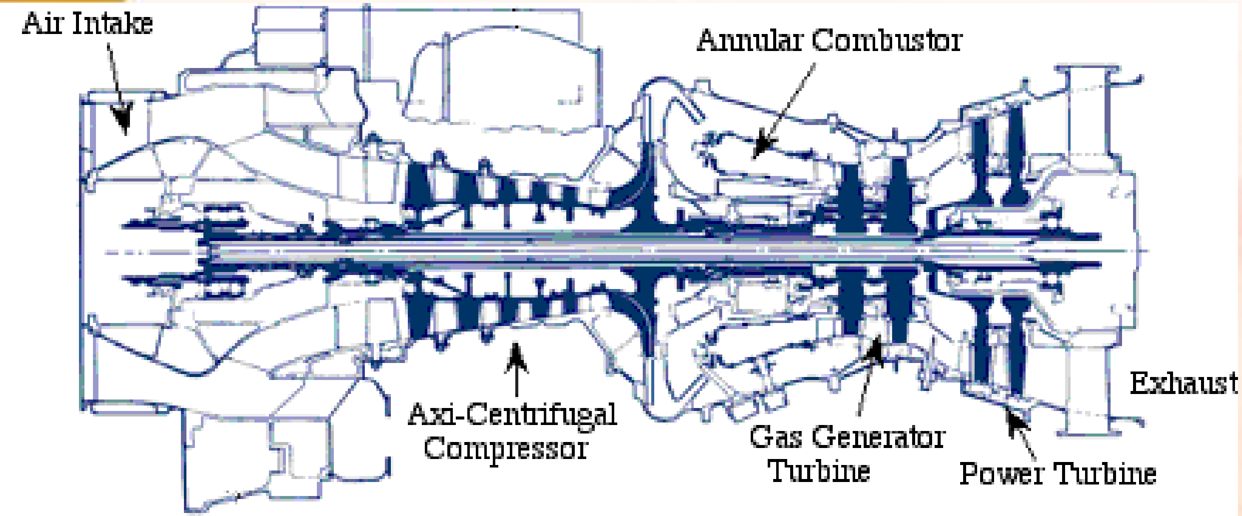
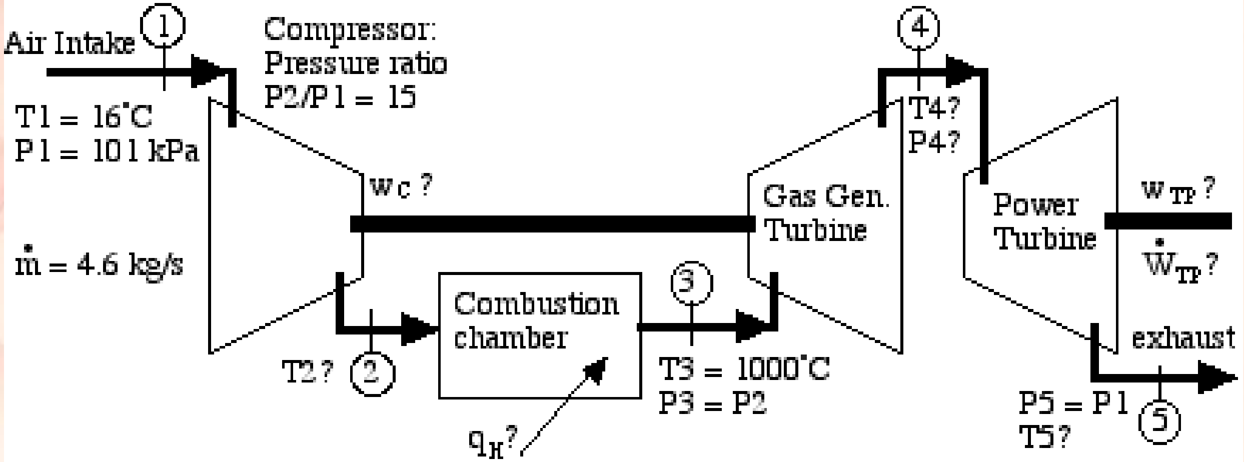
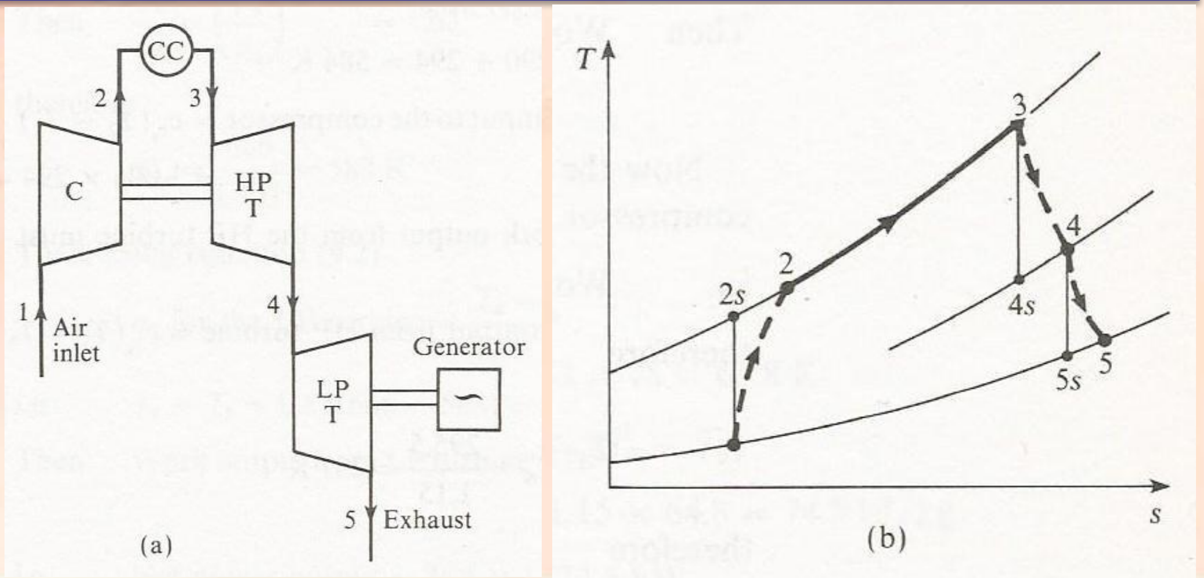
USE OF POWER TURBINE





Example 9.3

A gas turbine unit takes in air at 17 ^{o}C and 1.01 bar and the pressure ratio is 8/1. The compressor is driven by the HP turbine and the LP turbine drives a separate power shaft. The isentropic efficiencies of the compressor, HP turbine and LP turbine are 0.8, 0.85 and 0.83 respectively. Calculate the pressure and temperature of the gases entering the power turbine, the net power per kg/s mass flow rate, the work ratio and the cycle efficiency. The maximum cycle temperature is 650 ^{o}C. For the combustion process take c_p 1.11 kJ/kgK and γ = 1.4 and for the combustion and expansion process take c_p = 1.15 kJ/kgK and γ = 1.333.



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IMPROVEMENTS OF GAS TURBINE'S PERFORMANCE

The early gas turbines (1940s to 1959s) found only limited use despite their versatility and their ability to burn a variety of fuels, because its thermal efficiency was only about 17%. Efforts to improve the cycle efficiency are concentrated in three areas:

1. **Increasing the turbine inlet (or firing) temperatures.**
   The turbine inlet temperatures have increased steadily from about 540° C (1000° F) in the 1940s to 1425° C (2600° F) and even higher today.
2. **Increasing the efficiencies of turbo-machinery components (turbines, compressors).**
   The advent of computers and advanced techniques for computer-aided design made it possible to design these components aerodynamically with minimal losses.
3. **Adding modifications to the basic cycle (inter-cooling, regeneration or recuperation, and reheating).**
   The simple-cycle efficiencies of early gas turbines were practically doubled by incorporating inter-cooling, regeneration (or recuperation), and reheating.

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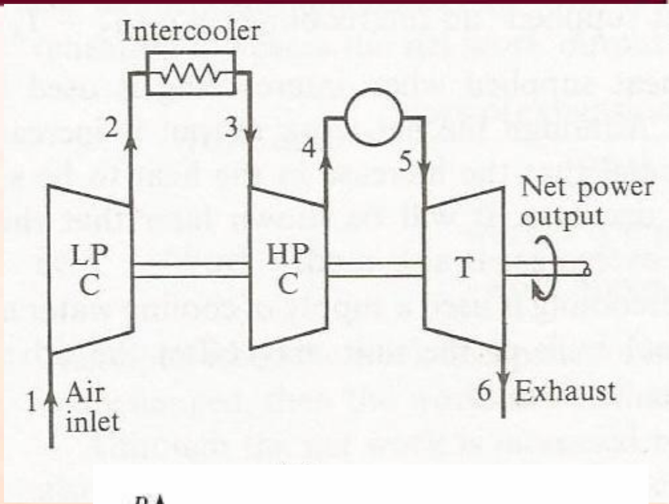
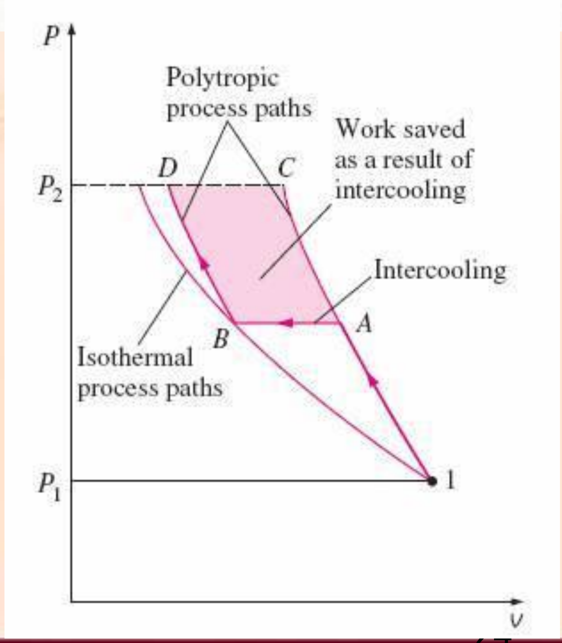
TWO STAGE COMPRESSION WITH INTERCOOLING

- The compressor work input can be reduced by carrying out the compression process in stages and with an intercooler between the stage, thus will increase the net work output and thermal efficiency.
- Process 1BD is isothermal compression, with a minimum work required
- Process 1AC is polytropic process for single stage compressor
- Process 1ABD is polytropic process for two stage compressor with intercooling
- The shaded area is the work saved as a result of intercooling process.





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TWO STAGE COMPRESSION WITH INTERCOOLING

- Processes 1-2-3-4 with intercooling between LP and HP compressor and process 1-A is a single stage compression without intercooling.
- Work input with intercooling

$$w_{in} = c_{pa}\left(T_2 - T_1\right) + c_{pa}\left(T_4 - T_3\right)$$

- Work input with intercooling

$$w_{in} = c_{pa}\left(T_A - T_1\right)$$

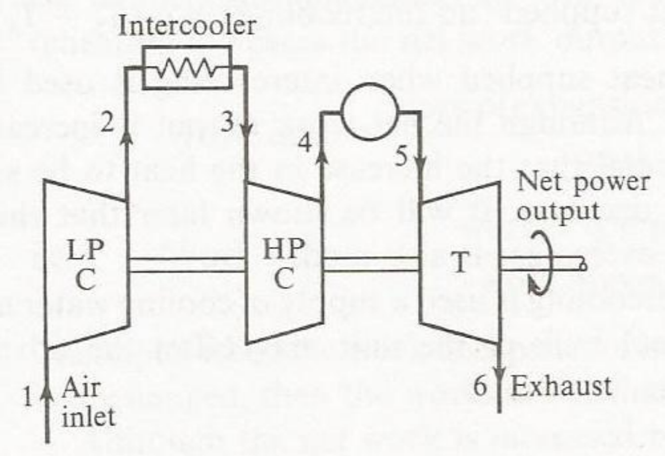
- Where

$$c_{pa}\left(T_2 - T_1\right) + c_{pa}\left(T_4 - T_3\right) < c_{pa}\left(T_A - T_1\right)$$

- Minimum work input requirement :
  a) Equal pressure ratio for each stage of compressor

  $P_2/P_1 = P_4/P_3$

  b) Complete intercooling ($T_1 = T_3$)



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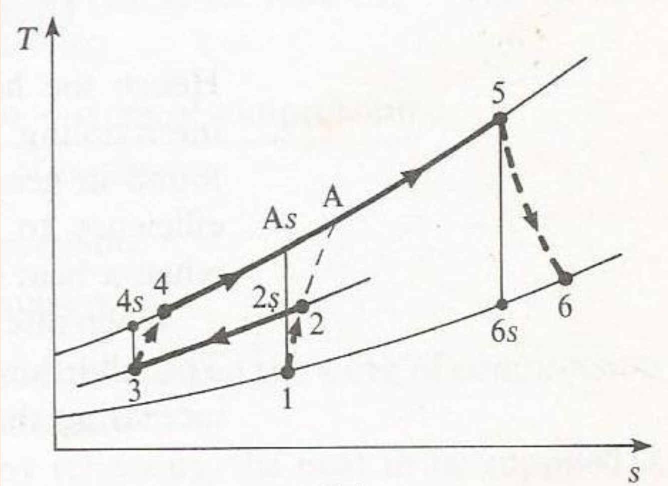

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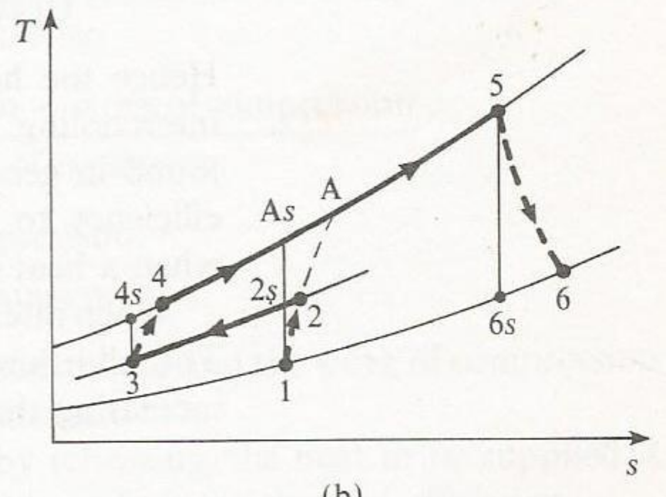
TWO STAGE COMPRESSION WITH INTERCOOLING



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$$w_{out} = w_T = c_{pg}\left(T_5 - T_6\right)$$

$$w_{in} = w_{C,LP} + w_{C,HP} = c_{pa}\left(T_2 - T_1\right) + c_{pa}\left(T_4 - T_3\right)$$

$$w_{net} = w_T - \left(w_{C,LP} + w_{C,HP}\right)$$
$$= c_{pg}\left(T_5 - T_6\right) - c_{pa}\left[\left(T_2 - T_1\right) - \left(T_4 - T_3\right)\right]$$

$$q_{supply} = q_{45} = c_{pg}\left(T_5 - T_4\right)$$

Thermal Efficiency, $\eta_{th} = \dfrac{w_{net}}{q_{supply}} = \dfrac{w_{56} - \left(w_{12} + w_{34}\right)}{q_{45}}$

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EXAMPLE

A 5000 kW gas turbine operates with two compressor stages with intercooling between stages. The overall pressure ratio is 9/1. A HP turbine is used to drive the compressors and a LP turbine drives the generator. The temperature of the gas at entry to the turbine is 650 ^{o}C. The compressor has equal pressure ratios and intercooling is complete between stages. The air inlet temperature to the gas turbine is 15 ^{o}C. The isentropic efficiency of each compressor stage is 0.8 and the isentropic efficiency of turbine is 0.85. Calculate

a) The cycle efficiency
b) The work ratio
c) The mass flow rate of the gases

For air take c_p = 1.005 kJ/kgK and γ = 1.4 and for the gases take, c_p = 1.15 kJ/kgK and γ = 1.333.

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EXAMPLE

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Solution :

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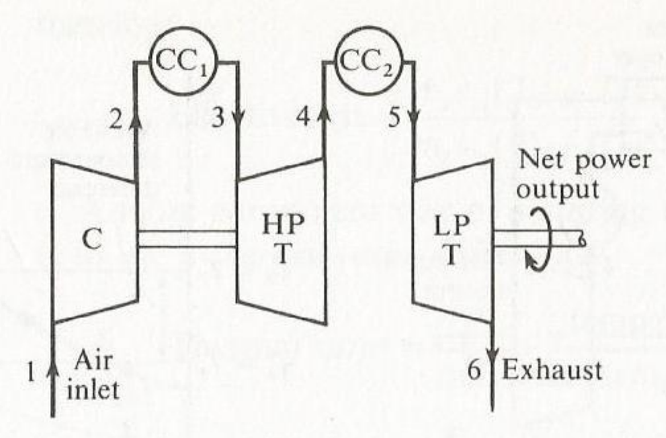
REHEAT CYCLE

- For the two stage expansion, work output from LP turbine can be increased by raising the inlet temperature of LP turbine.
- This can be done by installing second combustion chamber between the two turbine stages.
- Work input, $w_{in} = w_{12} = c_{pa}\left(T_2 - T_1\right)$
- Where,

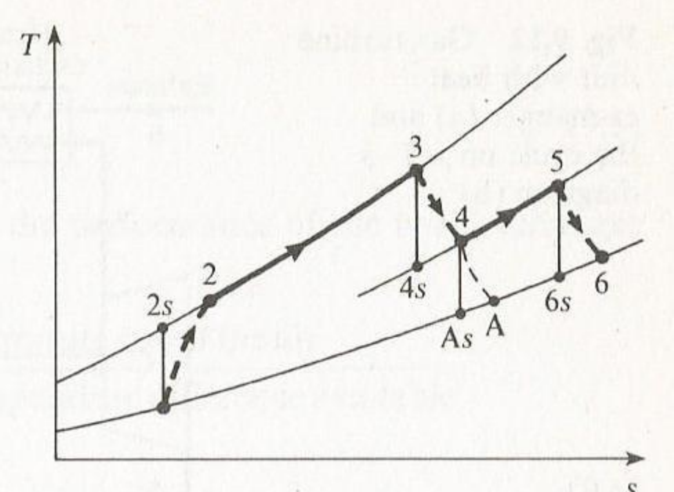
$$w_{12} = w_{T,HP} \Rightarrow c_{pa}\left(T_2 - T_1\right) = c_{pg}\left(T_3 - T_4\right)$$

$$w_{out} = w_{T,LP} = w_{56} = c_{pg}\left(T_5 - T_6\right)$$

$$q_{supply} = q_{23} + q_{45} = c_{pg}\left(T_3 - T_2\right) + c_{pg}\left(T_5 - T_4\right)$$



(a)



(b)

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EXAMPLE 9.4 Pg. 296

A 5000 kW gas turbine operates with two compressor stages with intercooling between stages. The overall pressure ratio is 9/1. A HP turbine is used to drive the compressors and a LP turbine drives the generator. The temperature of the gas at entry to the HP turbine is 650 °C and the gases are reheated to 650 °C after expansion in the first turbine. The compressor has equal pressure ratios and intercooling is complete between stages. The air inlet temperature to the gas turbine is 15 °C. The isentropic efficiency of each compressor stage is 0.8 and the isentropic efficiency of each turbine is 0.85. Calculate

1. The cycle efficiency
2. The work ratio
3. The mass flow rate of the gases

For air take c_p = 1.005 kJ/kgK and γ = 1.4 and for the gases take, c_p = 1.15 kJ/kgK and γ = 1.333.

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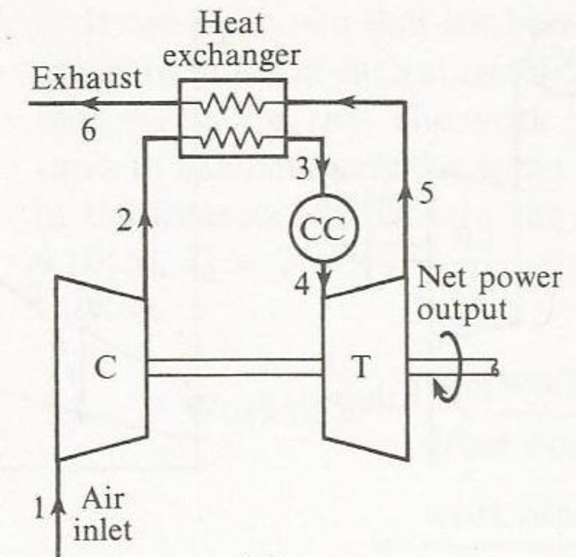
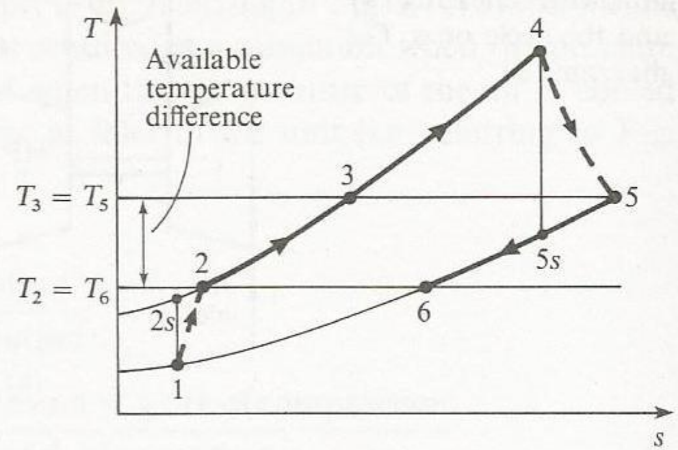
REGENERATIVE CYCLE (USE OF HEAT EXCHANGER)

- The exhaust gases leaving the turbine are still at high temperature (high energy) – waste of energy.
- Some of this energy can be recovered by passing the gasses from the turbine through a heat exchanger to heat the air leaving the compressor.
- Process 2-3 : Compressed air from the compressor is heated by exhaust gases from the turbine from T_2 to T_3.
- Process 5-6 : Exhaust gases will be cooled from T_5 to T_6 after giving up the heat.
- For an ideal case : $T_3 = T_5$ and $T_2 = T_6$



(a)

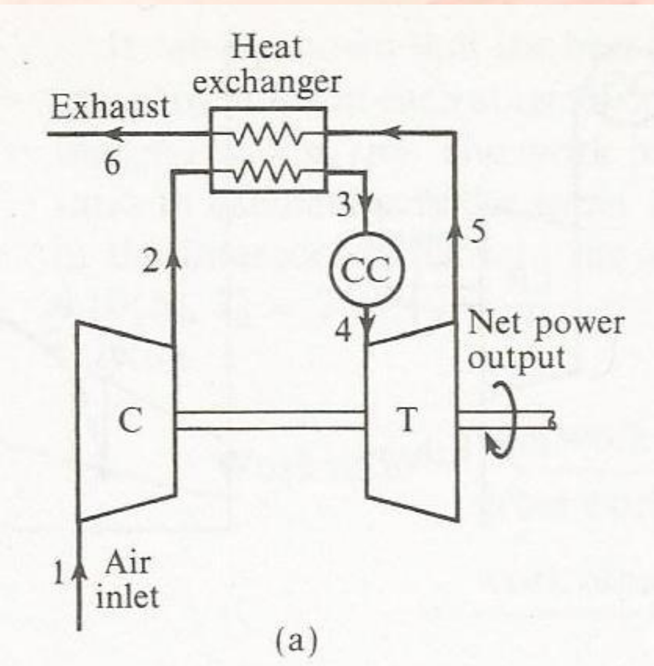


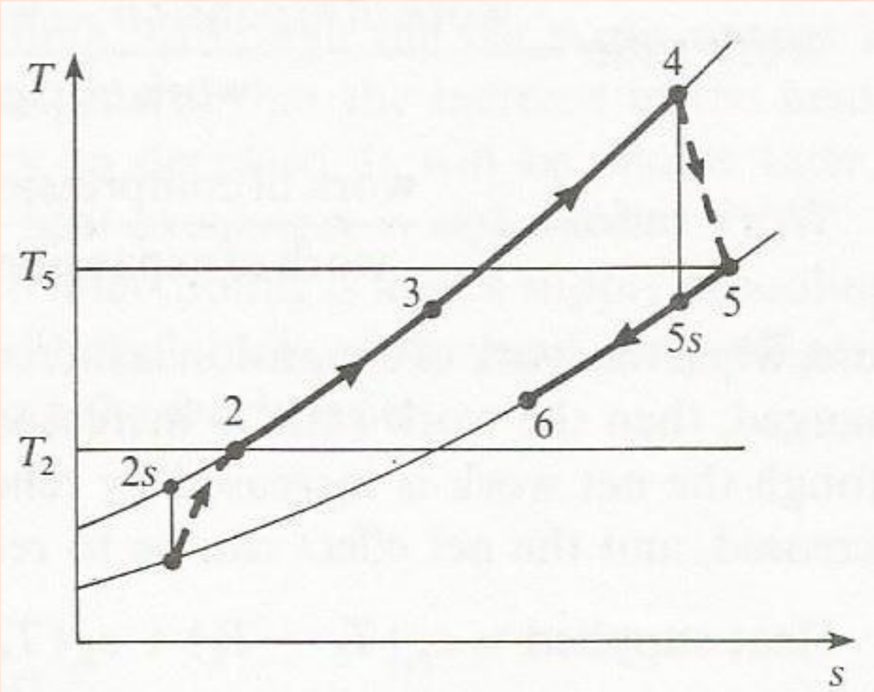
(b)

REGENERATIVE CYCLE (USE OF HEAT EXCHANGER)

- In practice $T_3 \neq T_5$ and $T_2 \neq T_6$
- If no heat is lost the heat exchanger to the surrounding, then

$$\dot{m}_a c_{pa}\left(T_3 - T_2\right) = \dot{m}_g c_{pg}\left(T_5 - T_6\right)$$





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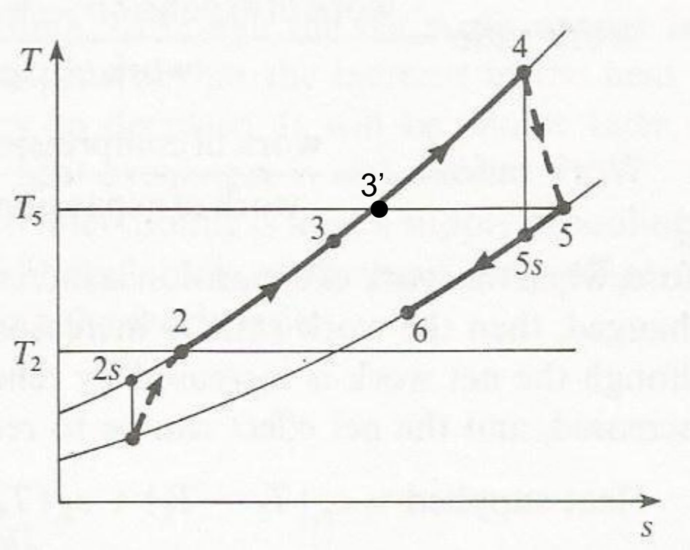
REGENERATIVE CYCLE (USE OF HEAT EXCHANGER)

- Actual and maximum heat can be transferred to air can be expressed as

$$Q_{actual} = h_3 - h_2 = m_a c_{pa}\left(T_3 - T_2\right)$$

$$Q_{max} = h_{3'} - h_2 = m_a c_{pa}\left(T_{3'} - T_2\right)$$

$$= m_a c_{pa}\left(T_5 - T_2\right) \Rightarrow T_5 = T_{3'}$$



- Heat exchanger effectiveness is used to allow for the temperature difference necessary for the transfer of heat and define as,

$$\textit{Effectiveness},\ \varepsilon = \frac{\text{Heat received by the air}}{\text{maximum possible heat could be transferred}}$$

$$= \frac{\dot{m}_a c_{pa}\left(T_3 - T_2\right)}{\dot{m}_a c_{pa}\left(T_{3'} - T_2\right)} = \frac{\left(T_3 - T_2\right)}{\left(T_5 - T_2\right)}$$

- Some times is called ***thermal ratio***

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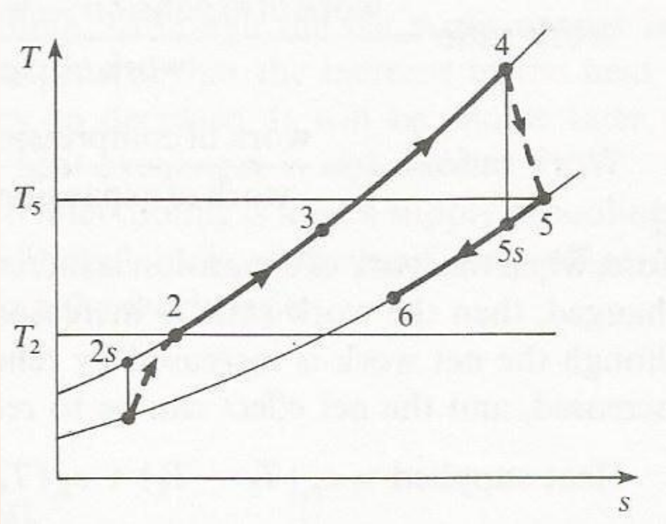
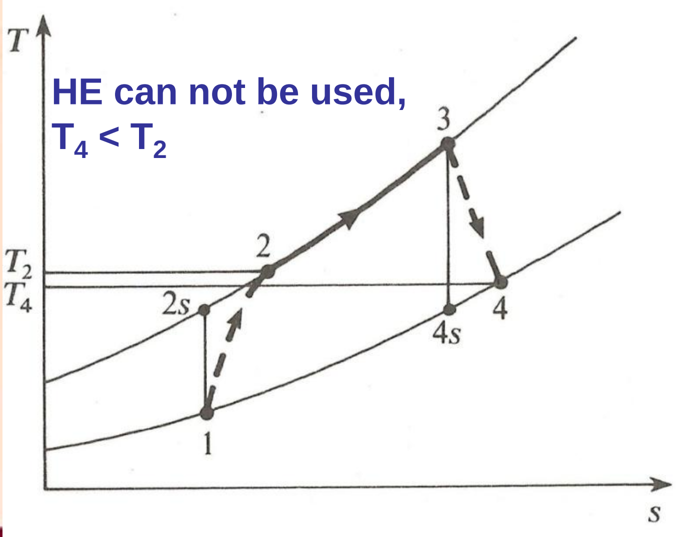
REGENERATIVE CYCLE (USE OF HEAT EXCHANGER)

- Heat supplied w/o HE = $Q_{42} = c_{pg}(T_4 - T_2)$
- Heat supplied with HE = $Q_{43} = c_{pg}(T_4 - T_3)$
- $c_{pg}(T_4 - T_2) > c_{pg}(T_4 - T_3)$
- *Heat to be supplied in the combustion chamber is reduced by using HE, thus, the thermal efficiency will increase.*
- The heat exchanger can be used only if the turbine exhaust temperature is higher than the compressor exit temperature ($T_4 > T_2$) with a sufficiently large temperature difference between them.





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EXAMPLE

Air enters the compressor of a regenerative gas turbine power plant at 15 ^oC and 1.01 bar and the pressure ratio is 9/1.The maximum temperature of the cycle is 650 ^oC. The generator has an effectiveness of 75 percent. For a compressor and turbine efficiency of 0.8 and 0.85 respectively, determine:

a) the amount of heat transfer in the generator
b) the thermal efficiency
c) the work ratio

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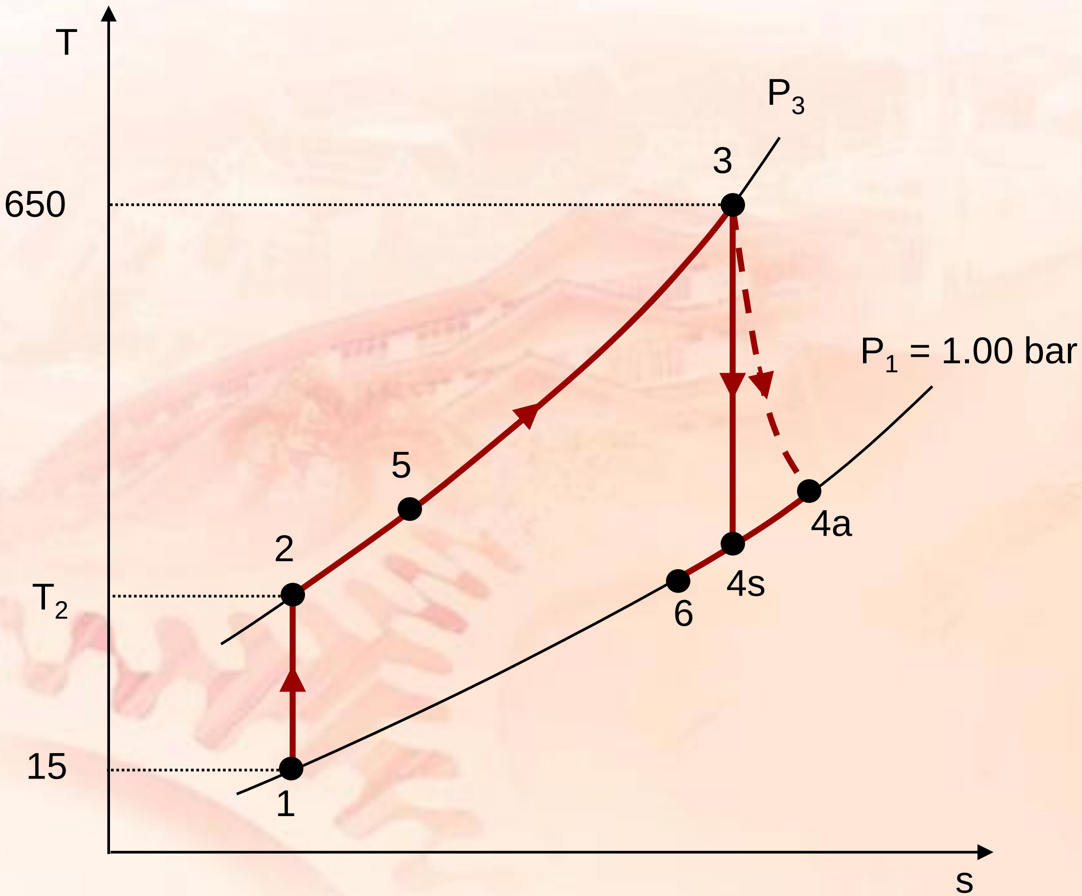
Solution



$$\varepsilon = \frac{h_5 - h_2}{h_{4a} - h_2} = 0.72$$

$$\eta_T = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} = 0.86$$

$$q_{gen} = h_5 - h_2$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{turb} - w_{comp}}{q_{in}}$$

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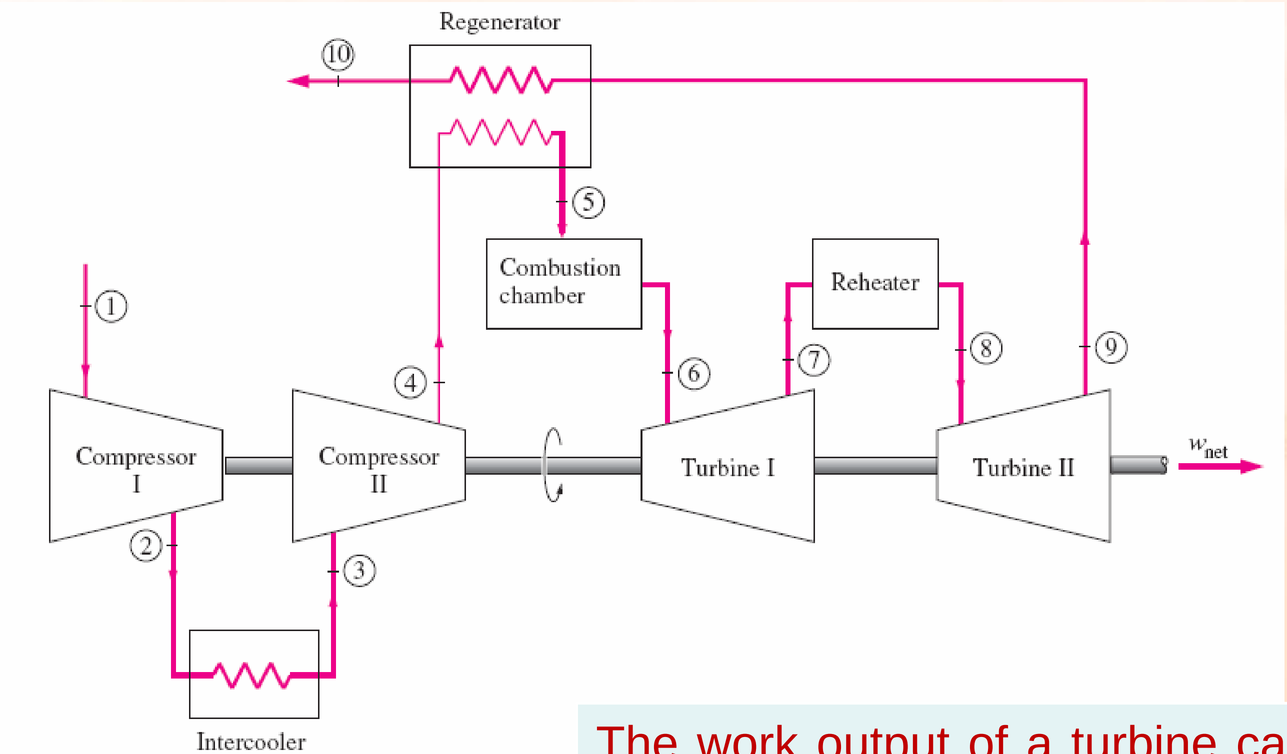
GAS TURBINE CYCLE WITH INTERCOOLING, REHEATING & REGENERATION



Physical arrangement of an **ideal two-stage** gas-turbine cycle with intercooling, reheating, and regeneration

The work output of a turbine can be increased by expanding the gas in stages and reheating it in between, utilizing a **multistage expansion** with **reheating.**

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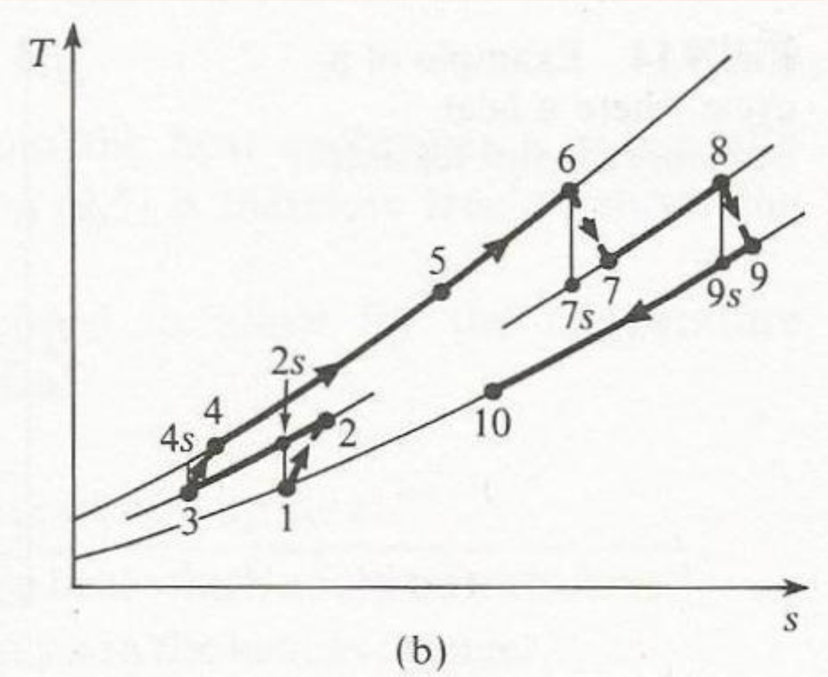
GAS TURBINE CYCLE WITH INTERCOOLING, REHEATING & REGENERATION

Conditions for Best Performance

The work input to a two-stage compressor is **minimized** when equal pressure ratios are maintained across each stage. This procedure also maximizes the turbine work output.Thus, for best performance,

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} \quad \text{and} \quad \frac{P_6}{P_7} = \frac{P_8}{P_9}$$

- Intercooling and reheating always **decreases** thermal efficiency unless are accompanied by **regeneration**.
- Therefore, intercooling and reheating are always **used in conjunction** with regeneration.



Example 9.4 pg 276

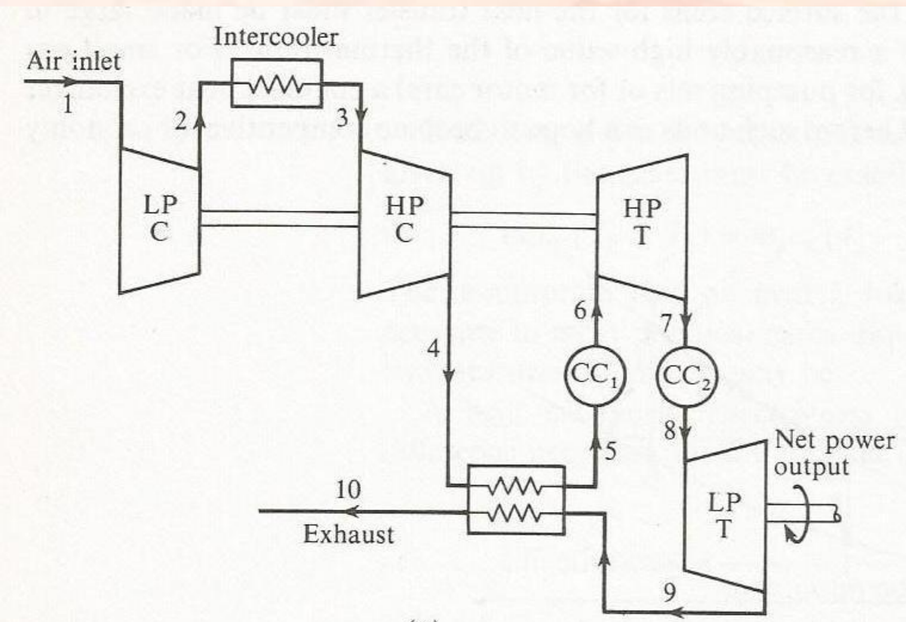
A 5000 kW gas turbine generating set operates with two compressor stages with intercooling between stages. The overall pressure ratio is 9/1. A HP turbine drives the generator. The temperature of the gases at entry to the HP turbine is 650 ^oC and the gases are reheated back to 650 ^oC after expansion in the first turbine. The exhaust gases leaving the LP turbine are passed through a heat exchanger to heat the air leaving the HP compressor. The compressors have equal pressure ratio and the intercooling is complete between stages. The air inlet temperature is 15 ^oC. The isentropic efficiency of each compressor is 0.8 and the isentropic efficiency of each turbine is 0.85. The heat exchanger effectiveness is 0.75. A mechanical efficiency of 98% can be assumed for both the power shaft and the compressor turbine shaft. Neglecting all pressure losses and changes in kinetic and potential energies, calculate,

a) the cycle efficiency
b) the work ratio
c) the mass flow rate, kg/s.

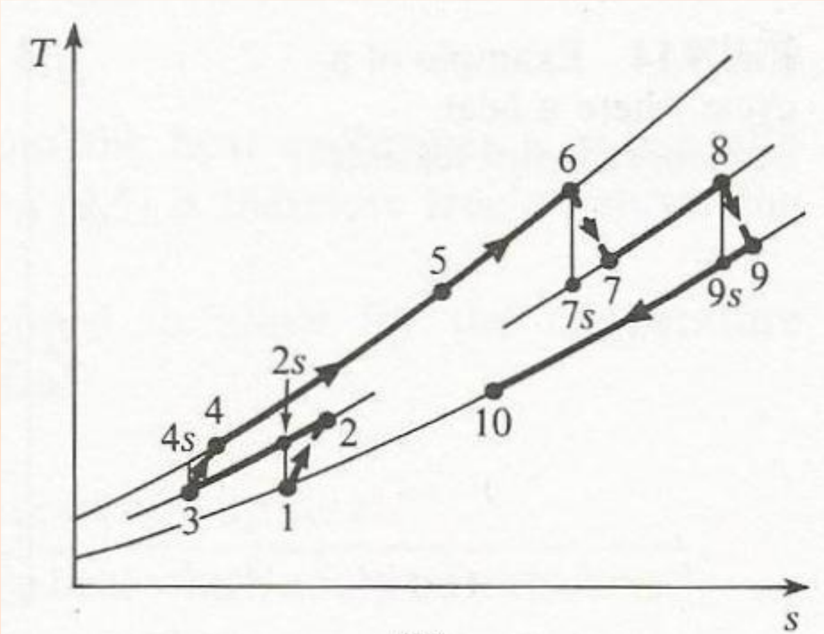
For air take c_{pa} =1.005 kJ/kgK and γ_a = 1.4 and for the gases take c_{pg} = 1.15 kJ/kgK and γ_g = 1.333.

Example 9.4 pg 276

A 5000 kW gas turbine generating set operates with two compressor stages with intercooling between stages. The overall pressure ratio is 9/1. A HP turbine drives the generator. The temperature of the gases at entry to the HP turbine is 650 ^{o}C and the gases are reheated back to 650 ^{o}C after expansion in the first turbine. The exhaust gases leaving the LP turbine are passed through a heat exchanger to heat the air leaving the HP compressor. The compressors have equal pressure ratio and the intercooling is complete between stages. The air inlet temperature is 15 ^{o}C. The isentropic efficiency of each compressor is 0.8 and the isentropic efficiency of each turbine is 0.85. The heat exchanger effectiveness is 0.75. A mechanical efficiency of 98% can be assumed for both the power shaft and the compressor turbine shaft. Neglecting all pressure losses and changes in kinetic and potential energies, calculate, the cycle efficiency, the work ratio and the mass flow rate, kg/s.
For air take c_{pa} =1.005 kJ/kgK and γ_a = 1.4 and for the gases take c_{pg} = 1.15 kJ/kgK and γ_g = 1.333.



(a)



(b)

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EXAMPLE 9-8 Pg 515

A gas turbine with two stages of compression and two stages of expansion has an overall pressure ratio of 8. Air enters each stage of the compressor at 300 K and each stage of turbine at 1300 K. Both compressors and turbines have the same pressure ratio. Determine the work ratio and thermal efficiency of the cycle if,

a) no regenerator
b) ideal regenerator with 100 percent effectiveness.

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EXAMPLE 9-8 Pg 515

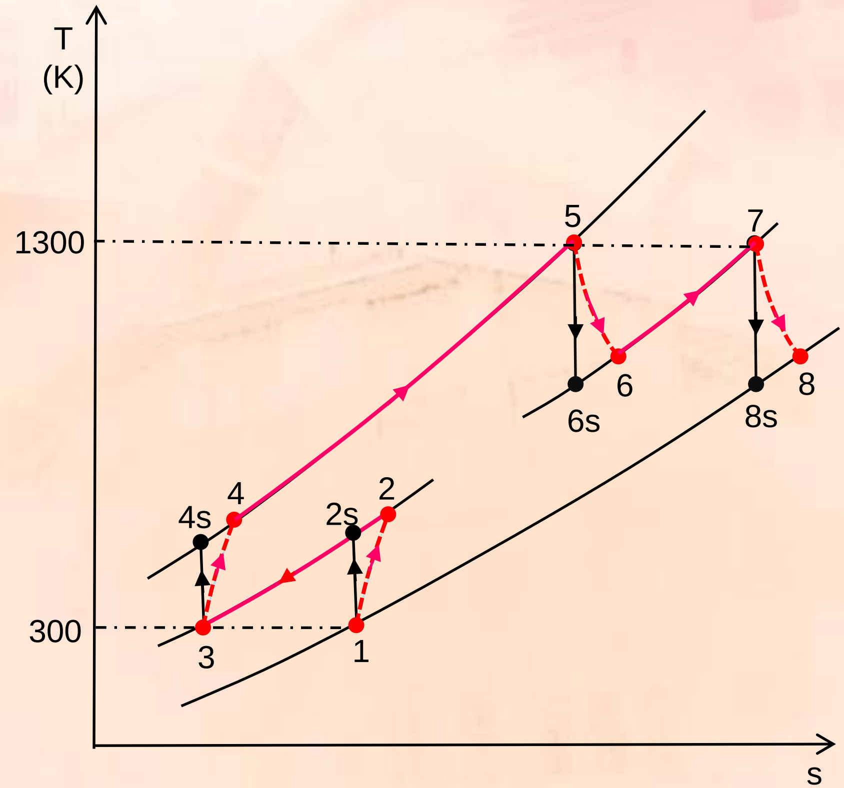
A gas turbine with two stages of compression and two stages of expansion has an overall pressure ratio of 8. Air enters each stage of the compressor at 300 K and each stage of turbine at 1300 K. Both compressors and turbines have the same pressure ratio. Determine the work ratio and thermal efficiency of the cycle if,

a) no regenerator

Solution :

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = \sqrt{8} = 2.83 \text{ and}$$

$$\frac{P_5}{P_6} = \frac{P_7}{P_8} = \sqrt{8} = 2.83$$



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EXAMPLE 9-8 Pg 515

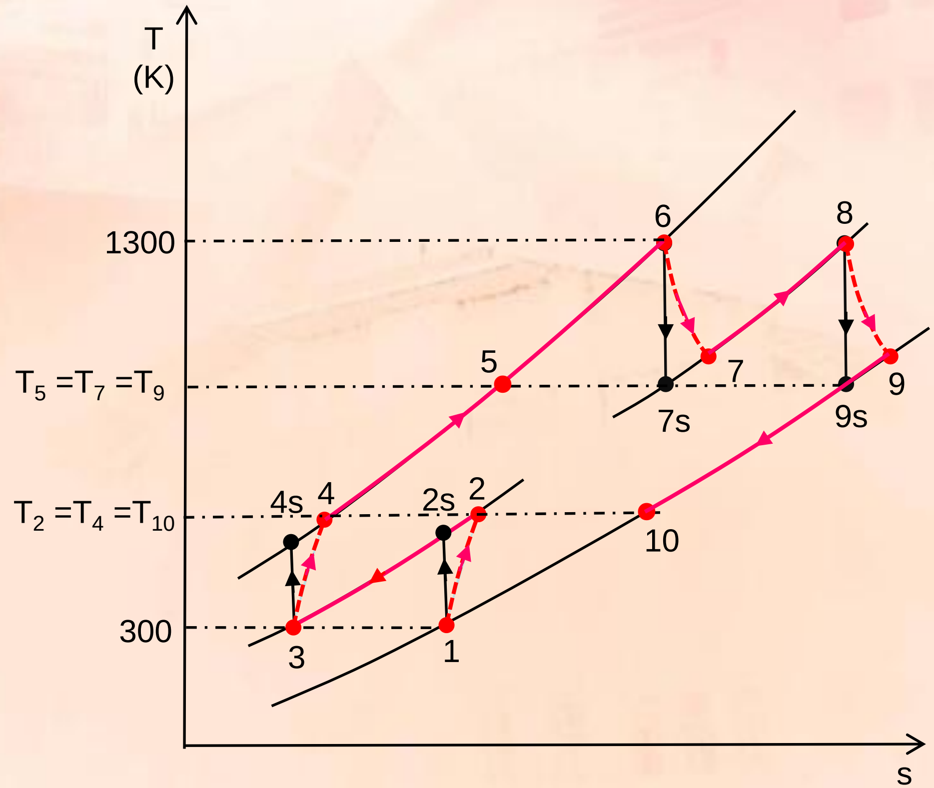
A gas turbine with two stages of compression and two stages of expansion has an overall pressure ratio of 8. Air enters each stage of the compressor at 300 K and each stage of turbine at 1300 K. Both compressors and turbines have the same pressure ratio. Determine the work ratio and thermal efficiency of the cycle if,

b) ideal regenerator with 100 percent effectiveness

Solution :

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = \sqrt{8} = 2.83 \quad \text{and}$$

$$\frac{P_6}{P_7} = \frac{P_8}{P_9} = \sqrt{8} = 2.83$$



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ASSIGNMENT 2

Consider an ideal gas-turbine cycle with **two stages** of compression and two stages of expansion. The pressure ratio across each stage of the compressor and turbine is 3. The air enters each stage of the compressor at 300 K and each stage of the turbine at 1200 K. Determine:

a) the **back work ratio**, and

b) the **thermal efficiency** of the cycle

assuming:

1. no regenerator is used, and
2. a regenerator with **75 percent** effectiveness is used.

c_{pa} = 1.005 kJ/kgK, γ_a = 1.4, c_{pg} = 1.15 kJ/kgK and γ_g = 1.33

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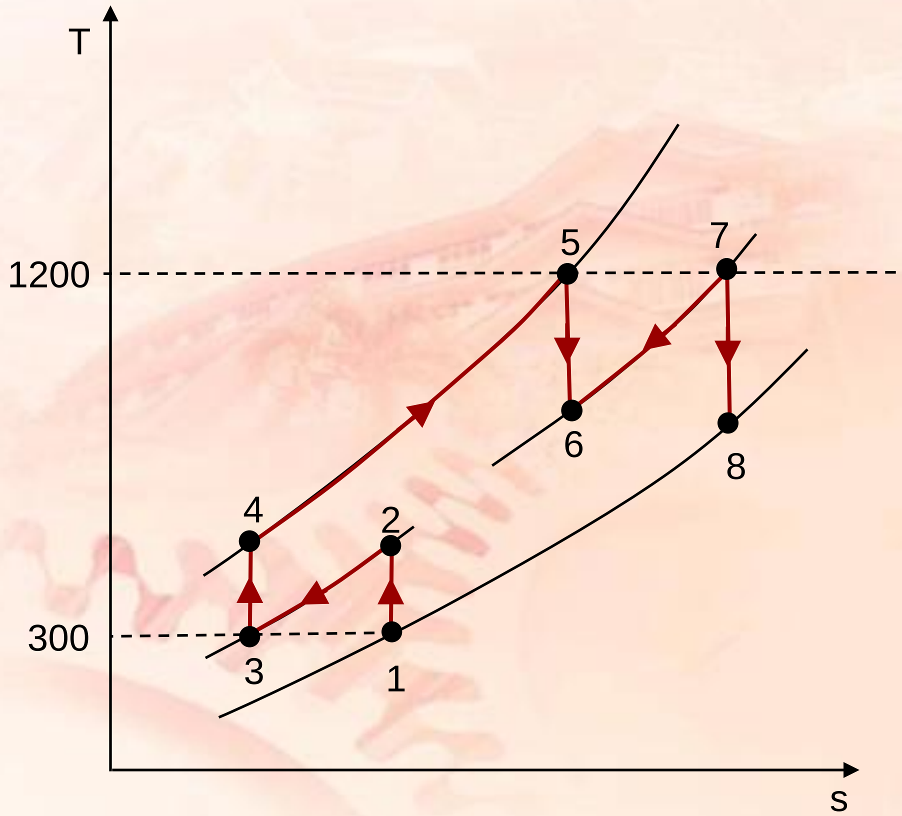
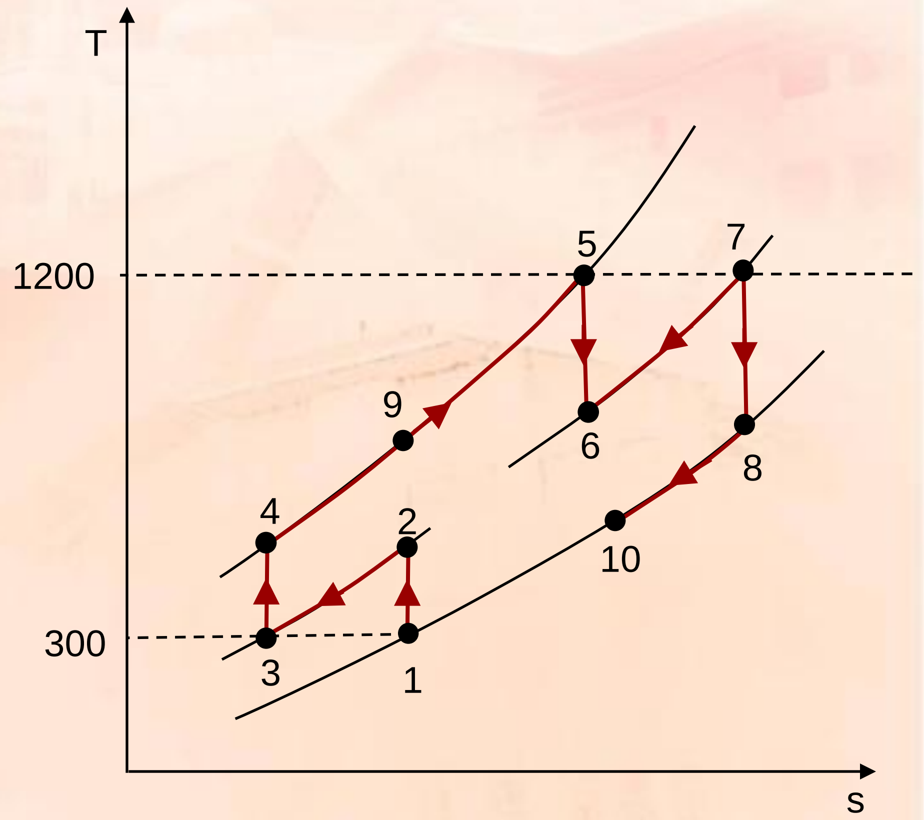
Prob. 9–124 (page 556)

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = \frac{P_5}{P_6} = \frac{P_7}{P_8} = 3$$





Q1 FINAL EXAM APRIL 2010

(b) A Brayton cycle with regeneration using air as the working fluid has a pressure ratio of 8. The air temperatures at entry to the compressor and at entry to the turbine are 310 K and 1200 K, respectively. Assume an isentropic efficiency of 80 % for the compressor, 85 % for the turbine, and the regenerator effectiveness of 70 %. Accounting for the variation of specific heats with temperature, determine:

(i) the air temperature at the turbine exit, (^{o}C)

(ii) the net power output if 100 kg/s of air flows through the cycle, (kW)

(iii) the thermal efficiency, (%)

(18 marks)

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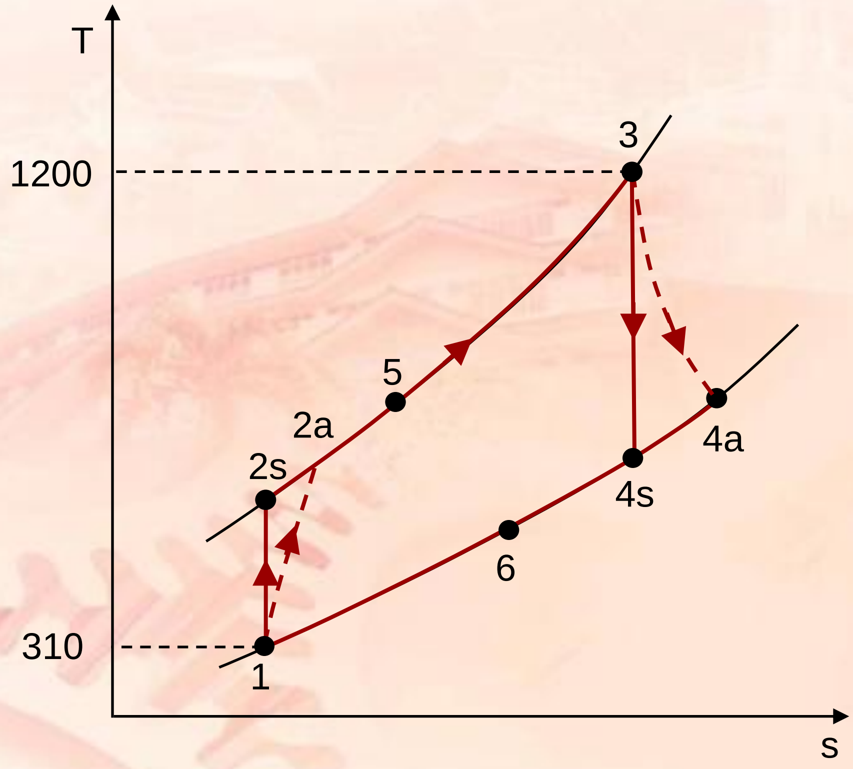

$$\eta_C = \frac{h_{2s} - h_1}{h_{2a} - h_1} = 0.80$$

$$\eta_T = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} = 0.85$$

$$\varepsilon = \frac{h_5 - h_{2a}}{h_{4a} - h_{2a}} = 0.70$$

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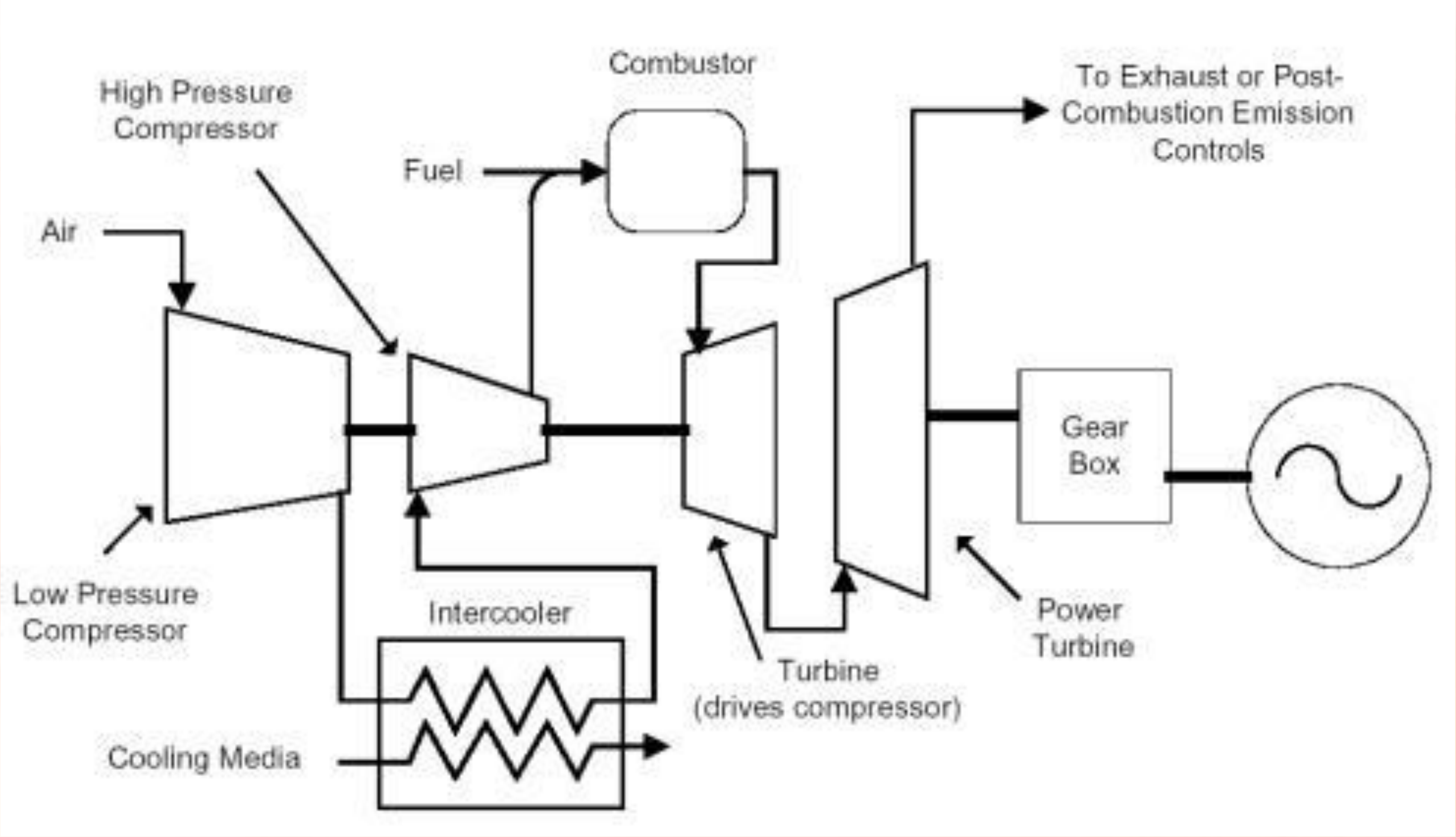
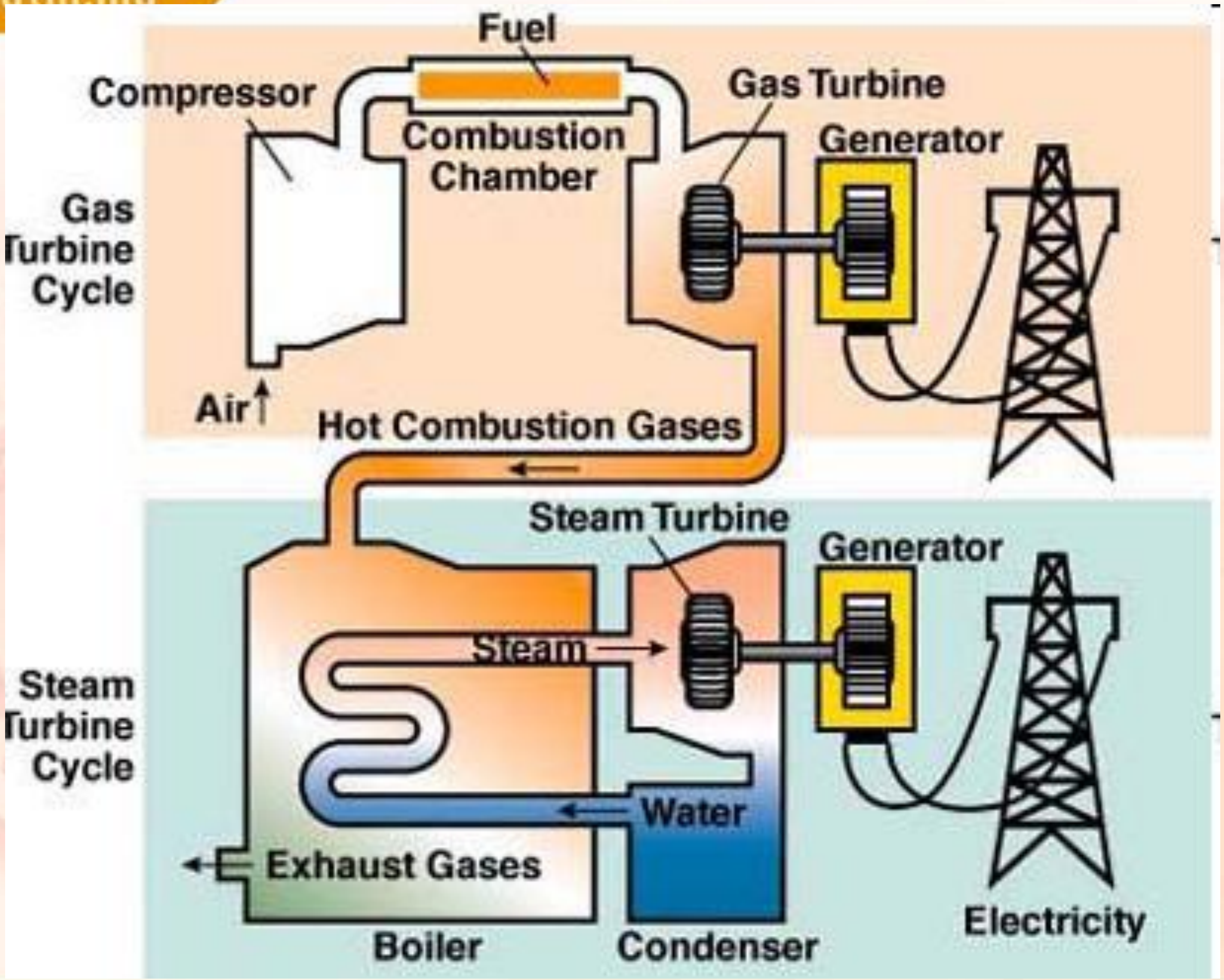
Two-Stage Compression, Two-stage expansion



COMBINED CYCLE POWER PLANT



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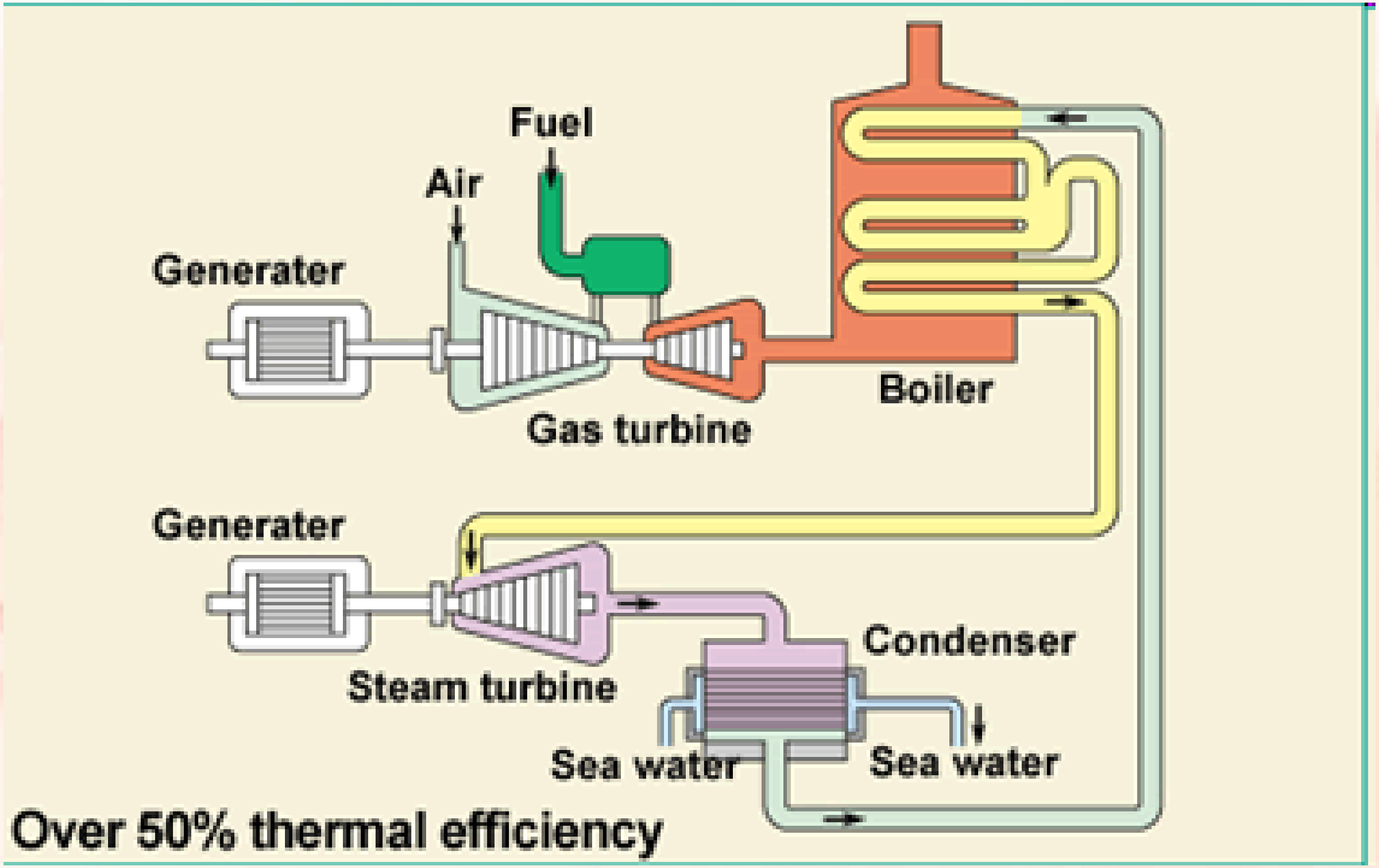

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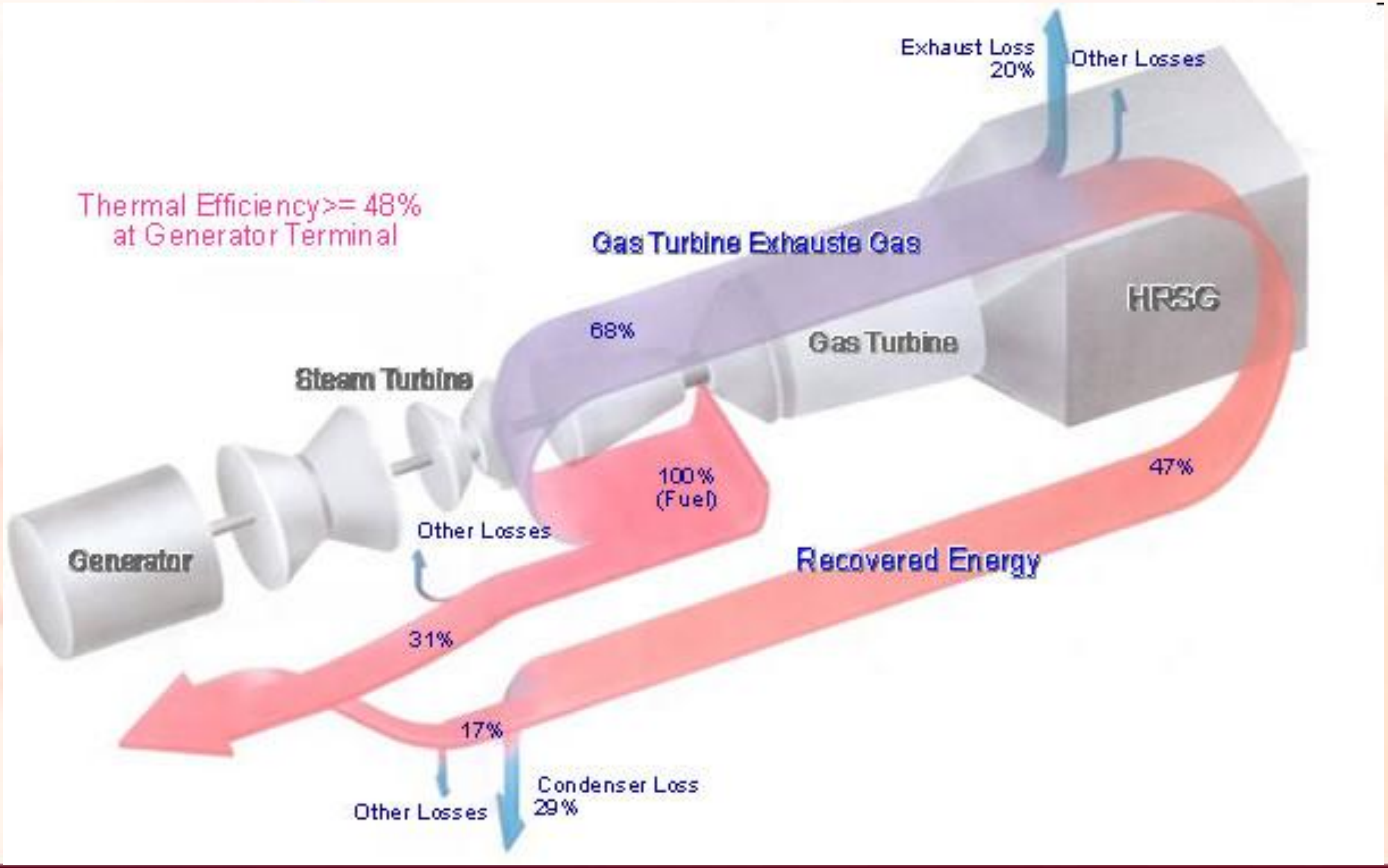

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