MCE535
Thermal Power and Propulsive Systems

Lecture 04: 04/10/2017

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Class: Thursday (3 – 5 pm)

Etiquettes and MOP

- Attendance is a requirement.
- There may be class assessments, during or after lecture.
- Computational software will be employed in solving problems
- Conceptual understanding will be tested
- Lively discussions are integral part of the lectures.

Lecture content

Gas Power Cycles:

- Brayton cycle: The ideal cycle for gas-turbine engines
- The Brayton cycle with regeneration
- The Brayton Cycle with Intercooling, Reheating and Regeneration
- Ideal Jet-Propulsion Cycles

Recommended Textbook:

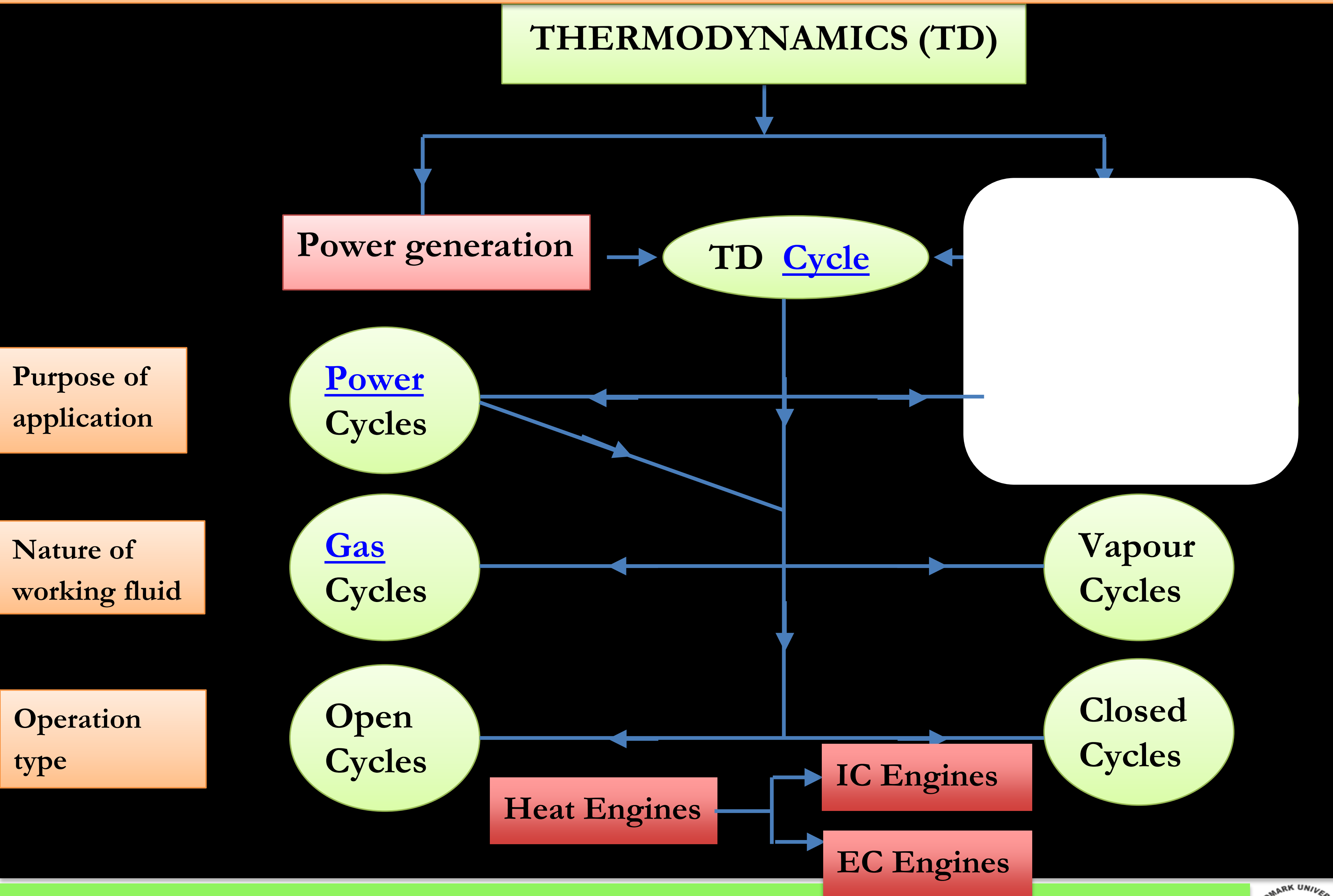
- Thermodynamics: An Engineering Approach by Cengel Y.A. & Boles M.A. 8th Edition

HANDS-ON ACTIVITY

- An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 95 kPa and 27 °C, and 750 kJ/kg of heat is transferred to air during the constant-volume heat-addition process. Taking into account the variation of specific heats with temperature, determine (*a*) the pressure and temperature at the end of the heat- addition process, (*b*) the net work output, (*c*) the thermal efficiency, and (*d*) the mean effective pressure for the cycle.
  Answers: (*a*) 3898 kPa, 1539 K, (*b*) 392.4 kJ/kg, (*c*) 52.3 percent, (*d*) 495 kPa

- Reconsider Problem 9–33. Using EES (or other) software, study the effect of varying the compression ratio from 5 to 10. Plot the net work output and thermal efficiency as a function of the compression ratio. Plot the *T-s* and *P-v* diagrams for the cycle when the compression ratio is 8.

AN OVERVIEW OF THERMODYNAMIC CYCLES



POWER CYCLES: BASIC CONSIDERATIONS

- **Idealizations**: thermodynamic cycles are modeled as ideal cycles so as to simplify the analysis of actual cycles.
- The effects of major parameters are the emphases of ideal cycles allowing conclusions obtained thereof to be applicable to actual cycles.

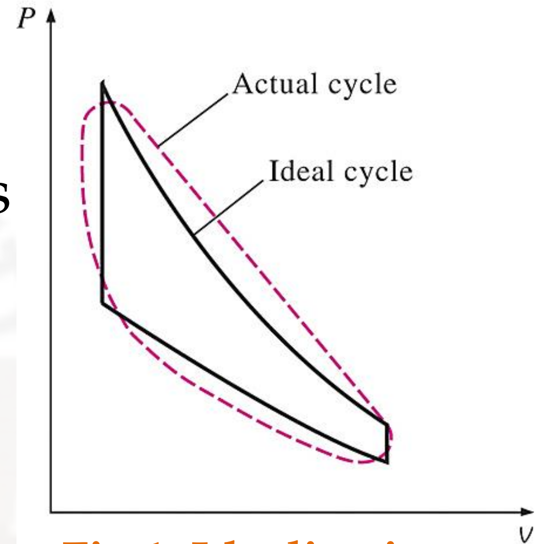


Fig 1: Idealization concept

- **Heat Engines (HE)** convert thermal energy to work. Their thermal efficiency, η_{th}, Eq.(P.1).

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \text{ or } \eta_{th} = \frac{w_{net}}{q_{in}} \qquad (P.1)$$

- Pls note that heat engines, such as the **Carnot cycle**, that are totally reversible have the highest η_{th} of all HE operating between the same temperature levels

Why then don't we use Carnot cycle as the model cycle for all HE?

Summary of idealizations and simplifications used in power cycle analysis

1. The cycle does not involve any **friction**. Therefore, the working fluid does not experience any pressure drop as it flows in pipes or heat exchangers.
2. All expansion and compression processes take place in a **quasi-equilibrium** manner.
3. The pipes connecting the various components of a system are **well insulated**, so heat transfer through them is negligible.
4. Changes in the **kinetic** and **potential energies** of the working fluid are also negligible with the exception of *nozzles* and *diffusers*.

THE CARNOT CYCLE

- The Carnot cycle is the most efficient HE that can operate between a heat source at temperature, T_H, and a sink at temperature T_L and it consist of four reversible processes namely:

Carnot Cycle

Process	Description
1-2	Isothermal heat addition
2-3	Isentropic expansion
3-4	Isothermal heat rejection
4-1	Isentropic compression

- Thermal efficiency for Carnot cycle is shown in Eq.(P.2)

$$\eta_{th} = 1 - \frac{T_L}{T_H} \qquad \text{(P.2)}$$

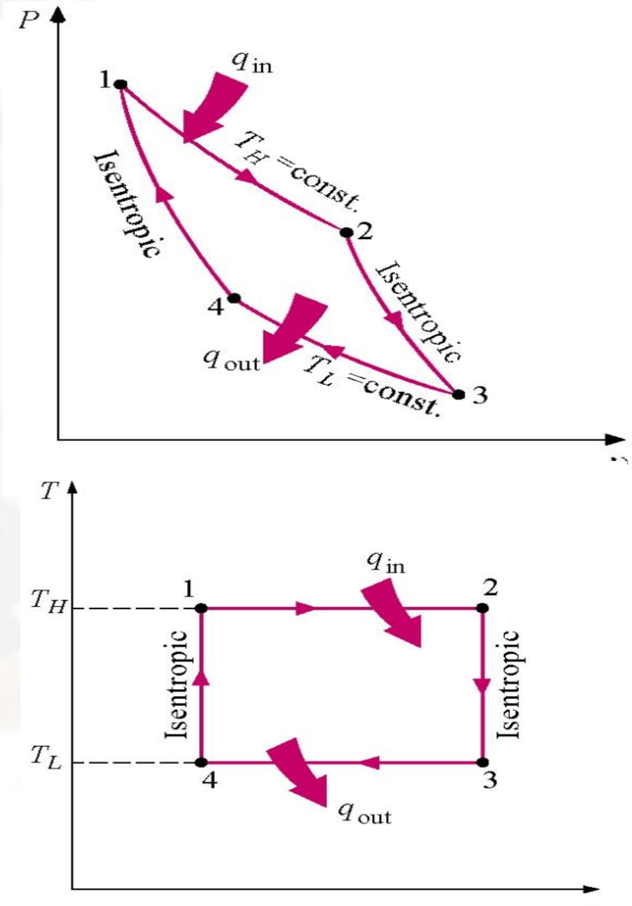


Fig 2: *P-v* and *T-s* diagrams of a Carnot cycle

LIST OF IDEAL AND ACTUAL CYCLES

- Table 1 is a list of ideal cycles and the actual cycles they represent.

Table 1: Ideal versus actual cycles and their applications

Working fluid nature	Ideal cycles	Actual cycles	Proponents	Application
Gas-power cycles	Otto cycle	Spark-ignition engine	Nikolaus Otto (1876)	Cars, small generators
	Diesel cycle	Compression-ignition engine	Rudolph Diesel (1890s)	Heavy-duty machines, trucks
	Brayton cycle	Gas-turbine engine	George Brayton (1870)	Light aircraft, Electric power generation
Vapour-power cycles	Rankine cycle	Steam power plant	William Rankine	Electric power generation

GAS POWER CYCLES: AIR-STANDARD ASSUMPTIONS

- Actual cycles are really complex; so some approximations, often referred to as **air-standard assumptions**, are made as follows.

Air-standard assumptions

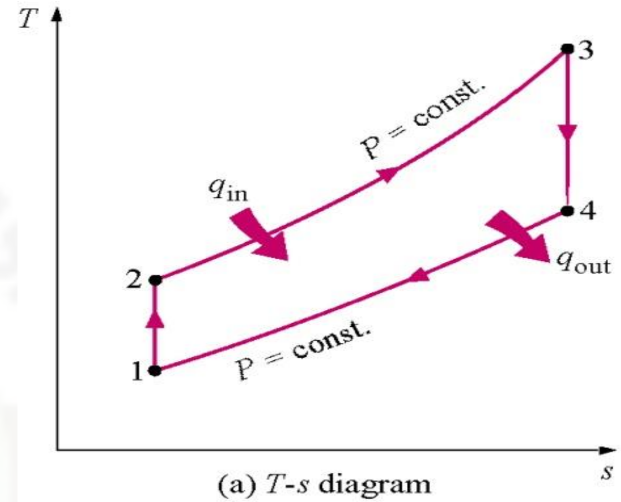
- The working fluid, circulating in a closed loop, is air, and it behaves as an ideal gas.
- All the processes in the cycle are internally reversible.
- The combustion process is replaced by heat-addition from external source.
- The exhaust process is replaced by heat rejection to the surroundings and it restores working fluid to initial state.

- When it is assumed that air has constant specific heats and the values at room temperature (25°C) are used, then it is referred to as **cold-air-standard assumptions**.

- Actual gas-turbines operate on open cycles but they are modeled as closed cycles based on the air-standard assumptions.
- The ideal cycle in which the working fluid of GT undergo is called a Brayton cycle and it comprises of ***four internally reversible*** processes.

Brayton Cycle

Process	Description
1-2	Isentropic compression (in a compressor)
2-3	Constant pressure heat addition
3-4	Isentropic expansion (in a turbine)
4-1	Constant pressure heat rejection



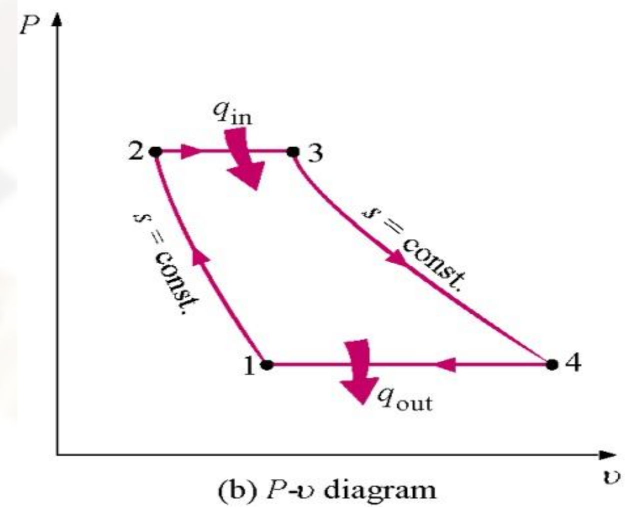


Fig 5: *T-s* and *P-v* diagrams for the ideal Brayton cycle

Thermal efficiency, η_{th}, of the Brayton cycle

$$\eta_{th,\ Brayton} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \qquad \text{(P.5)}$$

- Evaluating Q_{in} and Q_{out} through a series of manipulations based on theoretical knowledge of the processes, η_{th}, yields Eqs. (P.6) and (P.7)

$$\eta_{th} = 1 - \frac{T_1}{T_2} \qquad \text{(P.6)}$$

Is this the same as the Carnot cycle efficiency?

$$\eta_{th,\ Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}} \qquad \text{(P.7)}$$

- where $r_p = P_2/P_1$ is the pressure ratio of the gas turbine and k is the specific heat ratio of the working fluid.
- In GT engines, the ratio of compressor to turbine work is called back work ratio and it is usually very high.

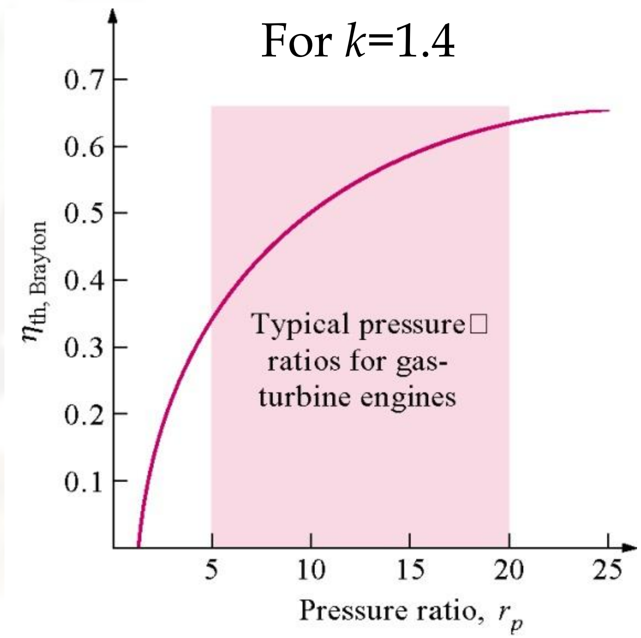


Fig 5: Thermal efficiency of the ideal Brayton cycle as a function of the pressure ratio

- The actual GT cycles differ from the idealized ones because:
  i. Pressure drops occur during heat addition and heat rejection processes.
  ii. The actual work input to the compressor is higher and the work output at the turbine is lower due to irreversibilities.
- These deviations are accounted for by the isentropic efficiencies of the turbines and compressors stated in Eqs.(P.8) and (P.9).

$$\eta_C = \frac{w_s}{w_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad \text{(P.8)}$$

$$\eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \qquad \text{(P.9)}$$

Where 2a and 4a are actual compressor and turbine exit states respectively, and 2s and 4s are the corresponding states for the isentropic case .

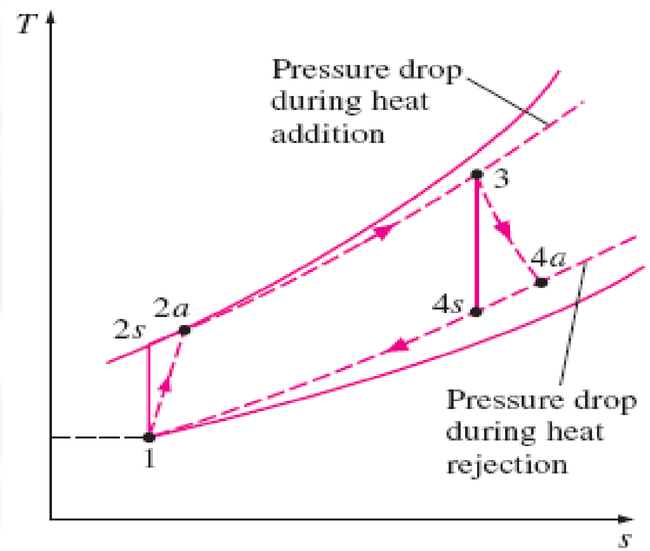


Fig 6: Deviation of an actual GT from ideal Brayton cycle as a result of irreversibilities

EXAMPLE

1. A gas-turbine power plant operating on an Ideal Brayton cycle has a pressure ratio, r_p, of 8. The gas temperature is 300 K at the compressor inlet and 1300 K at the turbine inlet. Utilizing the air-standard assumptions, determine (a) the gas temperature at the exits of the compressor and the turbine (b) the back work ratio, and (c) the thermal efficiency.
2. Assuming a compressor efficiency of 80% and turbine efficiency of 85%, determine (a) the back work ratio, (b) the thermal efficiency, and (c) the turbine exit temperature of the gas-turbine cycle discussed in Ex 1.

THE BRAYTON CYCLE WITH REGENERATION

- Regeneration: is transfer of heat from high-temperature gases at the turbine exit (state 4) to the high-pressure air at the compressor exit (state 2) prior to combustion (Fig 7a & 7b).
- This is achieved by the installation of a counter-flow heat exchanger, known as a regenerator or recuperator. The thermal efficiency of the cycle is significantly improved provided $T_4 >> T_2$.

η_{th}, of Brayton cycle with regeneration,

$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(k-1)/k}$$

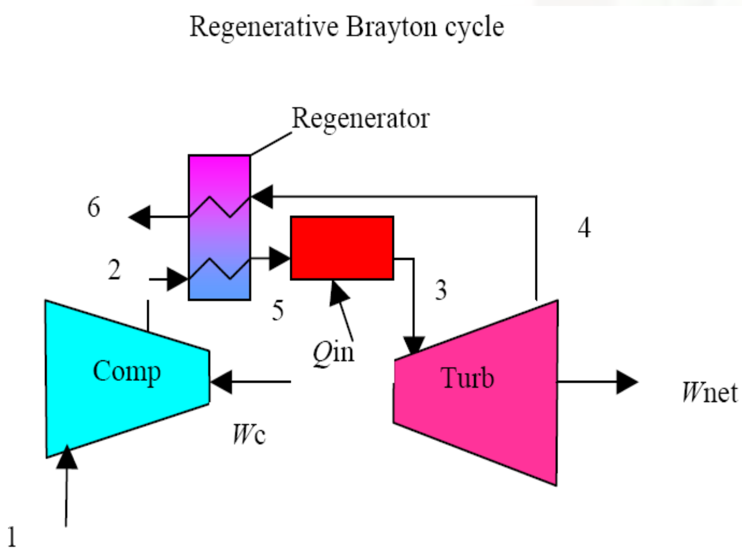


Fig 7a: A gas-turbine with regenerator

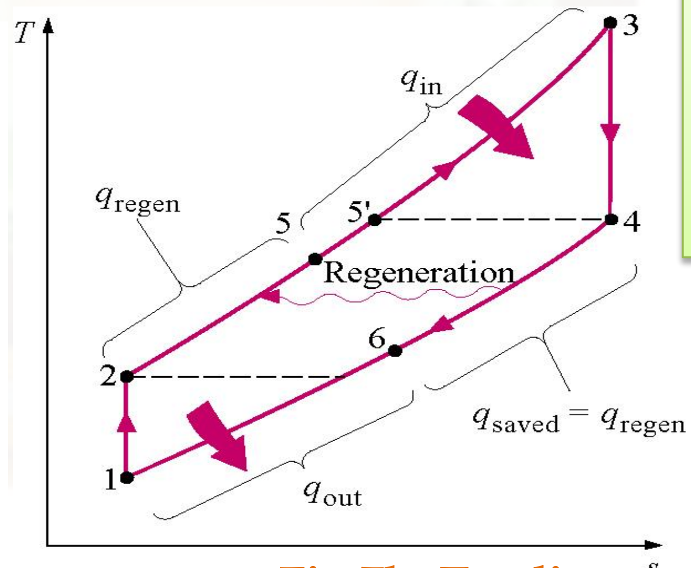


Fig 7b: *T-s* diagram of a Brayton cycle with regeneration

3. Determine the thermal efficiency of the gas-turbine described in Ex. 2 if a regenerator having an effectiveness of 80% is installed.

THE BRAYTON CYCLE WITH INTERCOOLING, REHEATING AND REGENERATION

- The net work output of a GT cycle can be increased either by reducing the compressor work input, or raising the turbine work input or both.
- Multistage compression with intercooling: this lowers the compressor work input by reducing the specific volume of the gas as it is being compressed between two specified pressures.
- Multistage expansion with reheating: this raises the turbine work output by increasing the specific volume of the gas as it is being compressed between two specified pressures. This is accomplished without raising the maximum temperature of the cycle.
- It is noteworthy that intercooling and reheating reduces back work ratio significantly. That notwithstanding, to increase the thermal efficiency of GT cycles operating on intercooling and reheating processes, regeneration must necessarily be incorporated.

THE BRAYTON CYCLE WITH INTERCOOLING, REHEATING AND REGENERATION

- To achieve a higher thermal efficiency for GT cycles, intercooling and reheating must necessarily be combined with regeneration (Fig 8a & b).

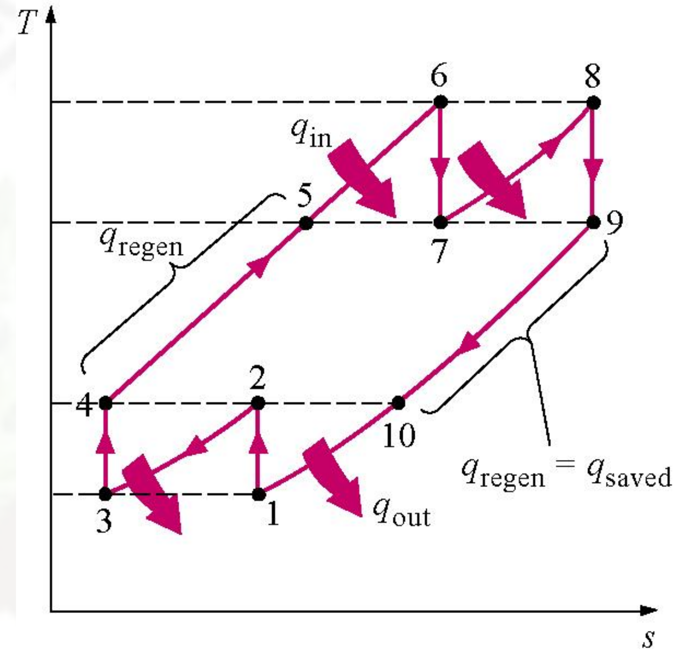


Fig 8b: *T-s* diagram of an ideal GT cycle with intercooling, reheating, and regeneration

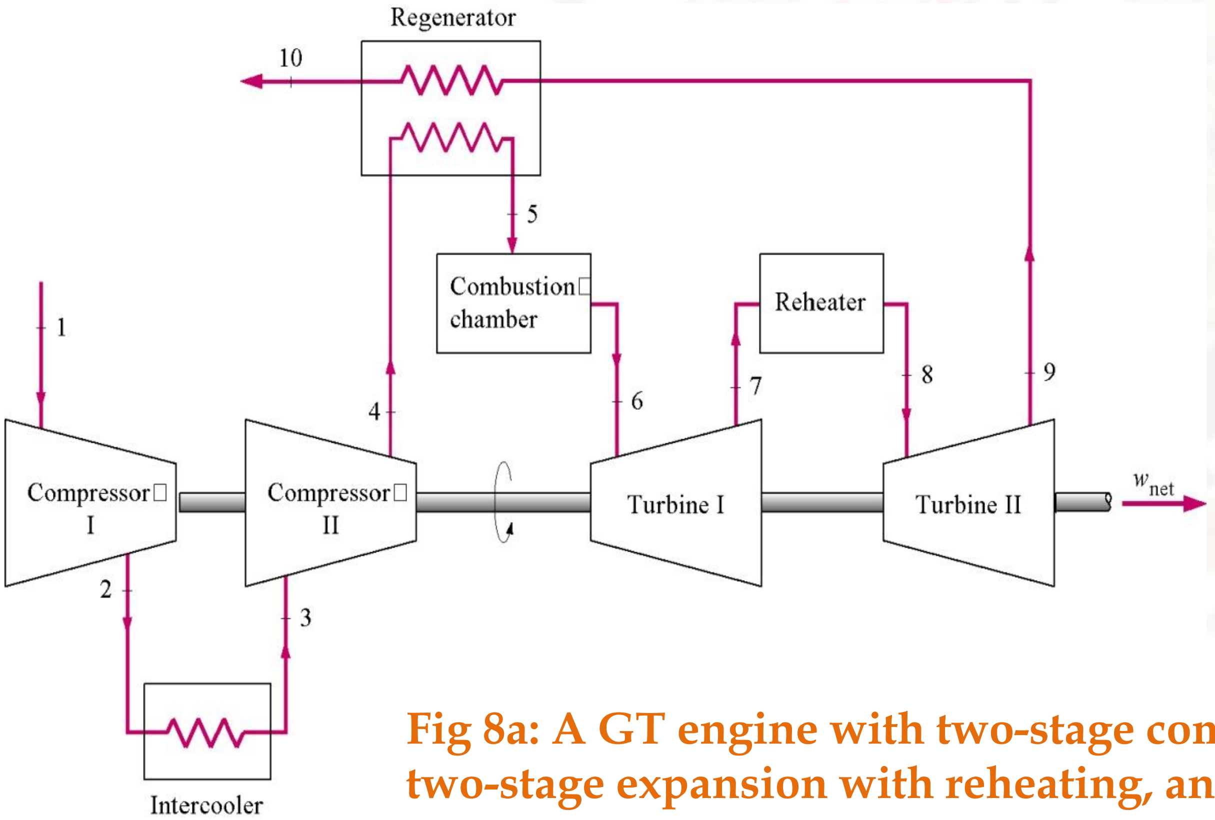


Fig 8a: A GT engine with two-stage compression with intercooling, two-stage expansion with reheating, and regeneration

IDEAL JET-PROPULSION (IJP) CYCLE

- **Jet-propulsion cycle**: an open cycle for an actual aircraft gas turbine.
- Differences between IJP and simple ideal Brayton cycles
  1. Exhaust gases are not expanded to ambient pressure in IJP (Fig 9b)
  2. Diffuser exists before compressor and nozzle after turbine (Fig 9a).
- The diffuser decelerates the inlet air and increases the pressure slightly, while the nozzle accelerates the relatively high-pressure exhaust gases and provides the thrust required to propel the aircraft.

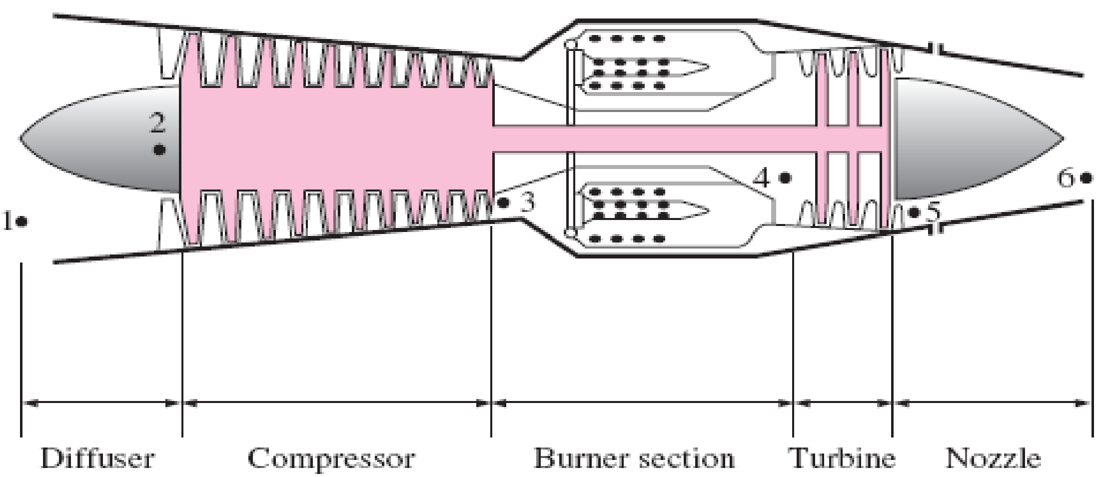


Fig 9a: Basic components of a turbojet engine

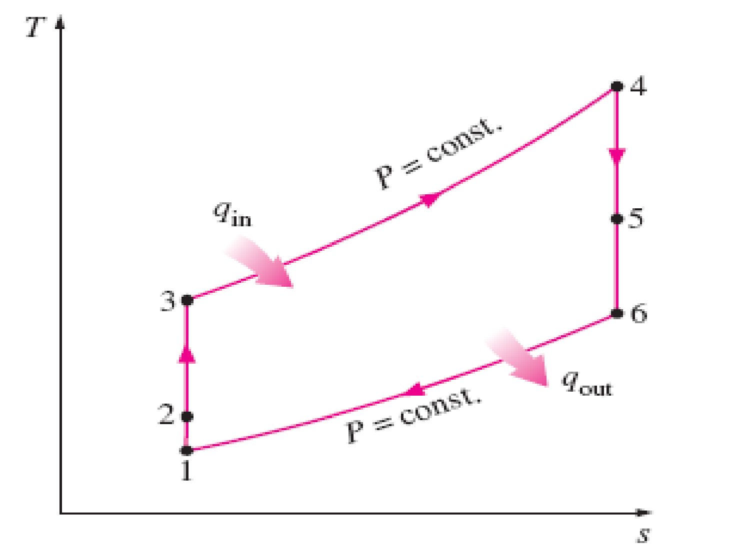


Fig 9b: *T-s* diagram for ideal turbojet cycle

IDEAL JET-PROPULSION (IJP) CYCLE

- **Propulsive force, F_p:** is the difference between the momentum of the relatively slow inlet air and the high-velocity exit gases (Eq. P.10)

$$F_p = (\dot{m}V)_{exit} - (\dot{m}V)_{inlet} = \dot{m}(V_{exit} - V_{inlet}) \quad \text{(N)} \qquad \text{P.10}$$

- **Propulsive power, W_p**: is the product of propulsive force and aircraft velocity (Eq. 11)

$$\dot{W}_p = F_p V_{aircraft} \quad \text{(kW)} \qquad \text{P.11}$$

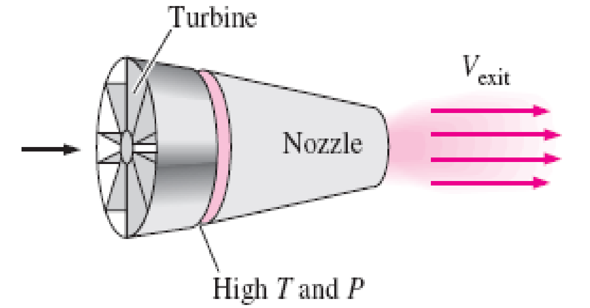


Fig 10: In jet engines high-pressure and high temp gases leaving the turbine are accelerated to provide thrust.

- **Note**: The net work output in a turbojet engine is zero. Therefore propulsive efficiency is

$$\eta_p = \frac{Propulsive\ power}{Energy\ input\ rate} = \frac{\dot{W}_p}{\dot{Q}_{in}} \qquad \text{P.12}$$

The propulsive efficiency is the measure of how efficiently the energy released during the combustion process is converted into propulsive energy.

Assignment

Thermodynamics: An Engineering Approach by Cengel Y.A. & Boles M.A. 8th Edition

From the above textbook, pp. 254-255 answer 1-4

1. Question 9-76C to 9-79C
2. Question 9-95C to 9-97C
3. Question 9-81 & 9-82
4. Question 9-104 & 9-105

Read about the following Turbofan, propjet, afterburner, ramjet, scramjet and rocket.