Lecture 8: Gas Power Systems

Course: MECH-422 – Power Plants

Instructor: Kashif Liaqat

Term: Fall 2021

BUITEMS – DEPARTMENT OF MECHANICAL ENGINEERING

Brief introduction to gas turbines

- **Gas turbines** are sometimes referred to as **combustion turbines** or **fire turbines** (the latter was common in older publications).

- They are commonly used in **aviation industry** to provide propulsion for commercial and military airplanes. They are also widely used to generate electricity in **utility power plants**, **backup power units**, and **emergency power units**.

Advantages of gas turbine engines:

- very high power-to-weight ratio (for same output, more compact than steam cycles)
- quick start-up and shutdown
- rapid load following
- relatively low capital costs
- relatively high efficiency
- low maintenance
- high availability
- high capacity factor
- short delivery and installation time
- no need for water (which is critically important in regions where water is not readily available)
- remote control capability

Disadvantages of standalone gas turbines:

- high temperature exhaust flow
- strong dependency of both power output and efficiency on ambient conditions
- inability to consume solid fuels

Gaseous working-fluid power cycles:

- internal combustion engines
- external combustion engines

Gas turbine power generation cycles need **four processes**:

- a compression process in a compressor
- a heat transfer from a high temperature thermal energy source to the working fluid in a combustor or a heat exchanger
- an expansion process in a turbine to produce work
- a heat transfer from the working fluid to the environment (a low temperature thermal reservoir)

Considering Gas Turbine Power Plants (1 of 5)

- Gas turbine power plants are more quickly constructed, less costly, and more compact than the vapor power plants.

- Gas turbines are suited for stationary power generation as well as for powering vehicles, including aircraft propulsion and marine power plants.

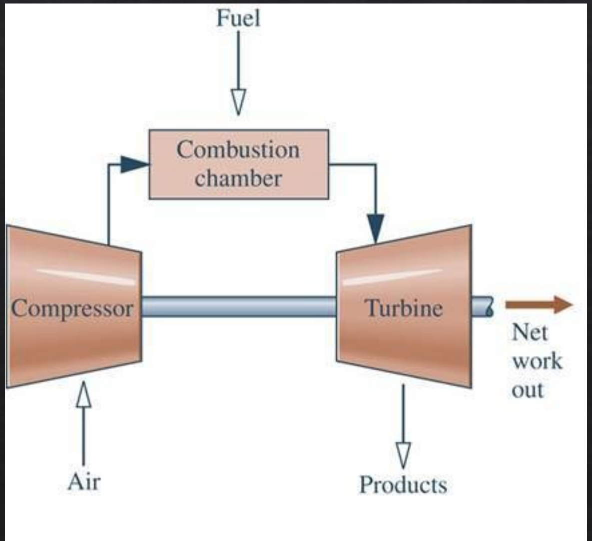
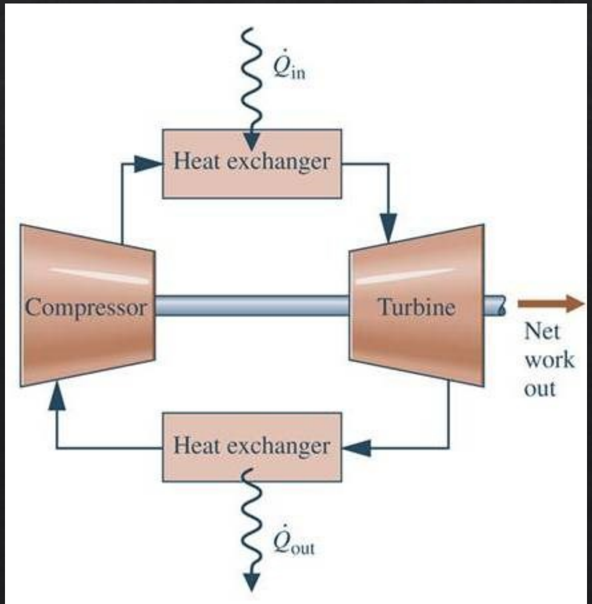
  - Gas turbines are
    - increasingly used for large-scale power generation, and
    - for such applications fueled primarily by natural gas, which is relatively abundant today.

Considering Gas Turbine Power Plants (2 of 5)

► Gas turbines may operate on an ***open*** or ***closed*** basis, as shown in the figures.

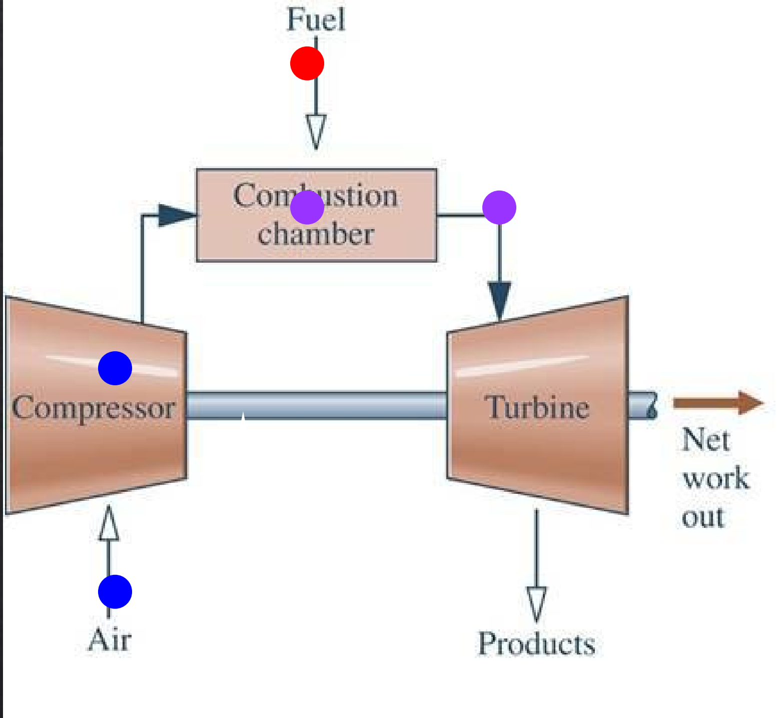
► The open gas turbine is more commonly used

► Study of the individual components of these configurations requires the ***control volume forms*** of the mass, energy, and entropy balances.

Open to the atmosphere	Closed
	

Considering Gas Turbine Power Plants (3 of 5)

- The ***open*** mode gas turbine is an ***internal combustion*** power plant.
  - **Air** is continuously drawn into the compressor where it is compressed to a high pressure.
  - **Air** then enters the combustion chamber (combustor) where it mixes with **fuel** and combustion occurs.
  - **Combustion products** exit at elevated temperature and pressure.
  - **Combustion products** expand through the turbine and then are discharged to the surroundings.



Part of the turbine work is used to drive the compressor.

The remainder is available as net work output to drive an electric generator, to propel a vehicle, or for other uses.

Considering Gas Turbine Power Plants (4 of 5)

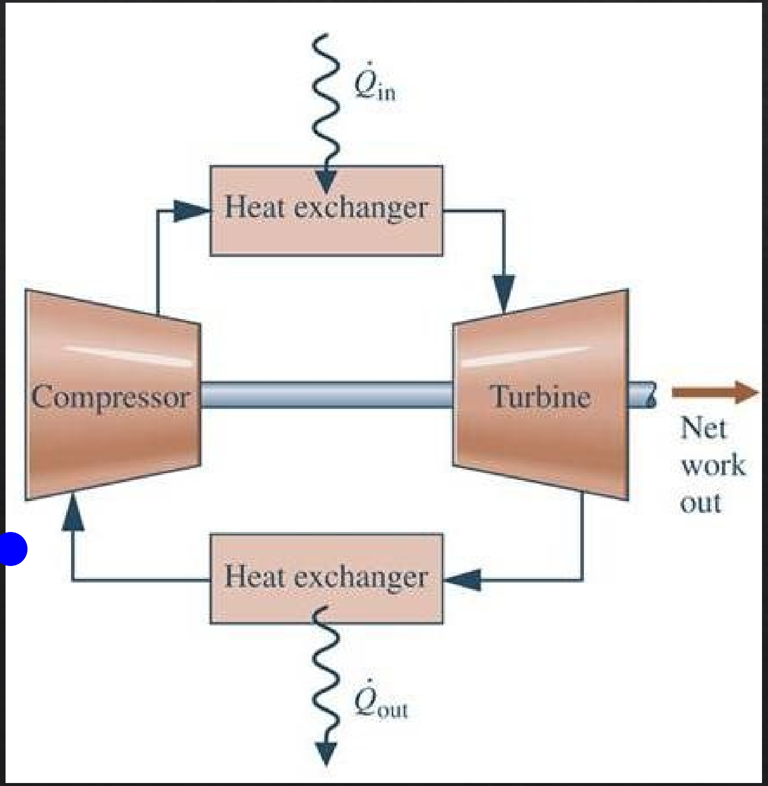
► The ***closed*** gas turbine operates as follows:

► A **gas** circulates through four components: turbine, compressor, and two heat exchangers at higher and lower operating temperatures, respectively.

► The turbine and compressor play the same roles as in the open gas turbine.

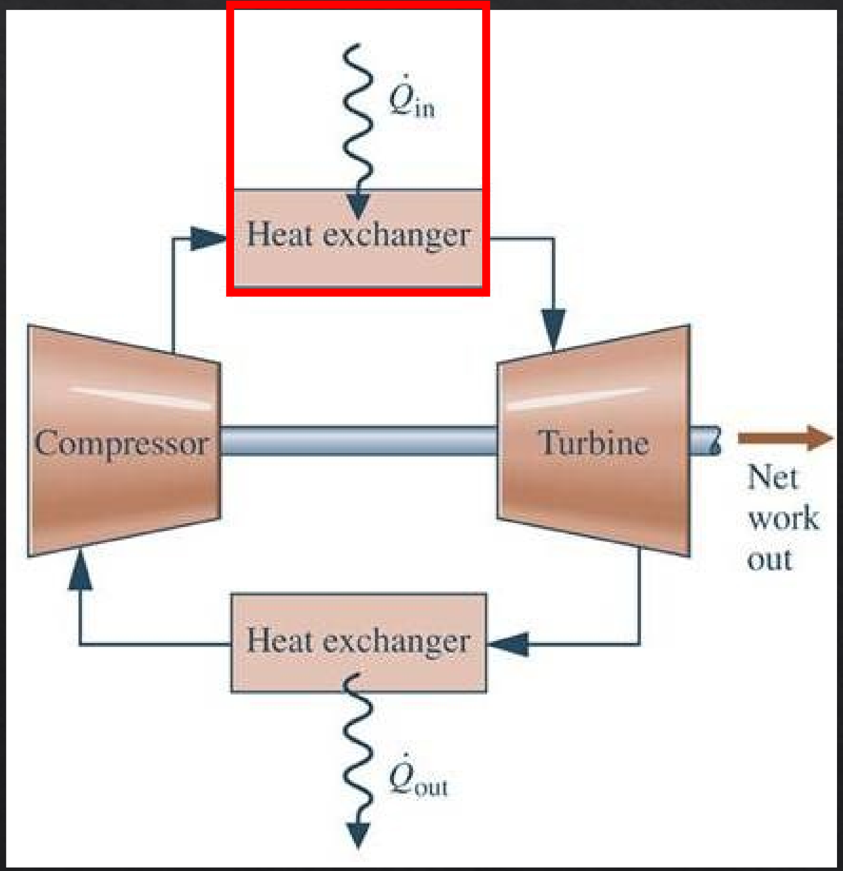
► As the gas passes through the higher-temperature heat exchanger, it receives energy by heat transfer from an ***external source***.

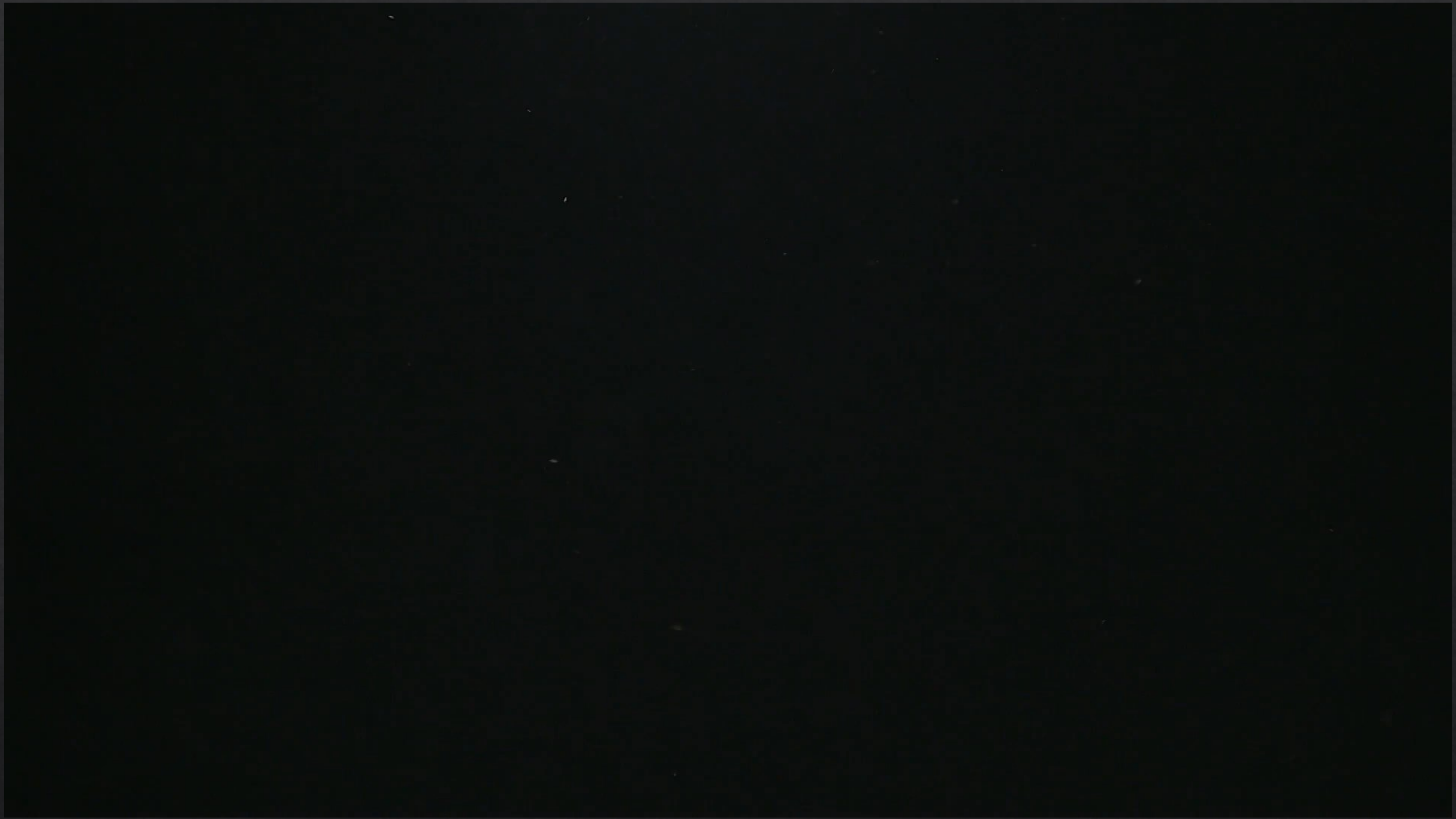
► The thermodynamic cycle is completed by heat transfer to the surroundings as the gas passes through the lower-temperature heat exchanger.



Considering Gas Turbine Power Plants (5 of 5)

- The heat transfer associated with the higher-temperature heat exchanger of the ***closed*** gas turbine originates from an ***external source***, which may include
  - ***External combustion*** of biomass, municipal solid waste, fossil fuels such as natural gas, and other combustibles.
  - **Waste heat** from industrial processes.
  - **Solar** thermal energy.
  - A gas-cooled **nuclear reactor**.





https://www.youtube.com/watch?v=jrWHi77oAWI

Air-Standard Analysis of Open Gas Turbine Power Plants

► To conduct ***elementary*** analyses of ***open*** gas turbine power plants, simplifications are required.

► Although highly idealized, an ***air-standard analysis*** can provide insights and qualitative information about actual performance.

► An ***air-standard analysis*** has the following elements:

- ► **The working fluid is air which behaves as an ideal gas.**
- ► **The temperature rise that would be brought about by combustion is accomplished by heat transfer from an external source.**
- ► **With an air-standard analysis, we avoid the complexities of the combustion process and the change in composition during combustion, which simplifies the analysis considerably.**
- ► **In a *cold* air-standard analysis, the specific heats are assumed constant at their ambient temperature values.**

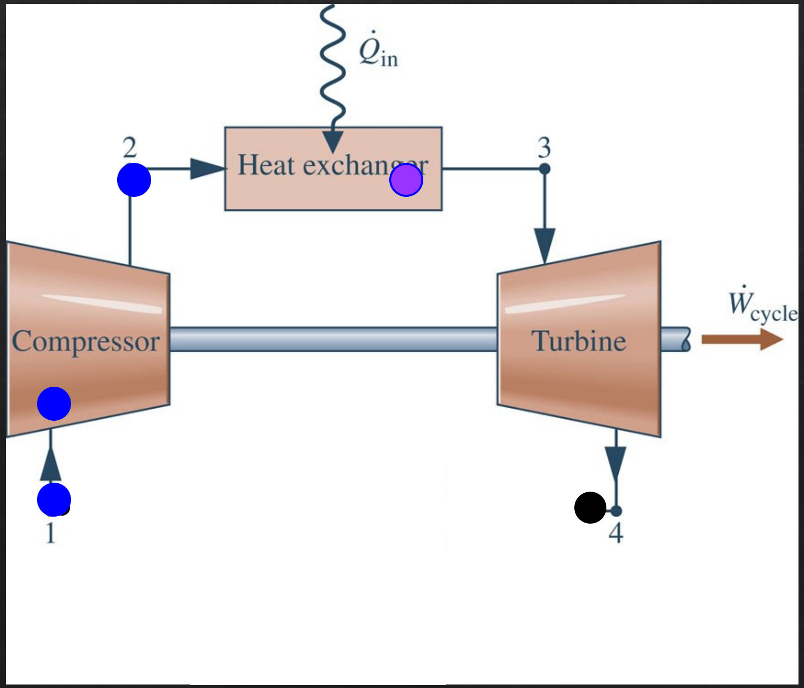
Air-Standard Brayton Cycle (1 of 6)

► Air circulates through the components:

► At state 1, air is drawn into the compressor from the surroundings.

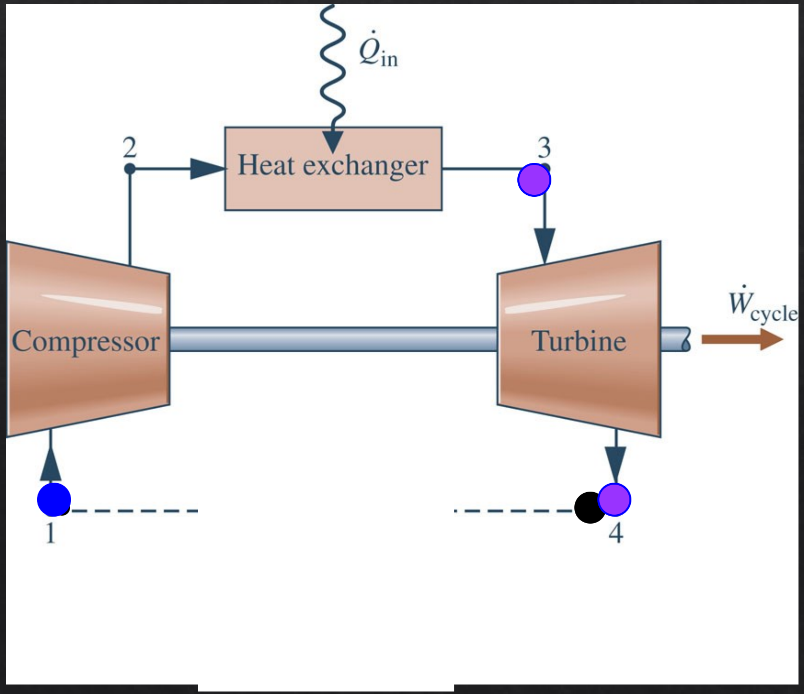
► **Process 1-2**: the air is compressed from state 1 to state 2.

► **Process 2-3**: The temperature rise that would be achieved in the actual power plant with combustion is realized here by heat transfer,



Air-Standard Brayton Cycle (2 of 6)

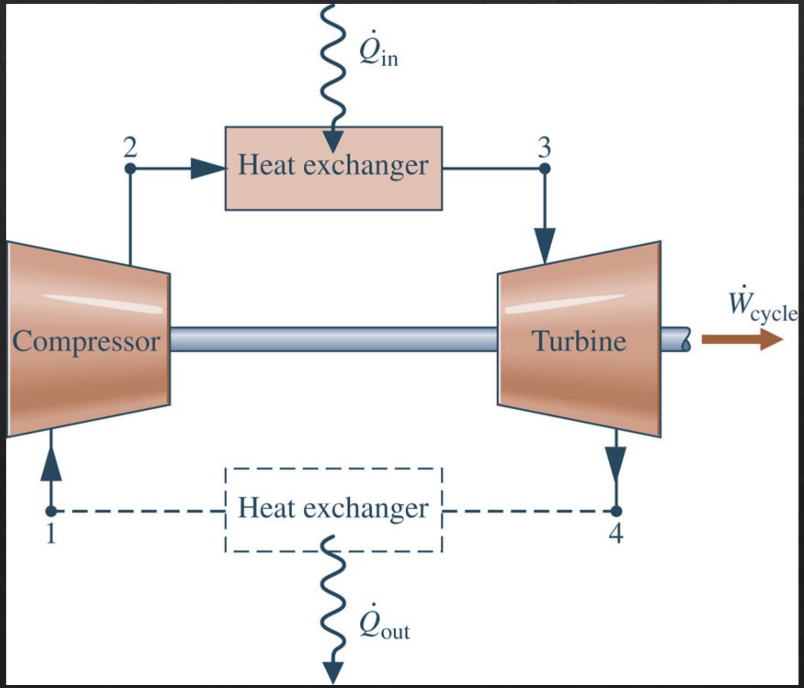
- **Process 3-4**: The high-pressure, high-temperature air expands through the turbine. The turbine drives the compressor and develops net power,
  - Air returns to the surroundings at state 4 with a temperature typically much greater than at state 1.
  - After interacting with the surroundings, each unit of mass returns to the same condition as the air entering at state 1, thereby **completing a thermodynamic cycle**.



Air-Standard Brayton Cycle (3 of 6)

- **Process 3-4**: The high-pressure, high-temperature air expands through the turbine from state 3 to state 4. The turbine drives the compressor and develops net power,

- Air returns to the surroundings at state 4 with a temperature typically much greater than at state 1.
- After interacting with the surroundings, each unit of mass returns to the same condition as the air entering at state 1, thereby **completing a thermodynamic cycle**.

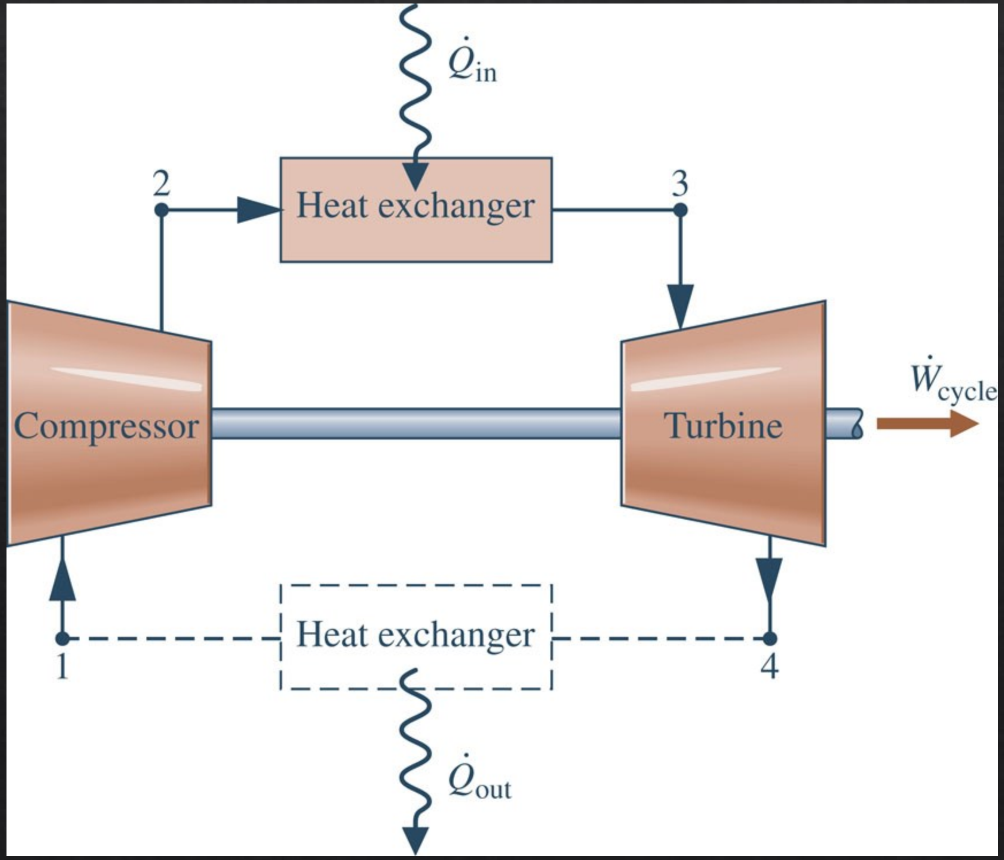


- We ***imagine*** process 4-1 being achieved by a heat exchanger, as shown by the dashed line in the figure.

Air-Standard Brayton Cycle (4 of 6)

► Cycle **1-2-3-4-1** is called the ***Brayton cycle***.

► The ***compressor pressure ratio***, p_2/p_1, is a key Brayton cycle operating parameter.



Air-standard analysis assumptions:

- The working fluid is air which always behaves according to the ideal gas model.
- All processes are internally reversible.
- They operate in a closed cycle.
- The air specific heat remains constant throughout the cycle at 300 K (cold air standard cycles).

Ideal Air-Standard Brayton Cycle (1 of 4)

- The ***ideal*** air-standard Brayton cycle provides an especially simple setting for study of gas turbine power plant performance.

- The ideal cycle adheres to additional modeling assumptions:
  - Frictional pressure drops are absent during flows through the heat exchangers. These processes occur at constant pressure. These processes are isobaric.
  - Flows through the turbine and pump occur adiabatically ***and*** without irreversibility. These processes are isentropic.
  - Accordingly, the ideal Brayton cycle consists of two isentropic processes alternated with two isobaric processes.

Ideal Air-Standard Brayton Cycle (2 of 4)

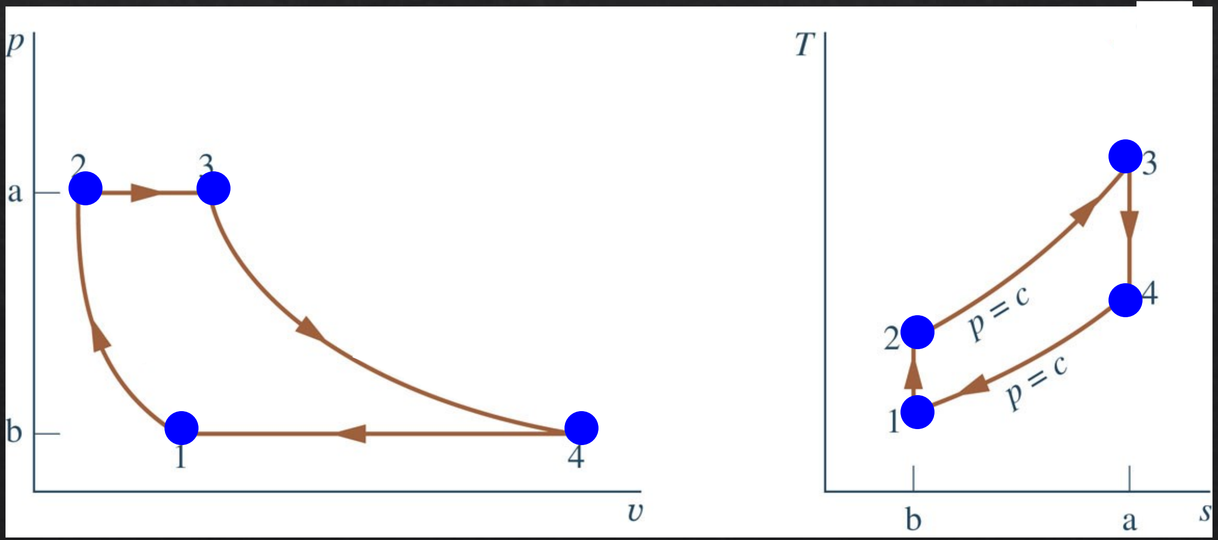
- The ideal air-standard Brayton cycle consists of four internally reversible processes:

Process1-2: Isentropic compression of air flowing through the compressor.

Process 2-3: Heat transfer *to* the air as it flows at constant pressure through the higher-temperature heat exchanger.

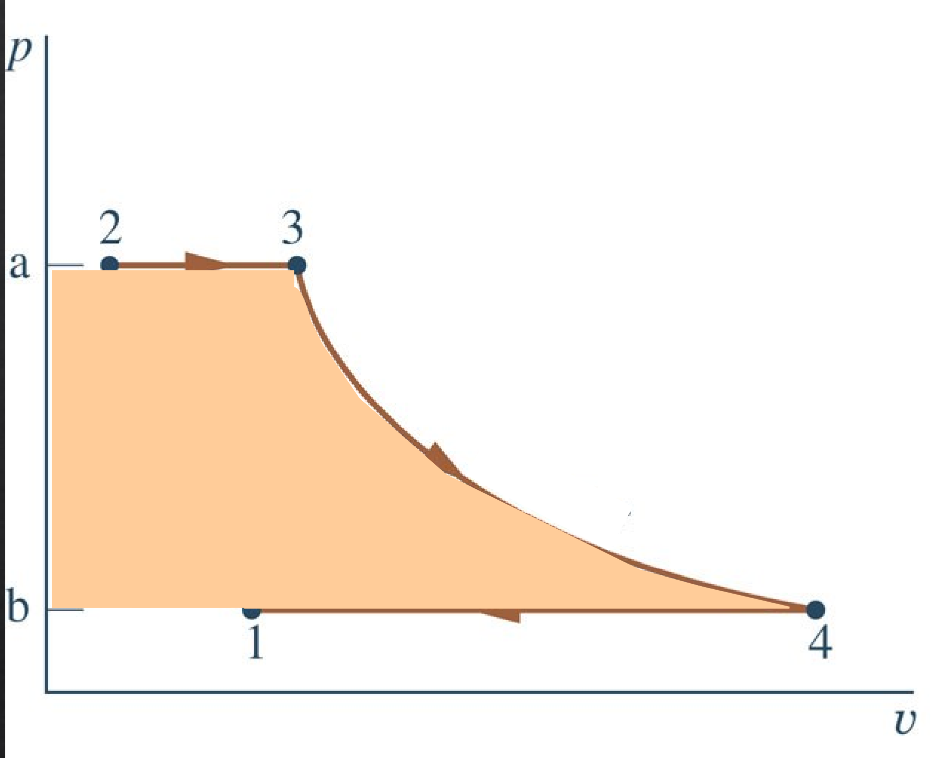
Process 3-4: Isentropic expansion of the air through the turbine.

Process 4-1: Heat transfer *from* the air as it flows at constant pressure through the lower-temperature heat exchanger.



Ideal Air-Standard Brayton Cycle (3 of 4)

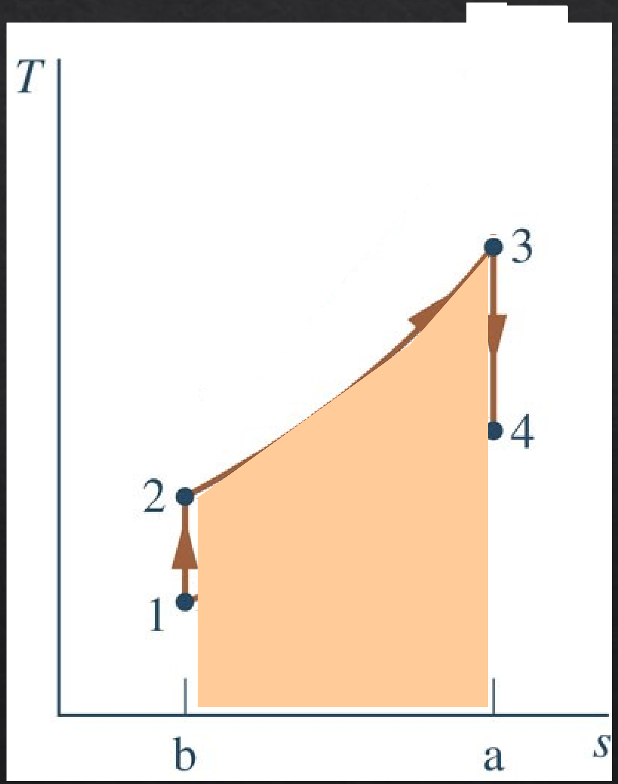
- Area **1-2-a-b-1** represents the compressor work input.
- Area **3-4-b-a-3** represents the turbine work output.
- Enclosed area **1-2-3-4-1** represents the net work developed.



Ideal Air-Standard Brayton Cycle (4 of 4)

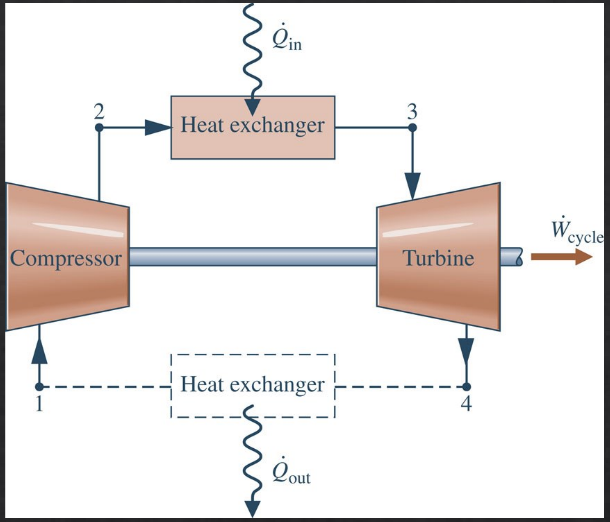
► On the *T-s* diagram, the heat transfer per unit of mass flowing is $\int T ds$. Thus, on a per unit of mass flowing basis,

- ► Area 2-3-a-b-2 represents the heat added.
- ► Area 4-1-b-a-4 represents the heat rejected.
- ► Enclosed area 1-2-3-4-1 represents the net heat added or equivalently, the net work developed.



Air-Standard Brayton Cycle – Method 1 (Air Property Table)

► Analyzing each component as a control volume at steady state, assuming the compressor and turbine operate adiabatically, and neglecting kinetic and potential energy effects, we get the following expressions for the principal work and heat transfers, which are positive in accord with our convention for cycle analysis.



Turbine

$$\dot{W}_{Turb} = \dot{H}_3 - \dot{H}_4 = \dot{m}(h_3 - h_4) \quad w_{Turb} = h_3 - h_4 \qquad (9.19)$$

Heat addition

$$\dot{Q}_H = \dot{H}_3 - \dot{H}_2 = \dot{m}(h_3 - h_2) \quad q_H = h_3 - h_2 \qquad (9.21)$$

Compressor

$$\dot{W}_{Comp} = \dot{H}_2 - \dot{H}_1 = \dot{m}(h_2 - h_1) \quad w_{Comp} = h_2 - h_1 \qquad (9.20)$$

Heat rejection

$$\dot{Q}_L = \dot{H}_4 - \dot{H}_1 = \dot{m}(h_4 - h_1) \quad q_L = h_4 - h_1 \qquad (9.22)$$

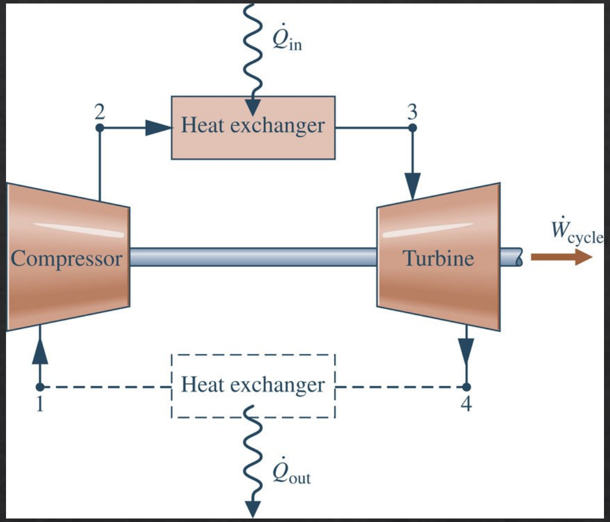
Air-Standard Brayton Cycle – Method 1 (Air Property Table)

For isentropic processes 1-2 and 3-4, using air property tables

$$\frac{p_2}{p_1} = \frac{p_{r2}}{p_{r1}} \tag{9.27}$$

$$\frac{p_3}{p_4} = \frac{p_{r3}}{p_{r4}} \tag{9.28}$$

where P_r is the relative pressure for isentropic processes given in ideal gas property tables.



Ideal Air-Standard Brayton Cycle – Method 2 (Cold Air Standard)

By assuming constant specific heats (as in cold air-standard analyses), Equations 9.9 and 9.10 can be simplified as

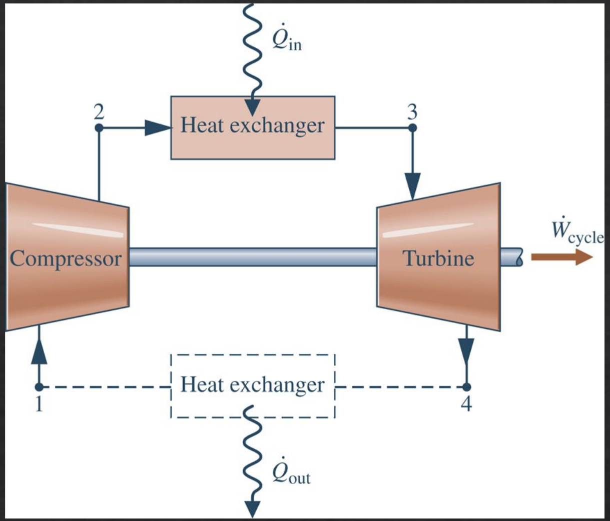
$$h_2 - h_1 = C_p\left(T_2 - T_1\right) \tag{9.12}$$

$$u_2 - u_1 = C_v\left(T_2 - T_1\right) \tag{9.13}$$

This assumption is acceptable for monoatomic gases and cases that the variation of the gas temperature is small so the changes in specific heats are negligible. But for other cases, this assumption may introduce a significant error to calculations. However, it is very helpful in developing qualitative expressions for cycles under investigation.

Similarly, if the specific heats are taken as constants, the change in specific entropy is

$$s_2 - s_1 = C_v \ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1} = C_p \ln\frac{T_2}{T_1} - R \ \frac{p_2}{p_1} \tag{9.14}$$



Ideal Air-Standard Brayton Cycle – Method 2 (Cold Air Standard)

Using the assumption of constant specific heat,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \tag{9.29}$$

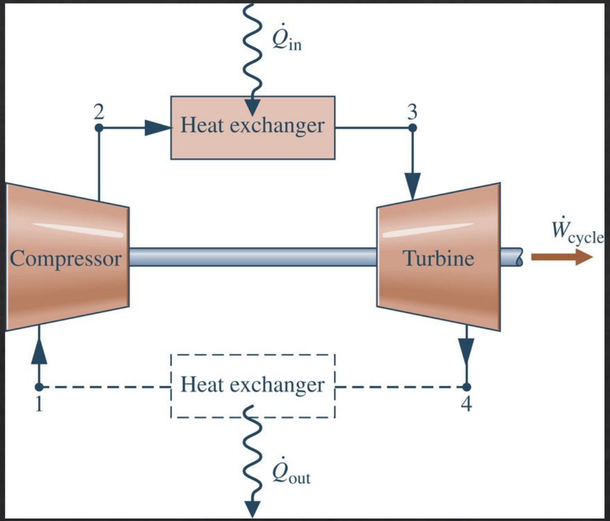
$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{k-1}{k}} \tag{9.30}$$

where k is the specific heat ratio of air. Note that in a cold air-standard cycle, k is constant because C_p and C_v are constant. In above equations, the ratio of the compressor outlet pressure to the compressor inlet pressure $\left(\frac{P_2}{P_1}\right)$ is called the **compressor pressure ratio** (**PR**), also known as the **compression ratio** (**CR**). Since the processes 2-3 and 4-1 are isobaric processes (assuming no pressure losses in the heat transfer processes):

$$P_2 = P_3 \quad \text{and} \quad P_1 = P_4 \Rightarrow \frac{P_2}{P_1} = \frac{P_3}{P_4} \tag{9.31}$$

This means that in the absence of frictional pressure drops, the pressure ratios of the compressor and turbine are equal. In a cold-standard air Brayton cycle using Equations 9.29 and 9.30

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \rightarrow (T_2T_4) = (T_1T_3) \tag{9.32}$$



Air-Standard Brayton Cycle

From the balance of energy rate equation

$$\dot{W}_{\text{Net}} = \dot{W}_{\text{Turb}} - \dot{W}_{\text{Comp}} = \dot{Q}_H - \dot{Q}_L = \dot{Q}_{\text{Net}} \tag{9.23}$$

The thermal efficiency of a power cycle can be found as follows:

$$\eta_{\text{Th}} = \frac{\dot{W}_{\text{Net}}}{\dot{Q}_H} = \frac{\dot{w}_{\text{Net}}}{\dot{q}_H} = \frac{\dot{q}_H - \dot{q}_L}{\dot{q}_H} = 1 - \frac{\dot{q}_L}{\dot{q}_H} = 1 - \frac{h_4 - h_1}{h_3 - h_2} \tag{9.24}$$

The back work ratio (BWR) of gas turbine plants is defined as the ratio of the power consumption in the compressor to the power production in the turbine.

$$\text{BWR} = \frac{\dot{W}_{\text{Comp}}}{\dot{W}_{\text{Turb}}} = \frac{h_2 - h_1}{h_3 - h_4} \tag{9.25}$$

Note: A relatively large portion of the work developed by the turbine is required to drive the compressor. For **gas turbines**, back work ratios range from 20% to 80% compared to only 1-2% for vapor power plants.

► These equations have been developed from mass and energy balances

End of Lecture!