Lecture 10: Gas Power Plant Modifications

Course: MECH-422 – Power Plants

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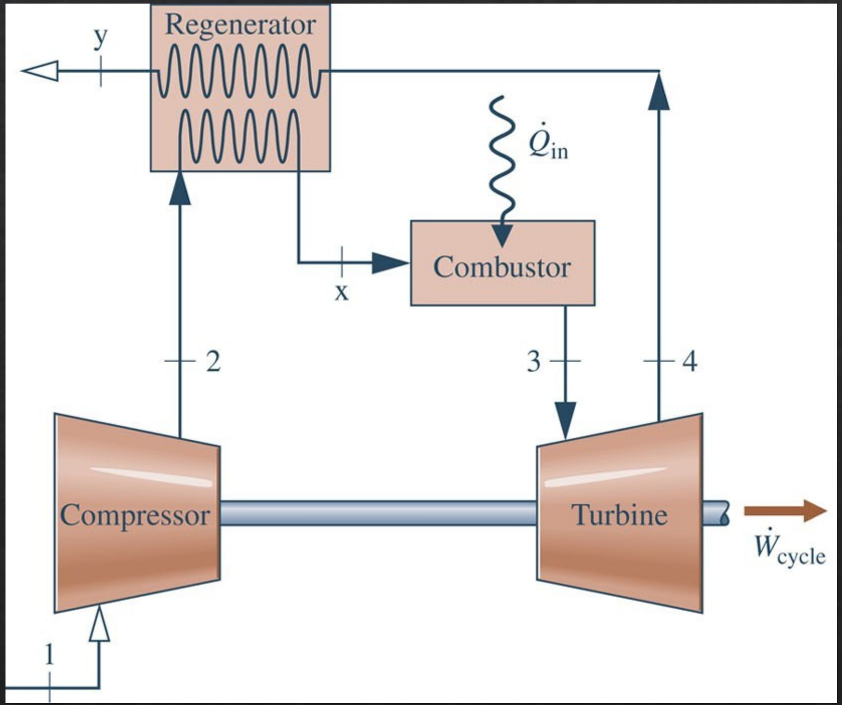
BUITEMS – DEPARTMENT OF MECHANICAL ENGINEERING

Regenerative Gas Turbines

► The hot turbine exhaust can be utilized with a preheater called a ***regenerator***.

► The regenerator allows air exiting the compressor to be preheated, process **2-x**, as the turbine exhaust gas cools, process **4-y**.

► Preheating reduces the heat added per unit of mass flowing (and thus the amount of fuel that must be burned):



With Regeneration

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

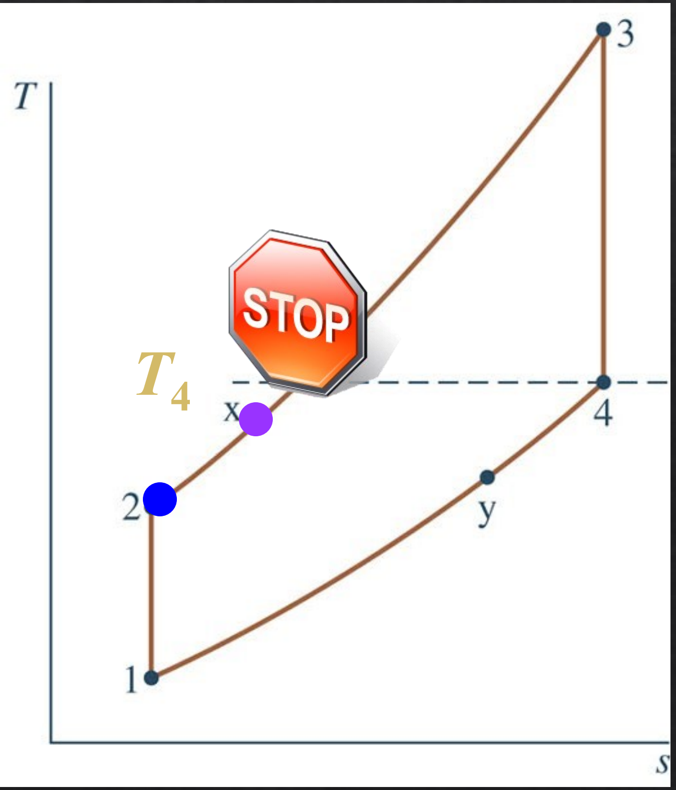
Without Regeneration

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

► The net work per unit of mass flowing is not altered with the inclusion of a regenerator. Accordingly, since the heat added is reduced, thermal efficiency increases.

Regenerator Effectiveness (1 of 3)

- Since a finite temperature difference must exist between the two streams of the regenerator for heat transfer to take place between the streams, the cold-side exiting temperature, T_x, must be less than the hot-side entering temperature, T_4.
  - As the stream-to-stream temperature difference becomes small T_x approaches T_4, but cannot exceed it. Accordingly, $T_x \leq T_4$.
  - As the enthalpy of the air varies only with temperature, we also have $h_x \leq h_4$.



Regenerator Effectiveness (2 of 3)

► The ***regenerator effectiveness*** is defined as the ratio of the ***actual*** enthalpy increase of the air flowing through the cold side of the regenerator, $h_x - h_2$, to the maximum theoretical enthalpy increase, $h_4 - h_2$.

$$\eta_{\text{reg}} = \frac{h_x - h_2}{h_4 - h_2}$$

Regenerator Effectiveness (3 of 3)

- In practice, regenerator effectiveness values range from 60-80%, approximately. Thus, the temperature T_x at the combustor inlet is invariably below the temperature T_4 at the turbine exit.
- Selection of a regenerator is largely an economic decision.
  - With regeneration less fuel is consumed by the combustor but another component, the regenerator, is required.
  - When considering use of a regenerator, the trade-off between fuel savings and regenerator cost must be weighed.

Gas Turbines with Regeneration

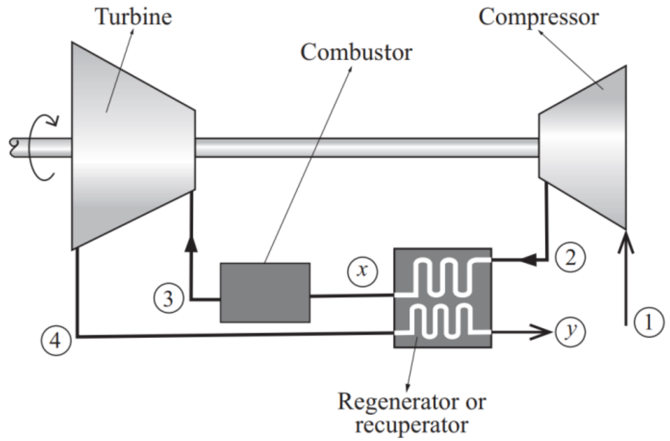
$$\eta_{\text{Reg}} = \frac{h_{x'} - h_2}{h_4 - h_2} \tag{9.49}$$

Note that $h_{x'} - h_2$ is the change of enthalpy in the cold stream in the real heat exchanger and $h_4 - h_2$ is the change of enthalpy in the cold stream in the ideal heat exchanger. A similar relationship can be expressed for the effectiveness of the regenerator based on the change of enthalpy in the hot stream.

$$\eta_{\text{Reg}} = \frac{h_4 - h_{y'}}{h_4 - h_2} \tag{9.50}$$

For a cold-standard air cycle (constant specific heat)

$$\eta_{\text{Reg}} = \frac{T_{x'} - T_2}{T_4 - T_2} = \frac{T_4 - T_{y'}}{T_4 - T_2} \tag{9.51}$$



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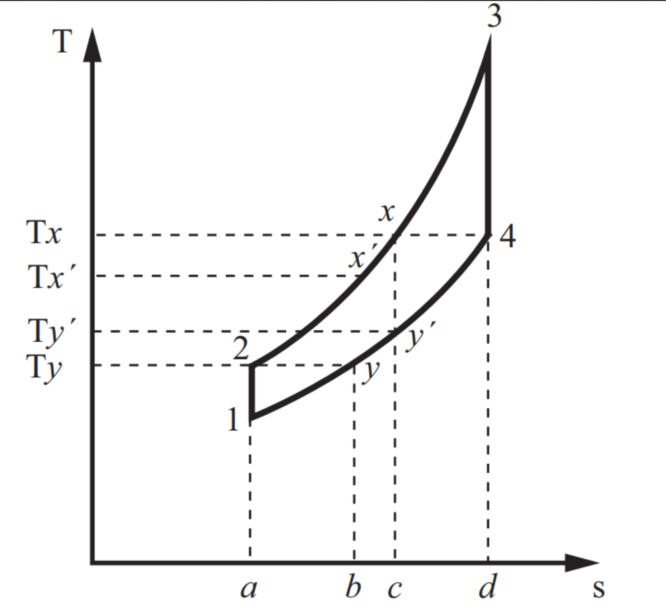


Example 9.6

In the cycle explained in Example 9.1, a regenerator with the effectiveness of 70% is incorporated into the cycle. Determine the energy transfer per second in each component (in kW), the net power generation (in kW), the back work ratio, and the efficiency of the cycle using data from the air property table.

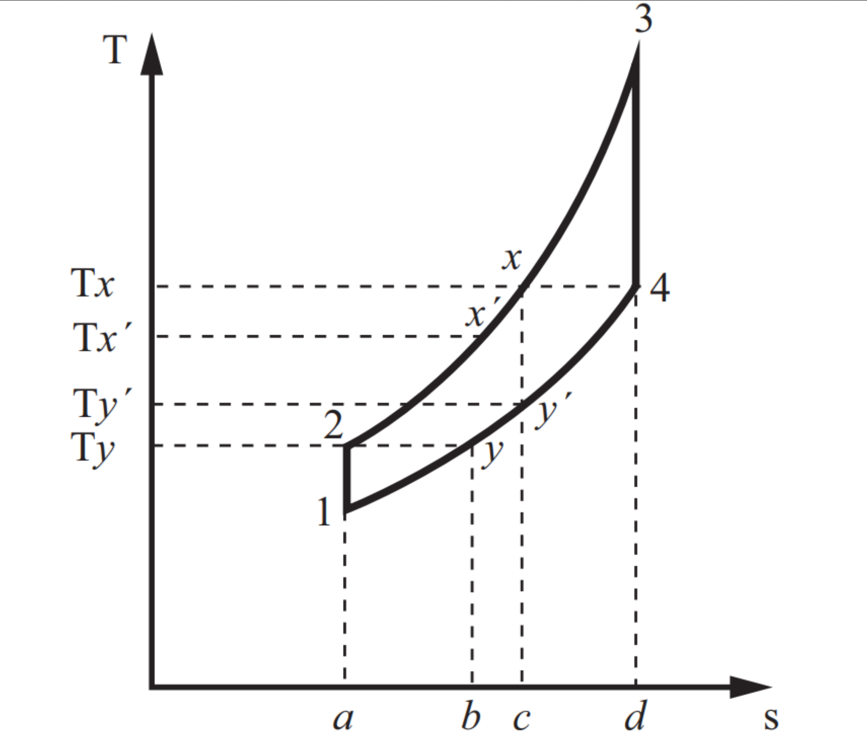
From Example 9.1

$$h_1 = 300.19 \;\; \text{kJ/kg}$$

$$h_2 = 722.91 \; \text{kJ/kg}$$

$$h_3 = 1880.1 \;\; \text{kJ/kg}$$

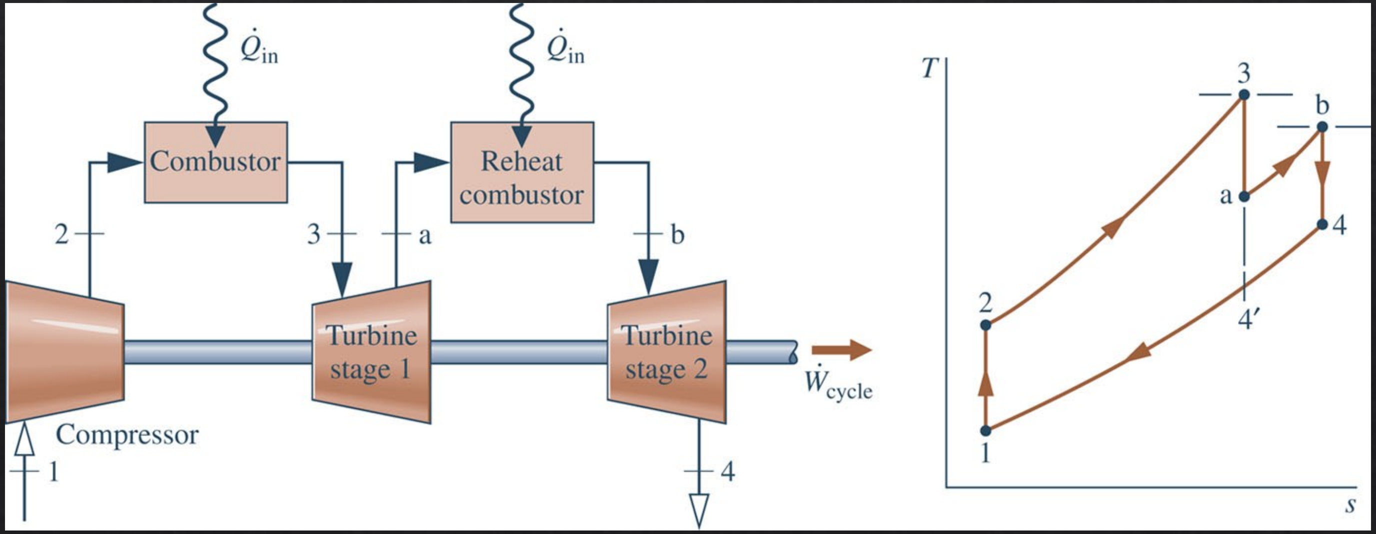
$$h_4 = 818.30 \; \text{kJ/kg}$$



Gas Turbines with Reheat and Regeneration (1 of 3)

► A modification of the Brayton cycle that increases the net work developed is ***multistage expansion with reheat***.

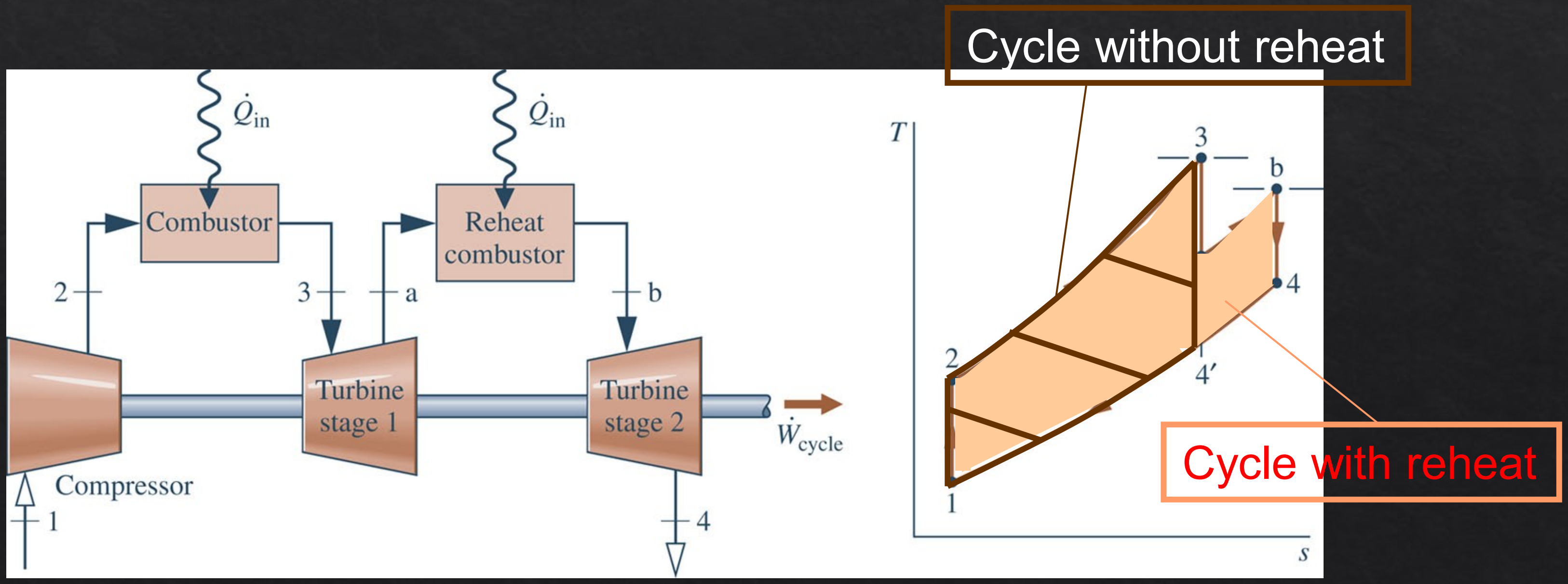
► The figure shows a cycle with two turbine stages and a reheat combustor between the stages.



Gas Turbines with Reheat and Regeneration (2 of 3)

► The ideal Brayton cycle with reheat is **1-2-3-a-b-4-1**. The ideal Brayton cycle without reheat is **1-2-3-4′-1**.

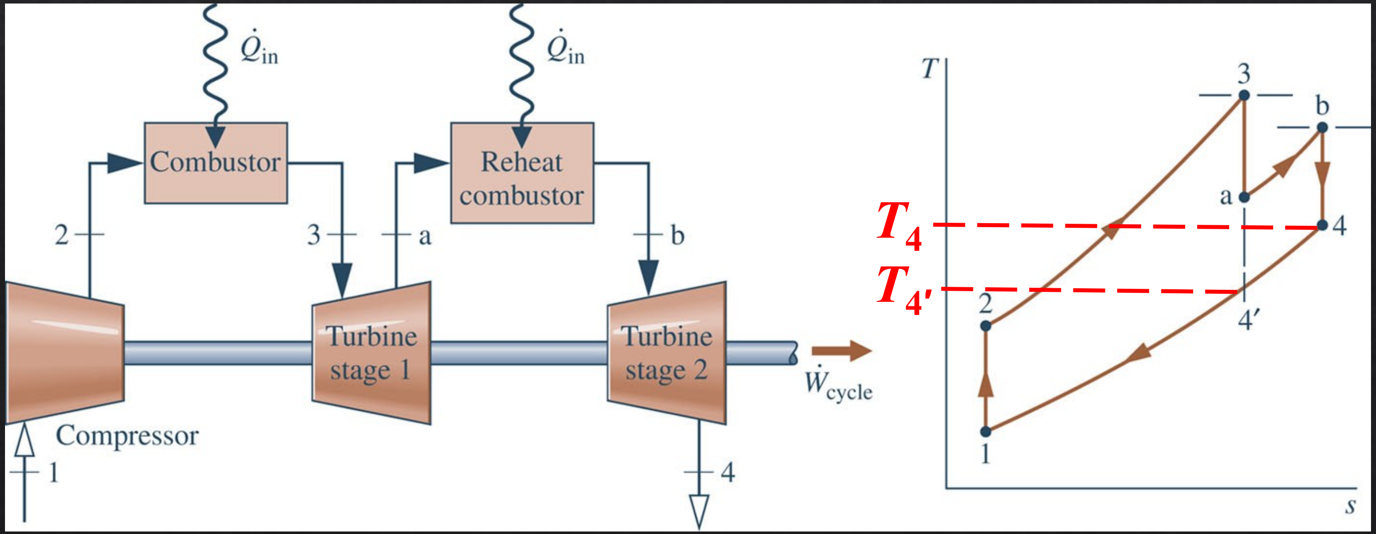
► The reheat cycle has a larger enclosed area than the cycle without reheat and thus a greater net work developed per unit of mass flowing, which is the aim.



Gas Turbines with Reheat and Regeneration (3 of 3)

► The figure also shows that the temperature at the exit of the second-stage turbine, state 4, is greater than at the exit of the single turbine of the cycle without reheat, state 4′. Accordingly, with reheat the potential for regeneration is also enhanced.

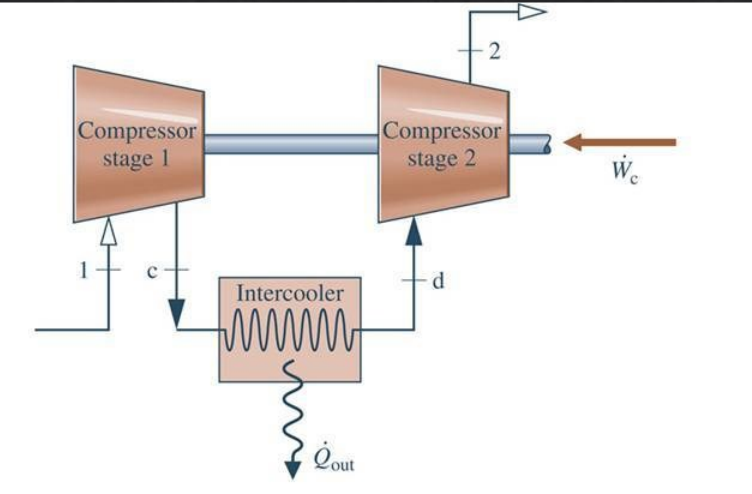
► When reheat and regeneration are used together, the thermal efficiency can increase significantly over that for the cycle without reheat.



Gas Turbines with Intercooling and Regeneration (1 of 5)

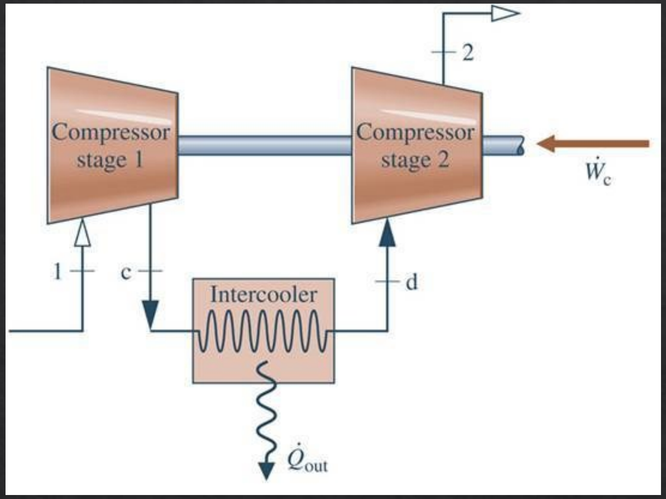
► Another modification of the Brayton cycle that increases the net work developed is ***compression with intercooling***.

► The figure shows two compressor stages and an intercooler between the stages.

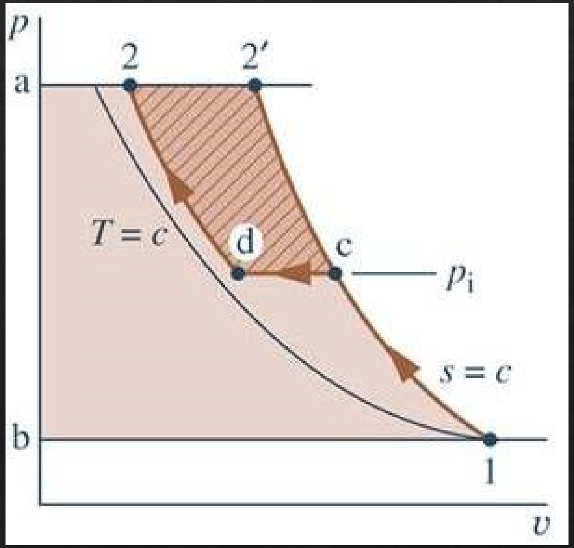


Gas Turbines with Intercooling and Regeneration (2 of 5)

► The accompanying p-v diagram shows the processes for internally reversible operation:



► **Process 1-c.** Isentropic compression from state 1, where pressure is p_1, to state c, where pressure is p_i.
► **Process c-d.** Constant-pressure cooling from temperature T_c to temperature T_d.
► **Process d-2.** Isentropic compression to state 2, where pressure is p_2.

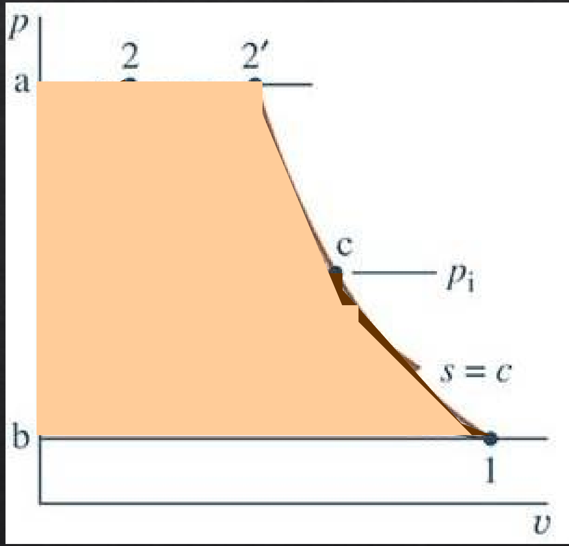


► Isentropic compression without intercooling is represented by process 1-c-2′.

Gas Turbines with Intercooling and Regeneration (3 of 5)

► Recalling that for such internally reversible processes the work input per unit of mass flowing is given by $\int v\,dp$, the following area interpretations apply, each per unit of mass flowing:

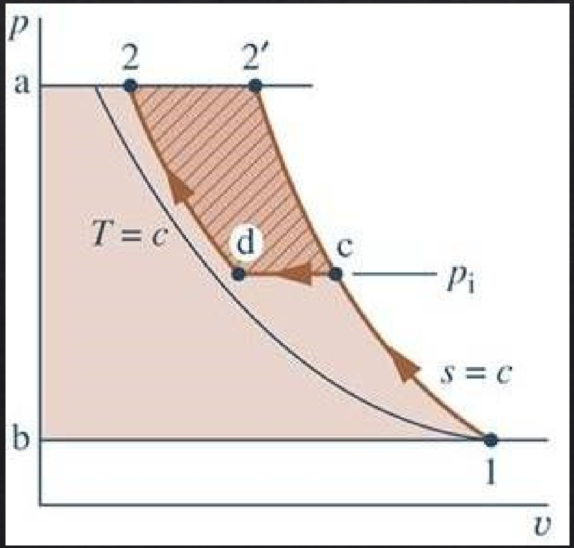
- ► **With intercooling**, area **1-c-d-2-a-b-1** represents the work input.
- ► **Without intercooling**, area **1-2′-a-b-1** represents the work input.
- ► The **cross-hatched area** **c-d-2-2′-c** represents the reduction in work achieved with intercooling.

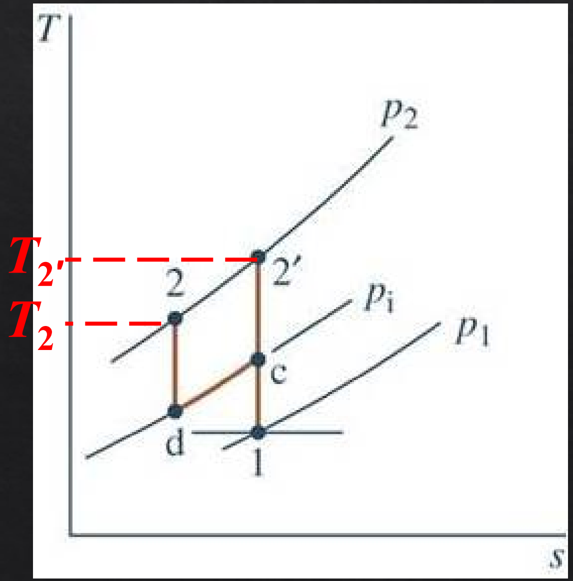


► If the total turbine work remains the same, a reduction in compressor work results in an increase in the net work developed, which is the aim.

Gas Turbines with Intercooling and Regeneration (4 of 5)

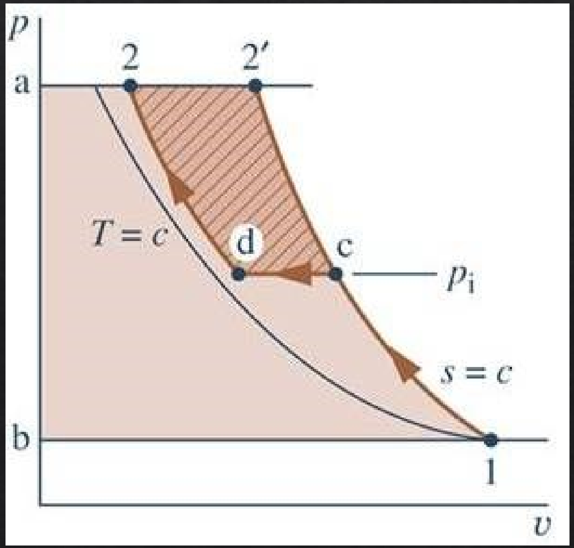
- While compression with ***and*** without intercooling each bring the air to the same final pressure, p_2, the final temperature with intercooling, T_2, is ***lower*** than the final temperature without intercooling, $T_{2'}$.
  - Comparing states 2 and 2′ on the *T*-*s* diagram, $T_2 < T_{2'}$.
  - The lower temperature at the compressor exit with intercooling enhances the potential for regeneration.

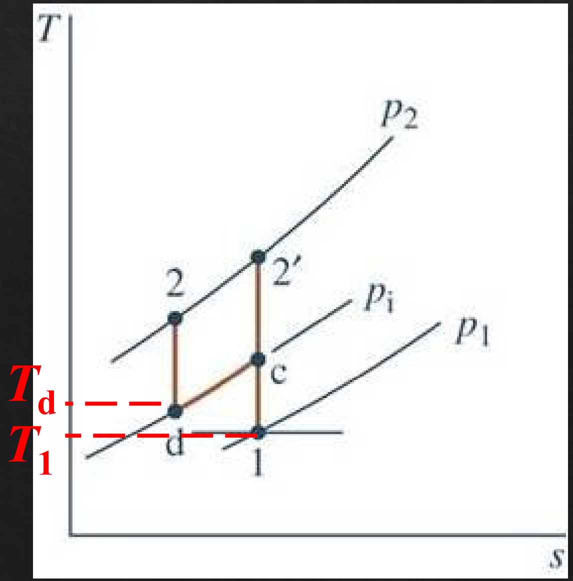




Gas Turbines with Intercooling and Regeneration (5 of 5)

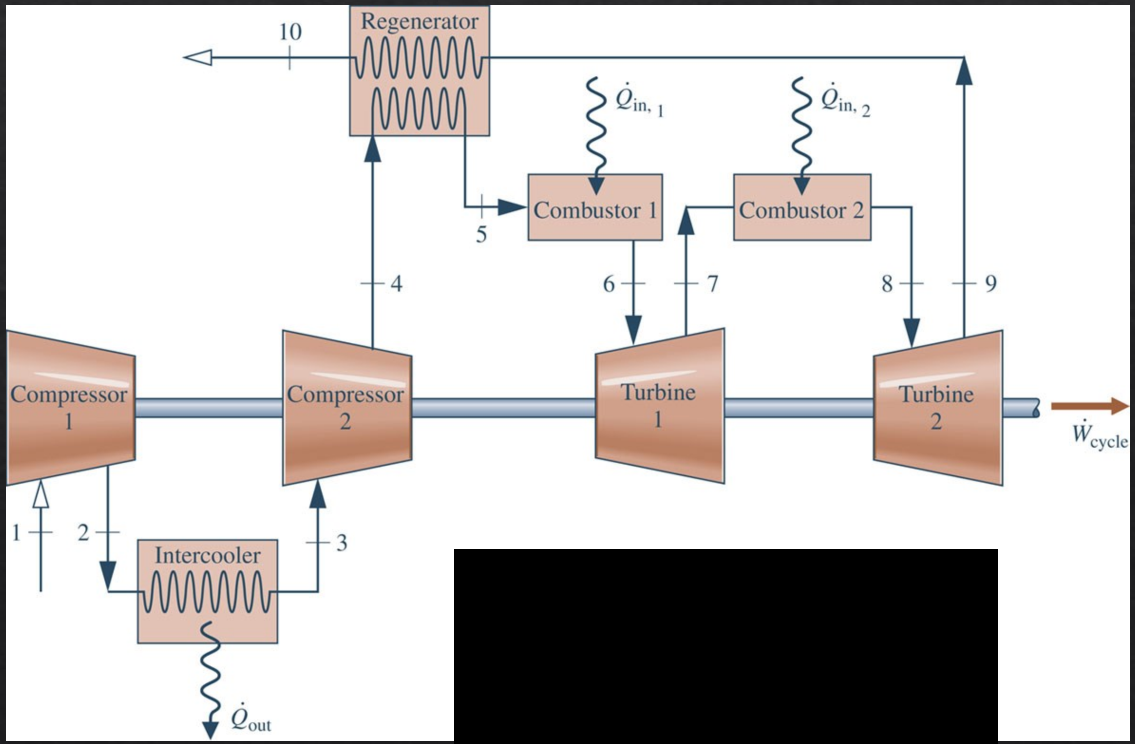
- When compression with intercooling is used together with regeneration, the thermal efficiency can increase significantly over that for the cycle without intercooling.
- The *T*-*s* diagram also shows that for cooling to the surroundings the temperature T_d at the intercooler exit cannot be less than T_1, the temperature of the air entering the compressor from the surroundings: $T_d \geq T_1$.





Regenerative Gas Turbine with Reheat and Intercooling (1 of 3)

- Shown here is a regenerative gas turbine that incorporates reheat and intercooling.
- With these modifications to the basic Brayton cycle:
  - The net work output is increased.
  - The thermal efficiency is increased.



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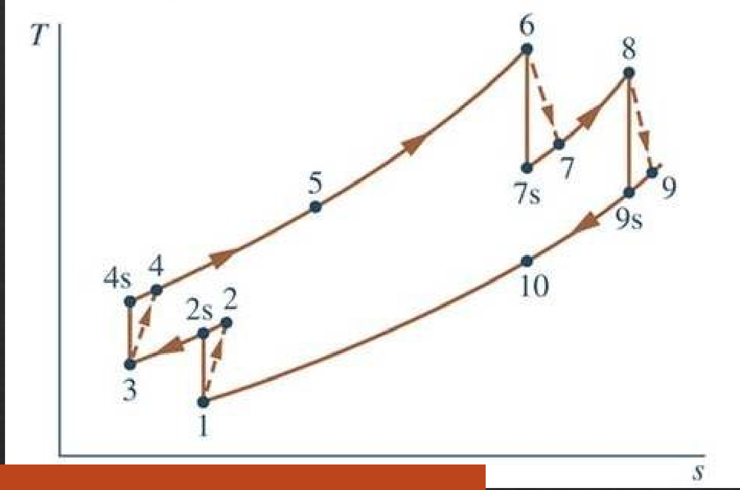
Regenerative Gas Turbine with Reheat and Intercooling (2 of 3)



► Applying mass and energy rate balances at steady state, we obtain the following expressions, each per unit of mass flowing:

► Total turbine work:

$$\frac{\dot{W}_t}{\dot{m}} = (h_6 - h_7) + (h_8 - h_9) = \eta_{t1}(h_6 - h_{7s}) + \eta_{t2}(h_8 - h_{9s})$$

where η_{t1} and η_{t2} denote the isentropic efficiencies of turbines 1 and 2, respectively.

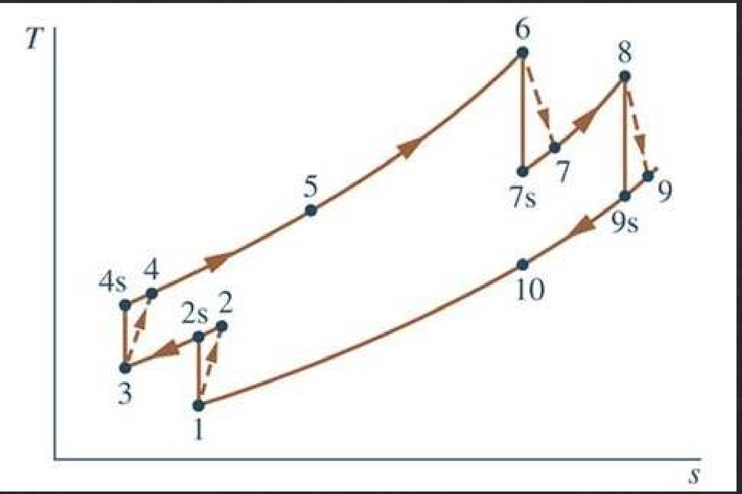
► Total compressor work:

$$\frac{\dot{W}_c}{\dot{m}} = (h_2 - h_1) + (h_4 - h_3) = (h_{2s} - h_1)/\eta_{c1} + (h_{4s} - h_3)/\eta_{c2}$$

where η_{c1} and η_{c2} denote the isentropic efficiencies of compressors 1 and 2, respectively.

Regenerative Gas Turbine with Reheat and Intercooling (3 of 3)

- Applying mass and energy rate balances at steady state, we obtain the following expressions, each per unit of mass flowing:



  - Total heat added:

$$\frac{\dot{Q}_{\text{in}}}{\dot{m}} = (h_6 - h_5) + (h_8 - h_7)$$

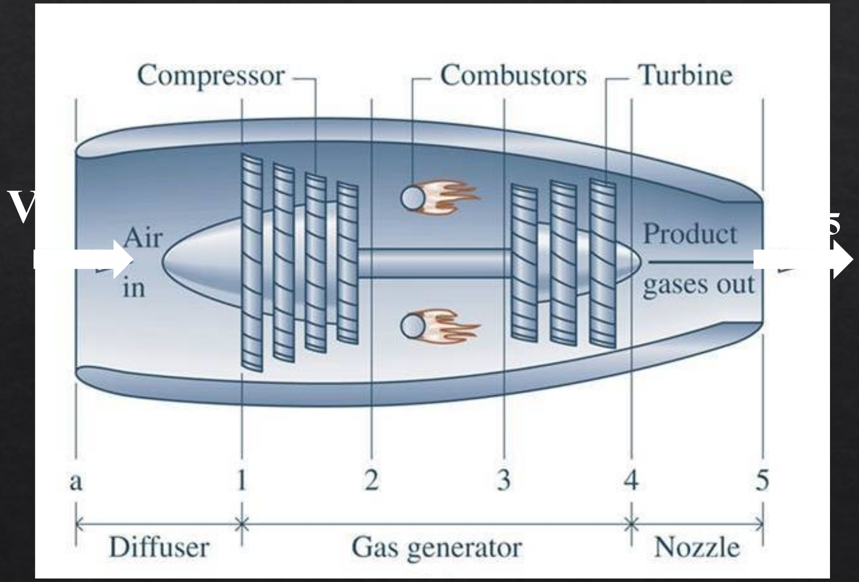
  - In this application, the regenerator effectiveness is:

$$\eta_{\text{reg}} = (h_5 - h_4)/(h_9 - h_4)$$

  - For cooling to the surroundings, the temperature at the exit of the intercooler, T_3, cannot be less than the temperature of the air entering the compressor from the surroundings: $T_3 \geq T_1$.

Gas Turbines for Aircraft Propulsion (1 of 5)

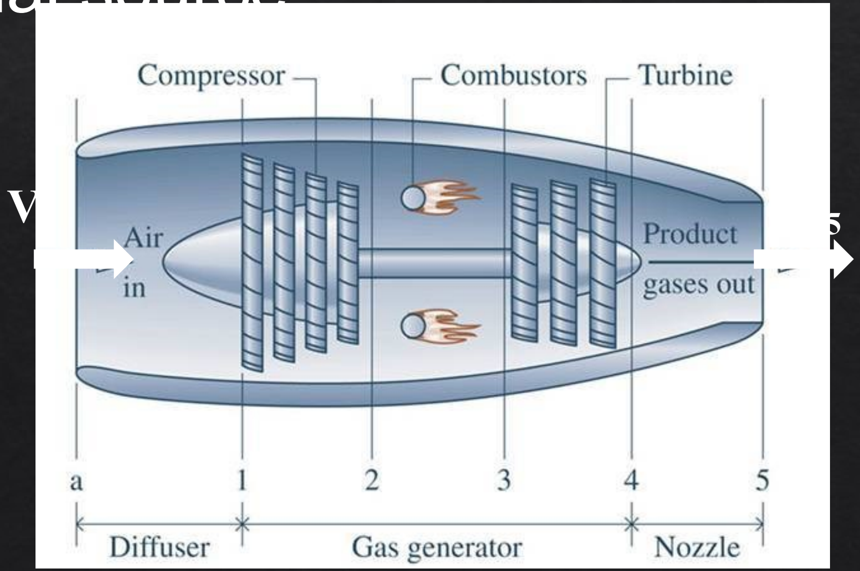
- Because of their favorable power-to-weight ratio, gas turbines are well suited for aircraft propulsion. The ***turbojet engine*** is commonly used for this purpose.
- The figure provides the schematic of a turbojet engine.



Gas Turbines for Aircraft Propulsion (2 of 5)

► The increase in velocity from diffuser inlet, $\mathbf{V}_a$, to nozzle exit, $\mathbf{V}_5$, gives rise to the ***thrust*** developed by the engine in accord with Newton's second law of motion.

► In harmony with air-standard analysis, we assume air modeled as an ideal gas flows through the engine shown in the schematic and the temperature rise that would be obtained with combustion is achieved by heat transfer from an external source.

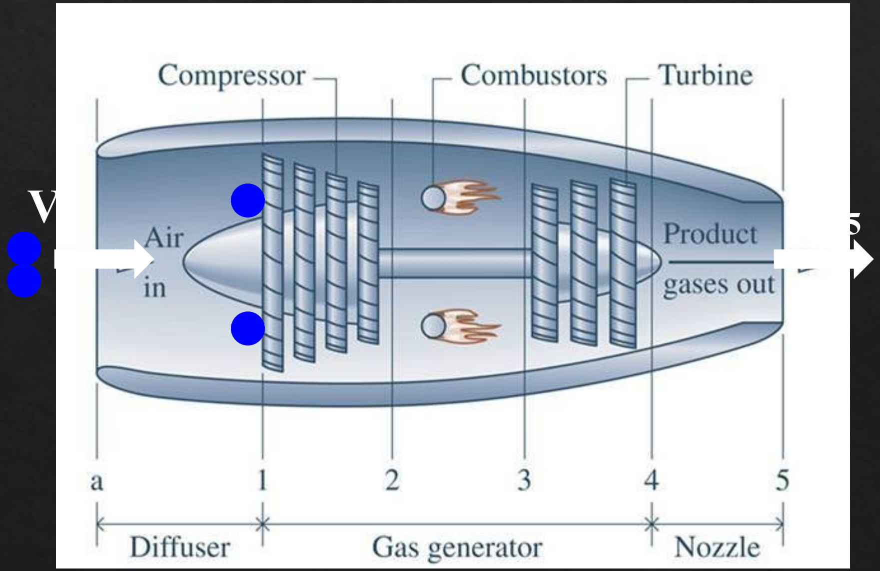


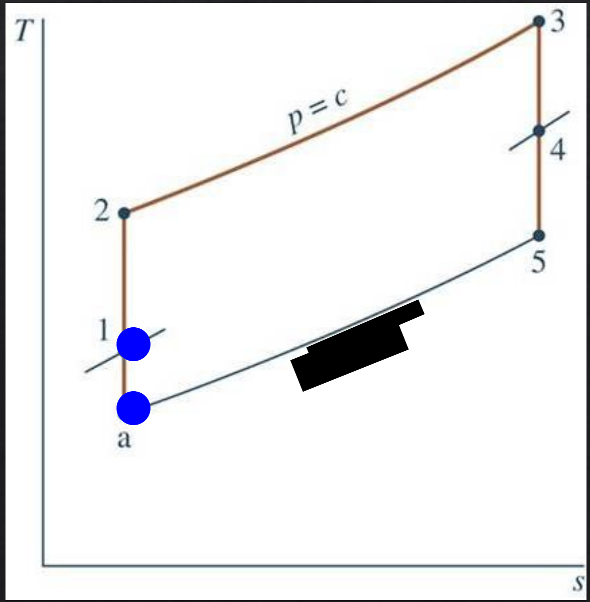
Gas Turbines for Aircraft Propulsion (3 of 5)

►If the air flows through the components of the turbojet engine without irreversibilities and stray heat transfer, air undergoes the five processes shown on the *T*-*s* diagram:

►**Process a-1**: Air at velocity V_a enters the diffuser and decelerates isentropically, while experiencing an increase in pressure.

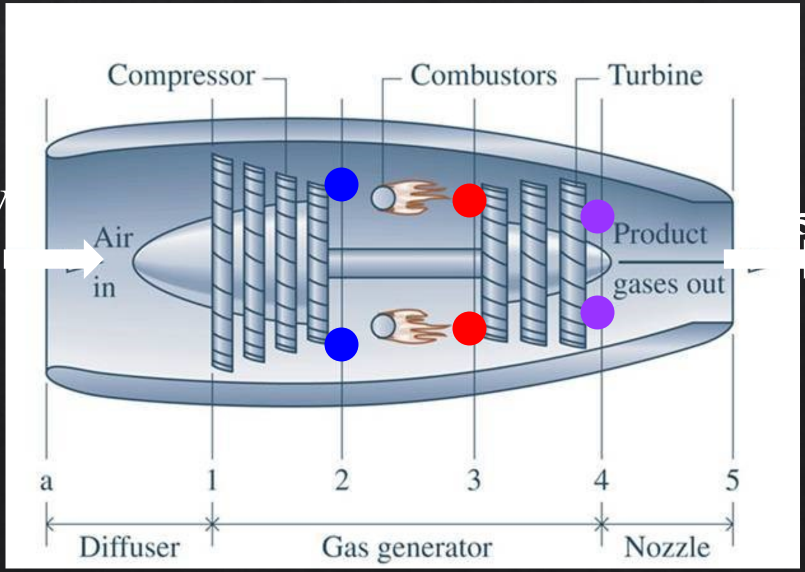
►**Process 1-2**: The air experiences a further increase in pressure isentropically, owing to work done by the compressor.

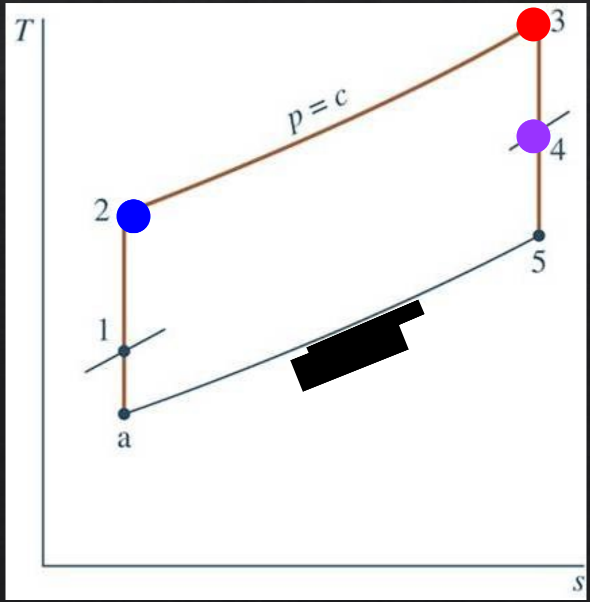




Gas Turbines for Aircraft Propulsion (4 of 5)

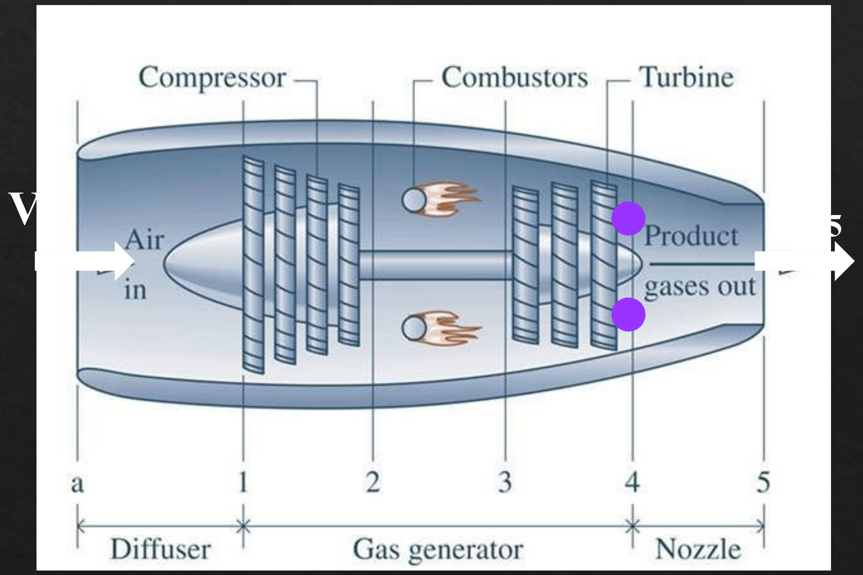
►**Process 2-3**: The temperature of the air increases at constant pressure as it receives a heat transfer from an external source.
►**Process 3-4**: The high-pressure, high-temperature air expands isentropically through the turbine, driving the compressor.

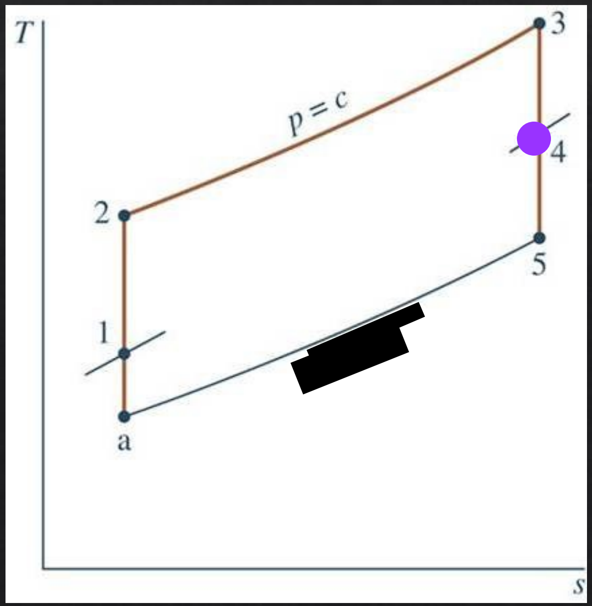




Gas Turbines for Aircraft Propulsion (5 of 5)

►**Process 4-5**: The air continues to expand isentropically through the nozzle, achieving a velocity, $\mathbf{V}_5$, at the engine exit much greater than the velocity, $\mathbf{V}_a$, at the engine inlet, and thereby developing ***thrust***.





<u>End of Lecture!</u>