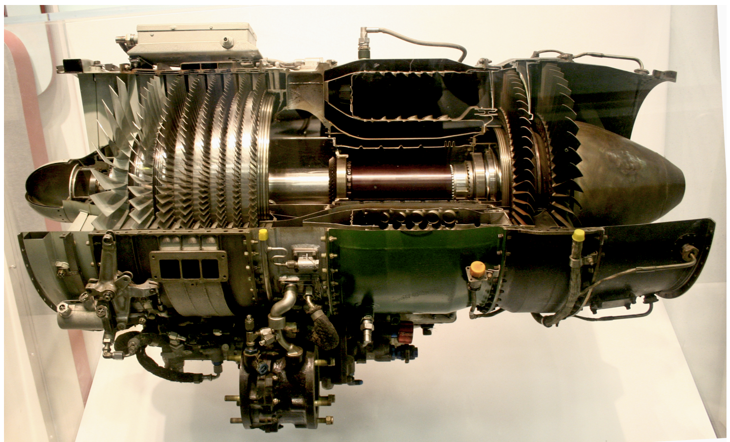
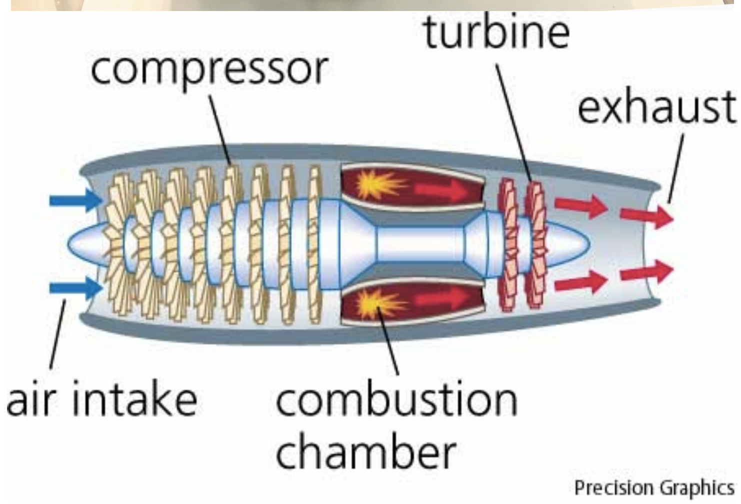


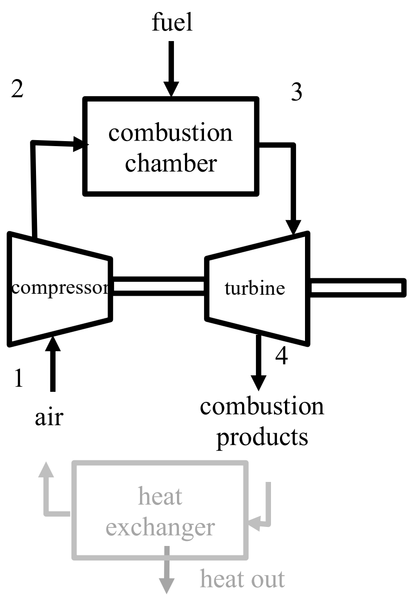


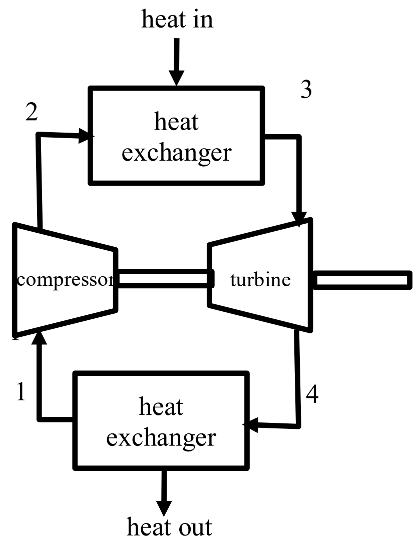
https://www.youtube.com/watch?v=x8DK4rM6Y90 (basic overview video)
https://www.youtube.com/watch?v=Or6mIaSWZ8g (hands-on)

ME 200 (Thermodynamics I)

Brayton Power Cycle

Open and Closed Gas Turbine Cycles





Air-Standard Analysis

1. The working fluid is air, which is treated as an ideal gas.
2. The combustion process is modeled as heat addition to the working fluid. The combustion process and the changes to the working fluid properties are ignored.
3. *Cold air-standard analysis*: The working fluid is treated as a perfect gas.

Air-Standard Brayton Cycle

Apply the 1st Law to air in the turbine and compressor:

$$\frac{\dot{W}_{\text{by turbine}}}{\dot{m}} = h_3 - h_4 \quad \text{and} \quad \frac{\dot{W}_{\text{on compressor}}}{\dot{m}} = h_2 - h_1$$

Apply the 1st Law to the air in the heat exchangers:

$$\frac{\dot{Q}_{\text{added}}}{\dot{m}} = h_3 - h_2 \quad \text{and} \quad \frac{\dot{Q}_{\text{removed}}}{\dot{m}} = h_4 - h_1$$

Thermal efficiency of the power cycle:

$$\eta = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_{\text{added}}} = \frac{\dot{W}_{\text{by turb.}}/\dot{m} - \dot{W}_{\text{on comp.}}/\dot{m}}{\dot{Q}_{\text{added}}/\dot{m}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} = \frac{(h_3 - h_2) - (h_4 - h_1)}{(h_3 - h_2)} = 1 - \frac{(h_4 - h_1)}{(h_3 - h_2)} = 1 - \frac{\dot{Q}_{\text{removed}}/\dot{m}}{\dot{Q}_{\text{added}}/\dot{m}}$$

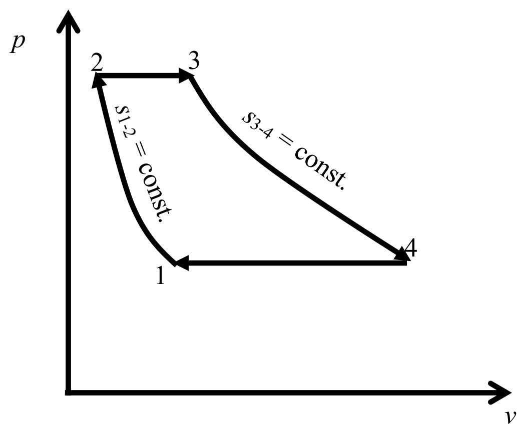
Back work ratio:

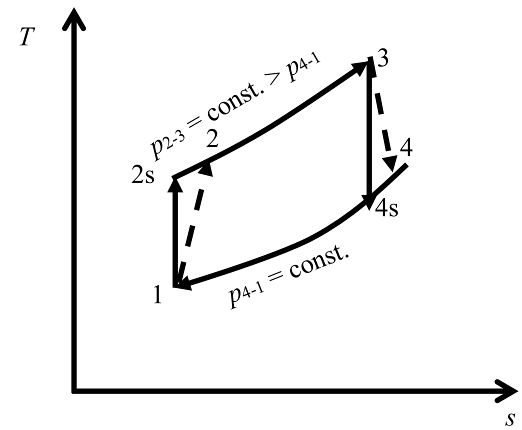
$$\text{bwr} \equiv \frac{\dot{W}_{\text{on comp.}}}{\dot{W}_{\text{by turb.}}} = \frac{\dot{W}_{\text{on comp.}}/\dot{m}}{\dot{W}_{\text{by turb.}}/\dot{m}} = \frac{h_2 - h_1}{h_3 - h_4}$$

Typical gas turbine bwr: 40 – 80%.
Typical vapor power plant (Rankine cycle) bwr: 1 – 2%.
The difference is due to the fact that the specific volume for a gas is large, but is small for a liquid. (Recall that for a steady, internally reversible, process with one inlet and one outlet and negligible changes in kinetic and potential energies: $\frac{\dot{W}_{by\ CV}}{\dot{m}} = -\int_1^2 v dp$.)

Ideal Air-Standard Brayton Cycle

Process 1 – 2s:	isentropic compression of the working fluid through the compressor
Process 2s – 3:	constant pressure heat transfer to the working fluid as it flows through the heat exchanger
Process 3 – 4s:	isentropic expansion of the working fluid through the turbine
Process 4s – 1:	constant pressure heat transfer from the working fluid as it flows through the heat exchanger





Assuming air is an ideal gas and an isentropic process (1-2s and 3-4s):

$$\frac{p_2}{p_1} = \frac{p_{2r}(T_{2s})}{p_{1r}(T_1)} \Rightarrow p_{r2}(T_{2s}) = p_{1r}(T_1)\underbrace{\left(\frac{p_2}{p_1}\right)}_{\text{compressor ratio}}$$

$$\frac{p_4}{p_3} = \frac{p_{4r}(T_{4s})}{p_{3r}(T_3)} \Rightarrow p_{4r}(T_{4s}) = p_{3r}(T_3)\left(\frac{p_4}{p_3}\right) = p_{3r}(T_3)\left(\frac{p_1}{p_2}\right)$$

Assuming air is a perfect gas and an isentropic process (1-2 and 3-4):

$$\frac{T_{2s}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \Rightarrow T_{2s} = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \quad \text{and} \quad \frac{T_{4s}}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{k-1}{k}} \Rightarrow T_{4s} = T_3\left(\frac{p_1}{p_2}\right)^{\frac{k-1}{k}}$$

Note: $\frac{T_{2s}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = \frac{T_3}{T_{4s}} \Rightarrow \frac{T_3}{T_{2s}} = \frac{T_{4s}}{T_1}$

Efficiency for a cold air-standard Brayton cycle (i.e., a perfect gas):

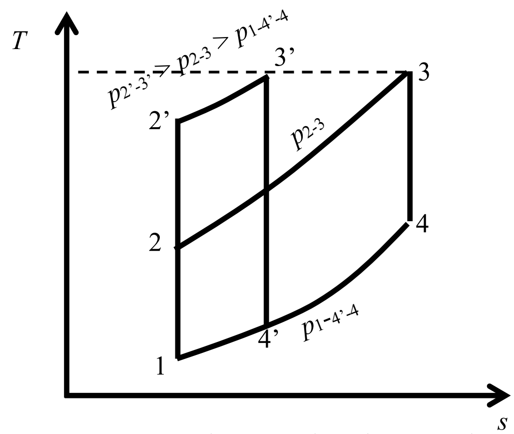
$$\eta = 1 - \frac{(h_4 - h_1)}{(h_3 - h_2)} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \left(\frac{T_1}{T_2}\right)\frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)}$$

$$\eta_s = 1 - \frac{T_1}{T_{2s}} = 1 - \frac{T_{4s}}{T_3} = 1 - \left(\frac{p_2}{p_1}\right)^{\frac{1-k}{k}}$$

Notes:

1. Typical pressure ratios: 5 – 20 => typical efficiencies: 35 – 60%.
2. A larger pressure ratio across the compressor (p_2/p_1) gives a larger efficiency. Alternately, increasing the temperature leading into the turbine (T_3) also leads to a larger efficiency; however, the temperature at the turbine inlet is typically limited by metallurgical considerations.

   Consider the case when T_3 is fixed (for example, due to metallurgical factors), but p_2/p_1 is varied, as shown in the following figure ($p_{2'}/p_1 > p_2/p_1$).



Cycle A: 1-2'-3'-4'
Cycle B: 1-2-3-4

$\eta_A > \eta_B$ but $\left(\dot{W}_{\text{net,out}}/\dot{m}\right)_B > \left(\dot{W}_{\text{net,out}}/\dot{m}\right)_A$

   The area enclosed by cycle B is larger than that for cycle A; hence, cycle B has a larger work per unit mass flow rate. In order for cycle A to produce the same work, a larger mass flow rate would be required, potentially requiring a larger set of components, which might be unacceptable for use on an aircraft where weight is a significant design factor. Hence, in aircraft applications, aircraft engine designers typically design for maximum work per unit mass flow rate, $\left(\dot{W}_{\text{net,out}}/\dot{m}\right)_{\text{max,fixed } T_3}$.

3. A larger value for the specific heat ratio k results in a larger efficiency. The specific heat ratio is governed by the type of fuel used.