Brayton Cycle

The Brayton cycle (or Joule cycle) represents the operation of a gas turbine engine. The cycle consists of four processes, as shown in Figure 3.13 alongside a sketch of an engine:

- a - b Adiabatic, quasi-static (or reversible) compression in the inlet and compressor;
- b - c Constant pressure fuel combustion (idealized as constant pressure heat addition);
- c - d Adiabatic, quasi-static (or reversible) expansion in the turbine and exhaust nozzle, with which we
    1. take some work out of the air and use it to drive the compressor, and
    2. take the remaining work out and use it to accelerate fluid for jet propulsion, or to turn a generator for electrical power generation;
- d - a Cool the air at constant pressure back to its initial condition.

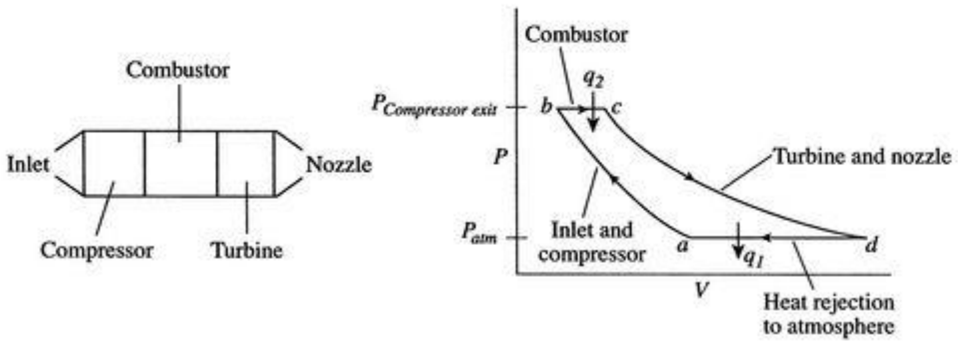
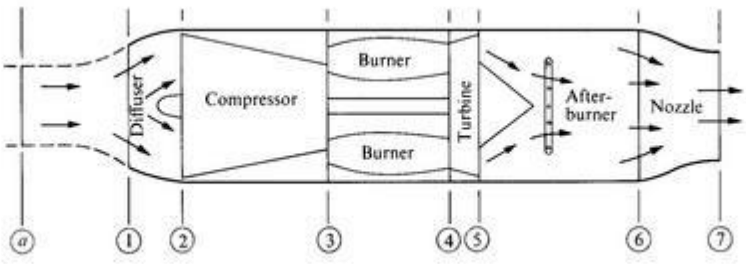


Figure 3.13: Sketch of the jet engine components and corresponding thermodynamic states

The components of a Brayton cycle device for jet propulsion are shown in Figure 3.14. We will typically represent these components schematically, as in Figure 3.15. In practice, real Brayton cycles take one of two forms. Figure 3.16(a) shows an ``open'' cycle, where the working fluid enters and then exits the device. This is the way a jet propulsion cycle works. Figure 3.16(b) shows the alternative, a closed cycle, which recirculates the working fluid. Closed cycles are used, for example, in space power generation.



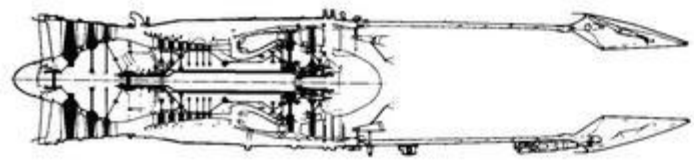


Figure 3.14: Schematics of typical military gas turbine engines. Top: turbojet with afterburning, bottom: GE F404 low bypass ratio turbofan with afterburning (Hill and Peterson, 1992).

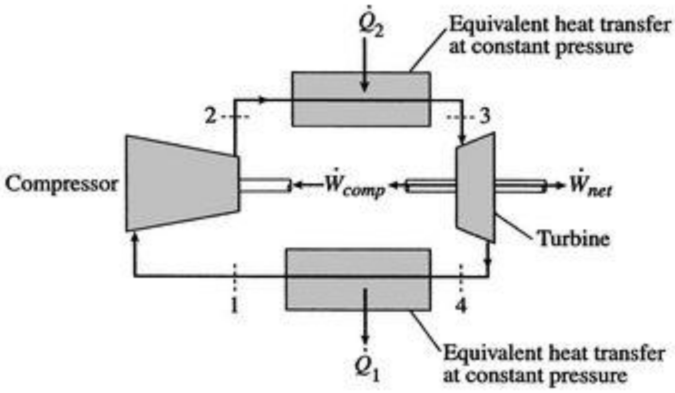
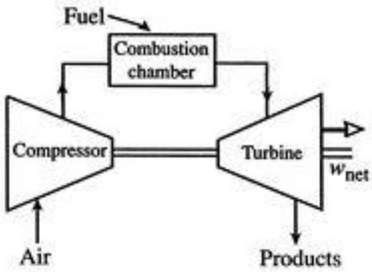


Figure 3.15: Thermodynamic model of gas turbine engine cycle for power generation



[Open cycle operation] [Closed cycle operation]

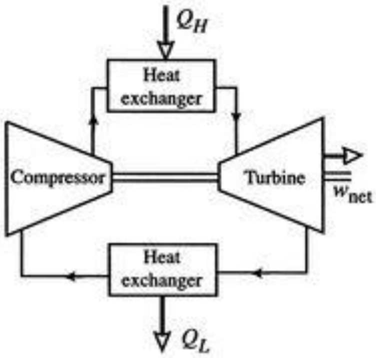


Figure 3.16: Options for operating Brayton cycle gas turbine engines

3.7.1 Work and Efficiency

The objective now is to find the work done, the heat absorbed, and the thermal efficiency of the cycle. Tracing the path shown around the cycle from a - b - c - d and back to a, the first law gives (writing the equation in terms of a unit mass),

$$\Delta u_{a\text{-}b\text{-}c\text{-}d\text{-}a} = 0 = q_2 + q_1 - w.$$

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Here Δu is zero because u is a function of state, and any cycle returns the system to its starting state[3.2]. The net work done is therefore

$$w = q_2 + q_1,$$

where q_1, q_2 are defined as heat received by the system (q_1 is negative). We thus need to evaluate the heat transferred in processes b-c and d-a.

For a constant pressure, quasi-static process the heat exchange per unit mass is

$$dh = c_p dT = dq, \quad \text{or} \quad [dq]_{\text{constant P}} = dh.$$

We can see this by writing the first law in terms of enthalpy (see Section 2.3.4) or by remembering the definition of c_p.

The heat exchange can be expressed in terms of enthalpy differences between the relevant states. Treating the working fluid as a perfect gas with constant specific heats, for the heat addition from the combustor,

$$q_2 = h_c - h_b = c_p(T_c - T_b).$$

The heat rejected is, similarly,

$$q_1 = h_a - h_d = c_p(T_a - T_d).$$

The net work per unit mass is given by

$$\text{Net work per unit mass } = q_1 + q_2 = c_p[(T_c - T_b) + (T_a - T_d)].$$

The thermal efficiency of the Brayton cycle can now be expressed in terms of the temperatures:

$$\eta = \frac{\text{Net work}}{\text{Heat in}} = \frac{c_p[(T_c - T_b) - (T_d - T_a)]}{c_p[T_c - T_b]} = 1 - \frac{(T_d - T_a)}{(T_c - T_b)} = 1 - \frac{T_a(T_d/T_a - 1)}{T_b(T_c/T_b - 1)} \quad (3..8)$$

To proceed further, we need to examine the relationships between the different temperatures. We know that points a and d are on a constant pressure process as are points b and c, and $P_a = P_d$; $P_b = P_c$. The other two legs of the cycle are adiabatic and reversible, so

$$\frac{P_d}{P_c} = \frac{P_a}{P_b} \quad \Rightarrow \quad \left(\frac{T_d}{T_c}\right)^{\gamma/(\gamma-1)} = \left(\frac{T_a}{T_b}\right)^{\gamma/(\gamma-1)}.$$

Therefore $T_d/T_c = T_a/T_b$, or, finally, $T_d/T_a = T_c/T_b$. Using this relation in the expression for thermal efficiency, Eq. (3.8) yields an expression for the thermal efficiency of a Brayton cycle:

$$\text{Ideal Brayton cycle efficiency: } \eta_B = 1 - \frac{T_a}{T_b} = 1 - \frac{T_{\text{atmospheric}}}{T_{\text{compressor exit}}}. \tag{3..9}$$

The temperature ratio across the compressor, $T_b/T_a = TR$. In terms of compressor temperature ratio, and using the relation for an adiabatic reversible process we can write the efficiency in terms of the compressor (and cycle) pressure ratio, which is the parameter commonly used:

$$\eta_B = 1 - \frac{1}{TR} = 1 - \frac{1}{PR^{(\gamma-1)/\gamma}}. \tag{3..10}$$

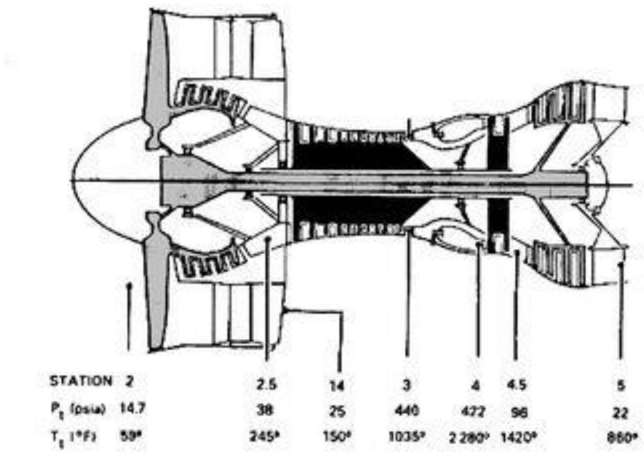

Figure 3.17: Gas turbine engine pressures and temperatures

Figure 3.17 shows pressures and temperatures through a gas turbine engine (the PW4000, which powers the 747 and the 767).

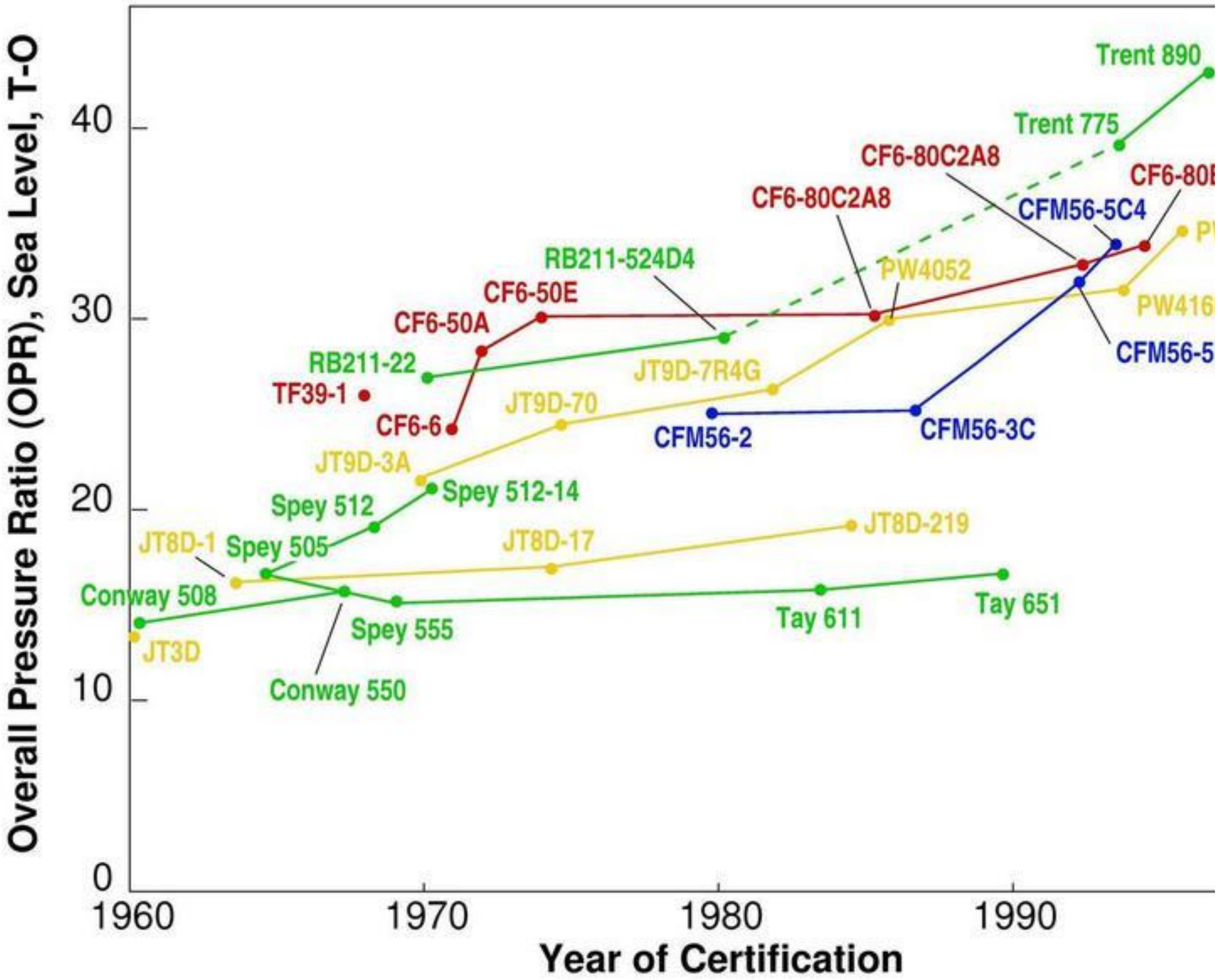

Figure 3.18: Gas turbine engine pressure ratio trends (Jane's Aeroengines, 1998)

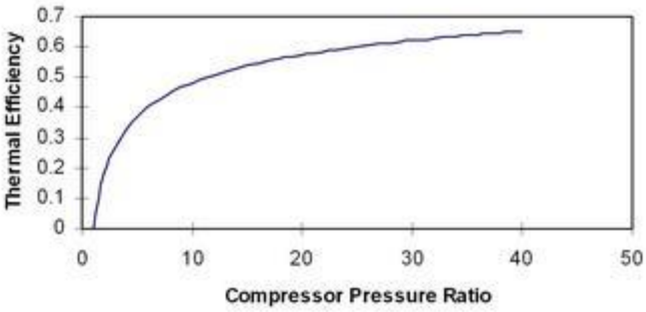

Figure 3.19: Trend of Brayton cycle thermal efficiency with compressor pressure ratio

Equation (3.10) says that for a high cycle efficiency, the pressure ratio of the cycle should be increased. This trend is plotted in Figure 3.19. Figure 3.18 shows the history of aircraft engine pressure ratio versus entry into service, and it can be seen that there has been a large increase in cycle pressure ratio. The thermodynamic concepts apply to the behavior of real aerospace devices.