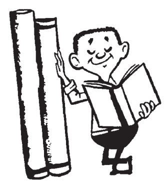
Jet Propulsion

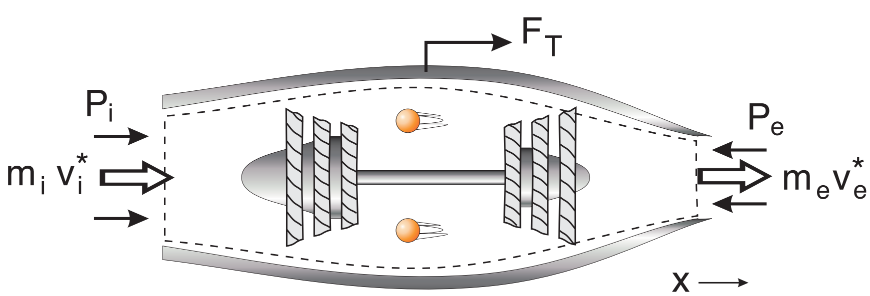


Reading	**Problems**
9-11	9-117, 9-121

Gas Turbines for Aircraft Propulsion

- gas turbines are well suited to aircraft propulsion because of their favorable power-to-weight ratio
- the exhaust pressure of the turbine will be greater than that of the surroundings
- gases are expanded in the turbine to a pressure where the turbine work is just equal to the compressor work plus some auxiliary power for pumps and generators i.e. the net work output is zero
- since the gases leave at a high velocity, the change in momentum that the gas undergoes provides a thrust to the aircraft
- typically operate at higher pressure ratios, often in the range of 10 to 25

Conservation of Momentum



where v_i^* is the velocity of the aircraft

$$\frac{d(Mom)_{x,cv}}{dt} = (\dot{M}om)_{x,in} - (\dot{M}om)_{x,out} + \sum F_x$$

for steady flow $\Rightarrow \dfrac{d}{dt} = 0$ and

$$\dot{m}_i v_i^* - \dot{m}_e v_e^* + F_T + P_i A_i - P_e A_e = 0$$

Since the air-fuel mass ratio is high

$$\dot{m}_{fuel} << \dot{m}_i \qquad \Rightarrow \; \dot{m}_i \approx \dot{m}_e$$

and

$$P_e \approx P_i \approx P_{atm}$$

Therefore

$$\begin{aligned} F_T &= \dot{m}_e v_e^* - \dot{m}_i v_i^* - \underbrace{P_{atm}(A_i - A_e)}_{negligible} \\ &= \dot{m}_i (v_e^* - v_i^*) \end{aligned}$$

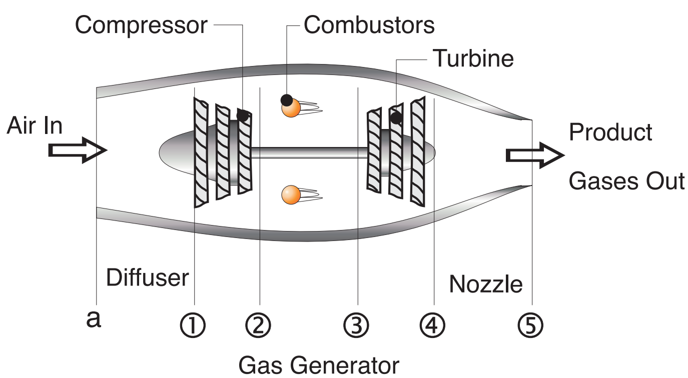
Specific Impulse: $I = \dfrac{F_T}{\dot{m}_i} = v_e^* - v_i^* = \dfrac{\text{thrust}}{\text{mass}}$

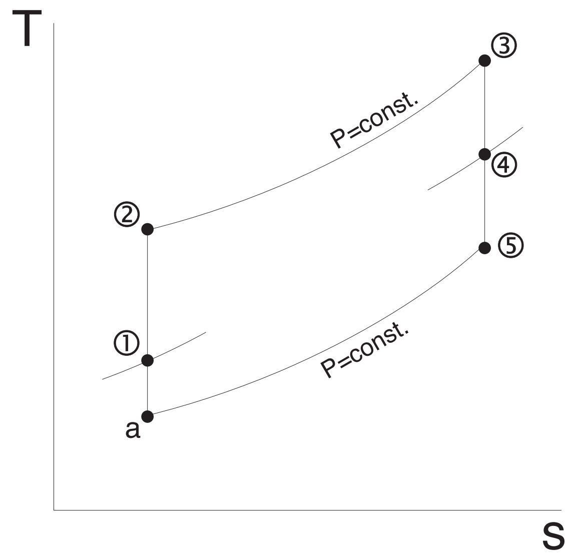
Propulsive Power: $\dot{W}_T = F_T \, v_i^* \approx \dot{m}_i (v_e^* - v_i^*) v_i^*$

Propulsive Efficiency: $\eta = \dfrac{\dot{W}_T}{\dot{Q}_{in}}$

Since the net work output is zero, we must define the propulsive efficiency as propulsive power over the heat flow rate in the combustion process. This then becomes a measure of how efficiently the energy released during the combustion process is converted to propulsive energy.

Turbojet Engine

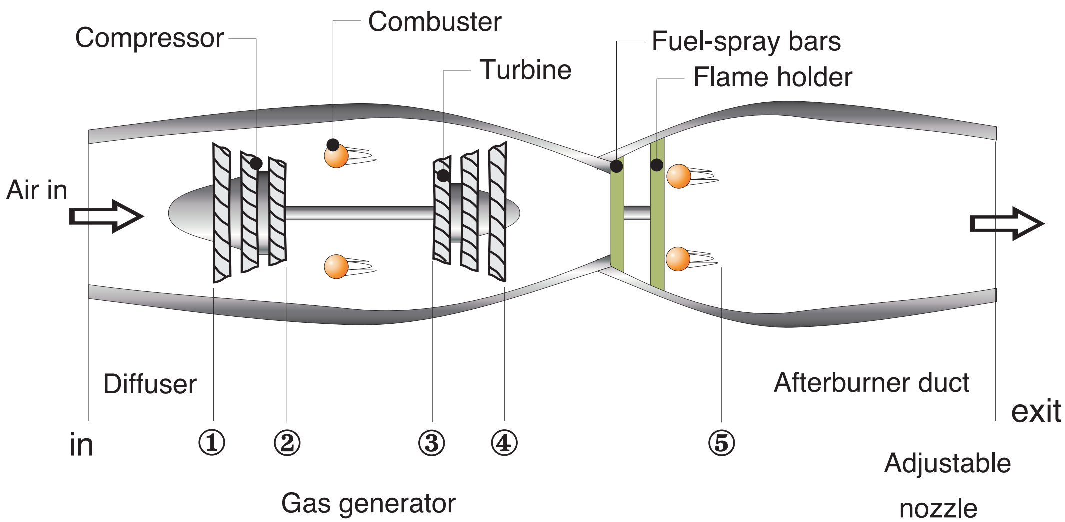




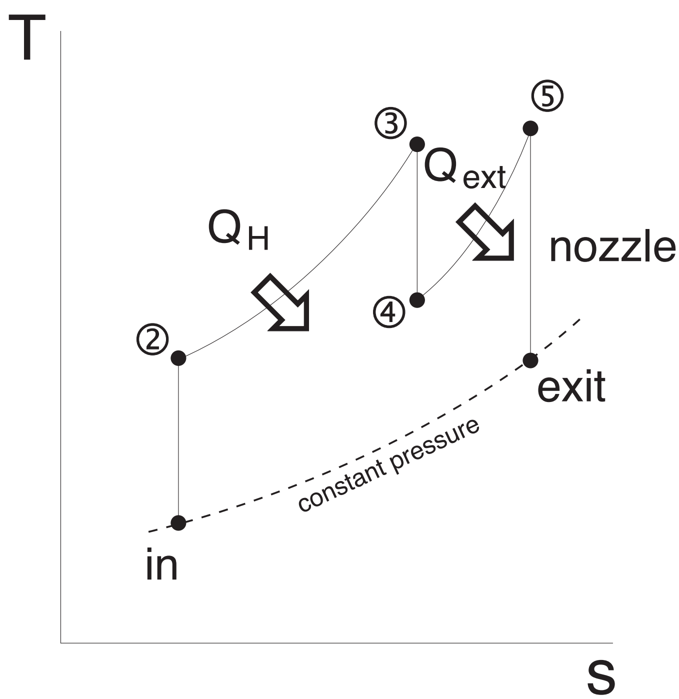
Sections

- **a-1**: **diffuser**
  - decelerates the incoming flow relative to the engine
  - a pressure rise known as a ram effect occurs, $v^* \ (\downarrow), \ \ P \ (\uparrow)$
- **1-4**: gas generator
  - compressor, combustor and turbine
    - 1-2: isentropic compression
    - 2-3: constant pressure heat addition
    - 3-4: isentropic expansion through the turbine during which work is developed
  - turbine power just enough to drive the compressor
  - air and fuel are mixed and burned in the combustion chamber at constant pressure
  - $P_T >> P_{atm}$
- **4-5**: nozzle
  - isentropic expansion through the nozzle, air accelerates and the pressure deceases
  - gases leave the turbine significantly higher in pressure than atmospheric pressure
  - gases are expanded to produce a high velocity, $v_e^* >> v_i^*$ results in a thrust
  - $v_1^* << v_a^*$ v_1^* is negligible
  - $v_4^* << v_5^*$ v_4^* is negligible

Afterburner



- similar to a reheat device
- produces a higher temperature at the nozzle inlet, $T_5 > T_4$
- results in an increase in velocity



By performing a 1st law energy over the nozzle we can obtain an expression for the exit velocity in terms of the entrance temperature to the nozzle.

$$\frac{d\cancel{E}^0}{dt} = \cancel{\dot{Q}}^0 + \cancel{\dot{W}}^0 + \left\{ \dot{m} \left[h_4 + \underbrace{\frac{(v_4^*)^2}{2}}_{\to 0} \right] \right\} - \left\{ \dot{m} \left[h_e + \frac{(v_e^*)^2}{2} \right] \right\}$$

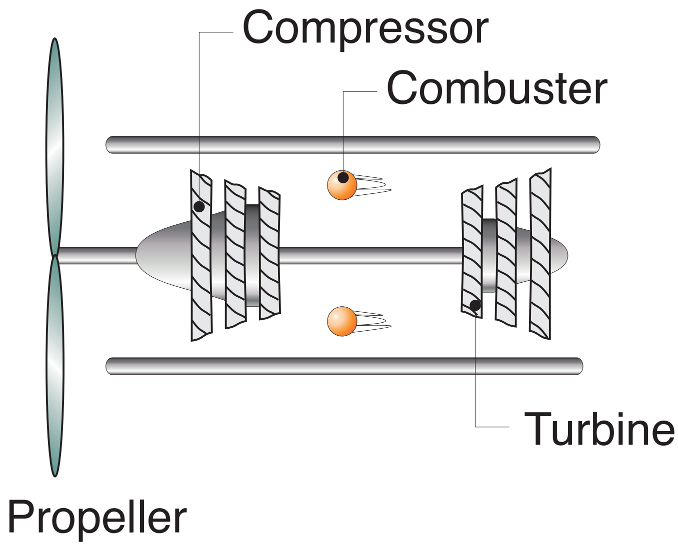
If we assume that the air velocity leaving the turbine is relatively small, the kinetic energy term at 4 can be assumed to go to zero and we get

$$\begin{aligned} v_e^* &= \sqrt{2(h_4 - h_e)} \\ &= \sqrt{2c_p(T_4 - T_e)} \end{aligned}$$

- exit velocity proportional to $v_e^* \propto \sqrt{2c_p(T_4 - T_e)}$
- afterburner is used to increase T_4 to T_5
- similar to a reheat device
- produces a higher temperature at the nozzle inlet

Other Types of Engines

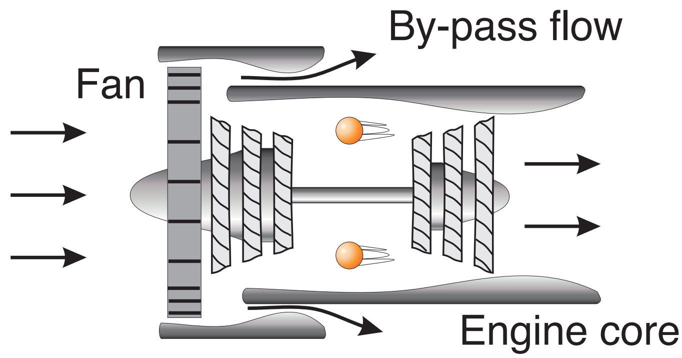
1. Turbo-Prop Engine



- gas turbine drives the compressor and the propeller
- most of the thrust is from the propeller
- works by accelerating large volumes of air to moderate velocities
- propellers are best suited for low speed ($<$ 300 mph) flight
- new turbo-props are suitable for velocities up to 500 mph
- by-pass ratio of 100:1 or more
- by-pass ratio defined as:

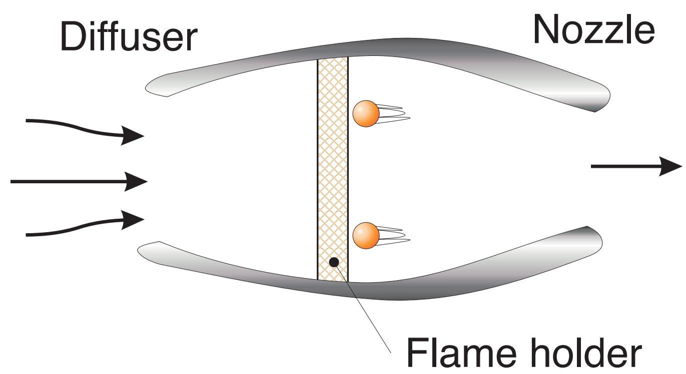
$$\text{bypass ratio} = \frac{\text{mass flow bypassing the combustion chamber}}{\text{mass flow through the combustion chamber}}$$

2. Turbo-Fan Engine (Ducted Turbo-Prop Engine)



- best choice for fuel economy and speed
- high speed exhaust gases are mixed with the lower speed air in the by-pass resulting in a considerable noise reduction
- by-pass ratio can be adjusted
- by-pass provides thrust for takeoff
- the core provides thrust for cruising
- typically used for speeds up to 600 mph
- increasing the by-pass ratio results in increased thrust
- typical by-pass ratios are 5-6

3. Ramjet



- no moving parts
- compression is achieved by decelerating the high-speed incoming air in the diffuser
- aircraft must already be in flight at a high speed
- used in aircraft flying above Mach 1

4. Pulse Jet Engine

- similar to a ram jet but lets in a slug of air at a time and then closes a damper during the combustion stage
- uses a shutter-type valve for damper control
- can be used effectively at low velocities
- used in German V1 missle
- the combustion firing rate was approximately 40 cycles/sec with a maximum flight velocity of 600 mph