

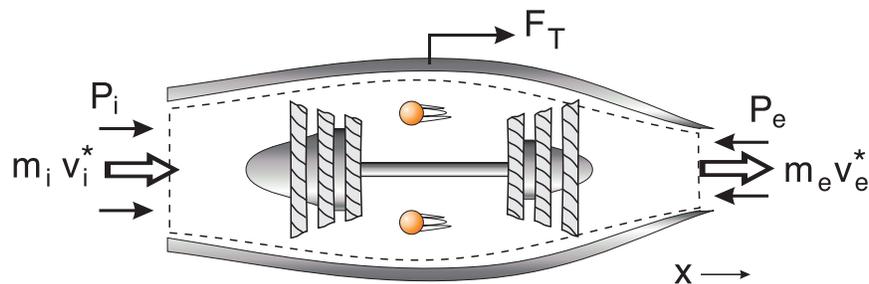
# Jet Propulsion

	<b>Reading</b> 8-11	<b>Problems</b> 8-113, 8-117
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## 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

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

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

$$\dot{m}_{fuel} \ll \dot{m}_i \quad \Rightarrow \quad \dot{m}_i \approx \dot{m}_e$$

and

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

Therefore

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

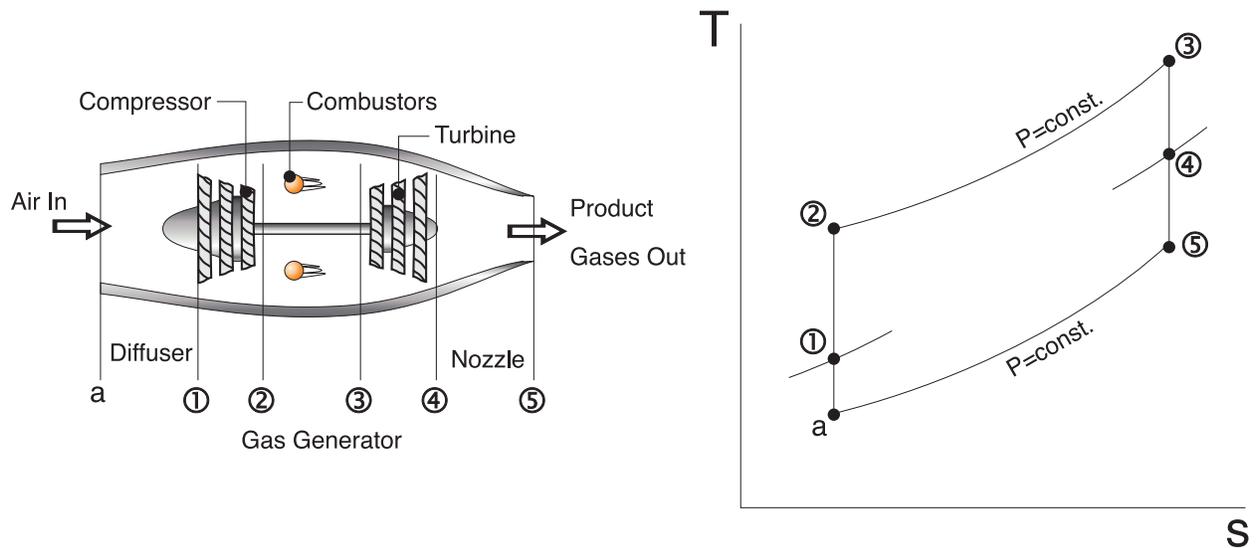
$$\text{Specific Impulse: } I = \frac{F_T}{\dot{m}_i} = v_e^* - v_i^* = \frac{\text{thrust}}{\text{mass}}$$

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

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

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.

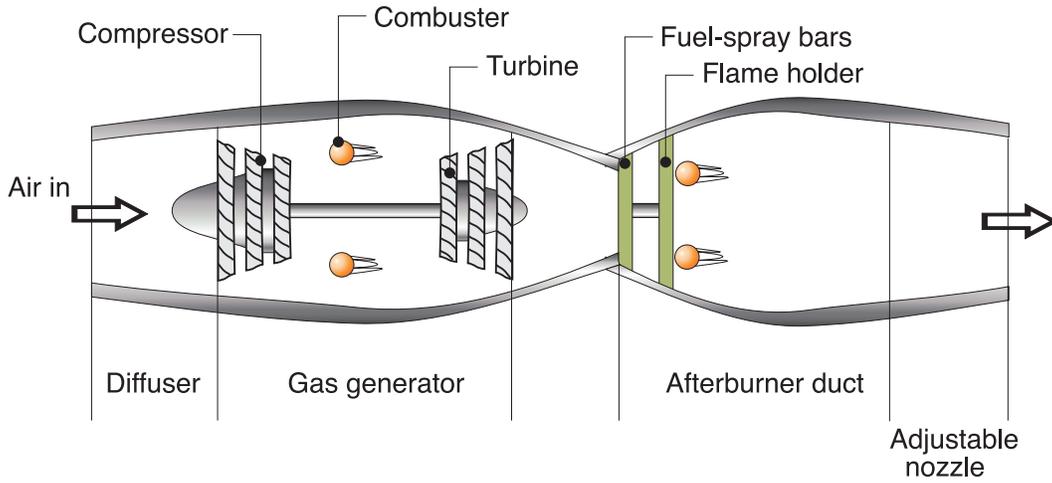
# Turbojet Engine



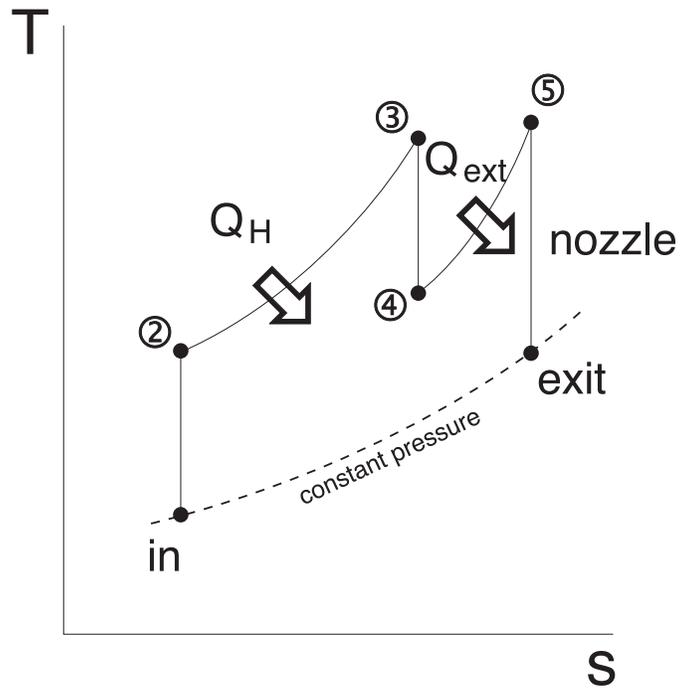
## Sections

- **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
  - $P_T \gg P_{atm}$
- **4-5: nozzle**
  - isentropic expansion through the nozzle, air accelerates and the pressure decreases
  - gases leave the turbine significantly higher in pressure than atmospheric pressure
  - gases are expanded to produce a high velocity,  $v_e^* \gg v_i^*$  results in a thrust
  - $v_1^* \ll v_a^*$        $v_1^*$  is negligible
  - $v_4^* \ll v_5^*$        $v_4^*$  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.

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

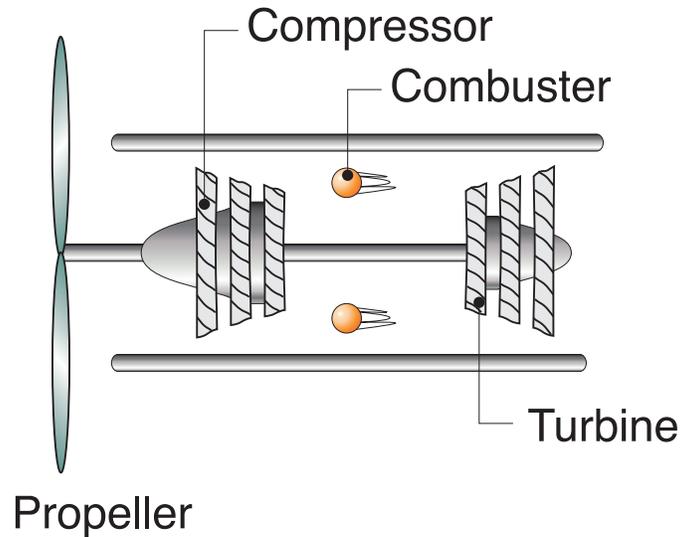
If we assume that the air velocity leaving the turbine is relatively small, the kinetic energy term at 4 can be assumed to go to zero and we get

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

- 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

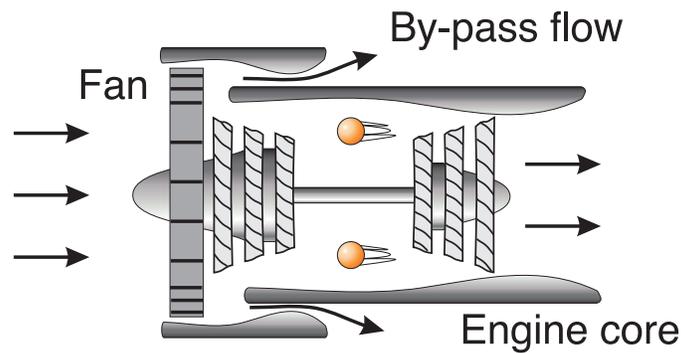
### 1. Turbo-Prop Engine



- 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:

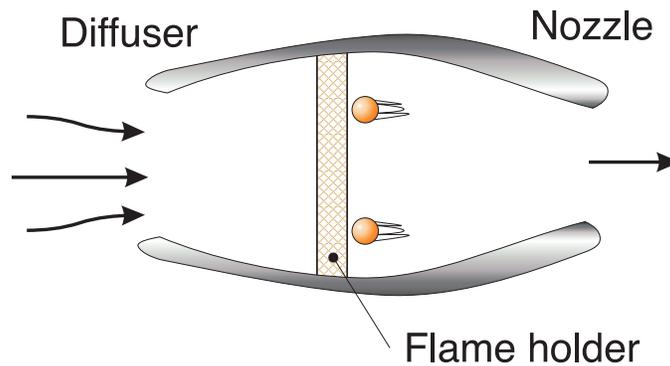
$$\text{bypass ratio} = \frac{\text{mass flow bypassing the combustion chamber}}{\text{mass flow through the combustion chamber}}$$

## 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 missile
- the combustion firing rate was approximately 40 cycles/sec with a maximum flight velocity of 600 mph