Chapter 3

Airbreathing Engine Performance Parameters

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- Thrust = momentum of air + static pressure differences

$$F = \left(\dot{m}_0 + \dot{m}_f\right)v_9 - \dot{m}_0 v_0 + A_9(p_9 - p_0)$$

$$= F_{uninstalled}$$

- Ram Drag

$$D_{ram} = \dot{m}_0 v_0$$

- Usually, $p_9 \approx p_0$ and neglecting fuel flow, then

$$F = q_m(v_9 - v_0)$$

1. Engine Thrust

Uninstalled Thrust

- Ram drag is simply the penalty of bringing air in the engine with a finite momentum.
- If $p_9 < p_0$, the nozzle is **overexpanded** which can happen in supersonic jets only (i.e. in convergent-divergent nozzles with area ratio larger than needed for perfect expansion.)
- If $p_9 = p_0$, the nozzle is **perfectly expanded** which is the case for ***all subsonic jets*** and sometimes in sonic or supersonic jets (i.e., with the right nozzle area ratio).
- If $p_9 > p_0$, the nozzle is **underexpanded** which can happen in sonic or supersonic jets only (i.e. with inadequate nozzle area ratio.)

1. Engine Thrust

Takeoff Thrust

- At takeoff, the air speed is often ignored in the thrust calculation, therefore the ram drag contribution to engine thrust is neglected, i.e.,

$$F_{takeoff} = F_g = \left(\dot{m}_0 + \dot{m}_f\right) v_9 + A_9 \left(p_9 - p_0\right)$$

- For a perfectly expanded nozzle, the pressure thrust term vanishes to give

$$F_{takeoff} \approx \left(\dot{m}_0 + \dot{m}_f\right) v_9 \approx \dot{m}_0 v_9$$

- Therefore, the takeoff thrust is proportional to the captured airflow.

1. Engine Thrust

Installed Thrust

- Installed thrust refers to the actual propulsive force transmitted to the aircraft by the engine, considering all the external losses.
- The installation losses to the thrust such as the nacelle skin friction and pressure drags are to be included.

$$F_{installed} = F_{uninstalled} - D_{nacelle}$$

- Here we focus mostly on the engine internal performance, i.e., the uninstalled characteristics, rather than the installed performance.

1. Engine Thrust

- Accurate installation drag accounting will require CFD analysis and wind tunnel testing at various flight Mach numbers and engine throttle settings.
- The force transmitted through the pylon to the aircraft is not the *uninstalled* thrust, rather the *installed* thrust and pylon drag.
- For jet engines, thrust cannot be directly equivalent to power.

$$P = \dot{m}_0 \frac{v_9^2 - v_0^2}{2} = \dot{m}_0 (v_9 - v_0) \frac{v_9 + v_0}{2} = F \frac{v_9 + v_0}{2}$$

- Roughly, Engine Power = 450m/s × *F*.

2. Specific Thrust

- In general, the magnitude of the thrust produced is directly proportional to the mass flow rates of the fluid flow through the engine.
- **Specific thrust** is the ratio of thrust to air mass flow rate, i.e.,

$$F_s = \frac{F}{\dot{m}_0} = \frac{\dot{m}_0(v_9 - v_0)}{\dot{m}_0} = v_9 - v_0 \quad \text{N.s/kg}$$

- On test bed, $v_0 = 0$, v_9 is specific thrust.
- Nondimensional specific thrust:

$$= \frac{F}{\dot{m}_0 a_0}$$

2. Specific Thrust

- Specific thrust in a cycle analysis is usually to be maximized, i.e. to produce thrust with the least quantity of airflow rate, or equivalently to produce thrust with a minimum of the engine frontal area.
- ***Thrust-to-Weight Ratio*** is an important characteristic which represents design quality of aerodynamics, thermodynamics and structure of an engine.
  - Turbojet——3.5~4
  - Turbojet afterburner——5~6
  - Turbofan afterburner——8
  - Fourth generation——10
- On ground (zero speed), it is the ratio of the thrust at maximum power over the weight of engine .

3. Thrust Specific Fuel Consumption (TSFC)

- Sometimes referred just as Specific Fuel Consumption (sfc).
- Defined as *the ratio of the fuel flow rate per unit thrust force produced*.
- Alternatively, consumption of fuel per hour to generate unit Newton of thrust. This is an economic characteristic.

$$sfc = \frac{\dot{m}_f}{F}(kg/N.s) = \frac{3600\dot{m}_f}{F}(kg/hr.N)$$

- Here： $\dot{m}_f$ is the rate of consumption of kerosene, kg/s.
- In the commercial airliners, sfc represents perhaps the most important parameter of the engine.
- In military aircrafts, sfc takes a second role to other performance parameters, such as stealth, agility, maneuverability and survivability.

3. Thrust Specific Fuel Consumption (TSFC)

- The fuel-to-air ratio is expressed as,

$$f = \frac{\dot{m}_f}{\dot{m}_0}$$

- Thus,

$$sfc = \frac{3600\,f}{F_s}$$

- Since,

$$\dot{m}_f LHV = \dot{m}_0 q_a$$

where q_a is the amount of heat added per kg to the total air mass flow.

$$sfc = \frac{3600\dot{m}_0 q_a}{LHV \cdot F} = \frac{3600 q_a}{LHV \cdot F_s}$$

4. Specific Impulse

- It is defined as *the ratio of thrust produced per unit propellant weight flow rate*.

$$I_{sp} = \frac{F_s}{\dot{m}_p g_0} [s]$$

- For a rocket engine,

$$\dot{m}_p = (\dot{m}_f + \dot{m}_{ox})$$

- For an airbreathing engine,

$$\dot{m}_p = \dot{m}_f$$

- All propulsors, rockets, and airbreathers can thus be compared using a unifying figure of merit, namely their specific impulse in seconds. An added benefit of specific impulse is that it has the same unit [s] in both metric and British systems.

5. Thermal Efficiency

- It is *the ability of an engine to convert the thermal energy inherent in the fuel (unleashed in the chemical reaction) to a net kinetic energy gain of the working medium.*
- It is denoted by the symbol n_{th} .

$$n_{th} = \frac{\Delta KE}{\gamma_{thermal}} = \frac{\dot{m}_9 \frac{V_9^2}{2} - \dot{m}_0 \frac{V_0^2}{2}}{\dot{m}_f Q_R} = \frac{\left(\dot{m}_0 + \dot{m}_f\right) V_9^2 - \dot{m}_0 V_0^2}{2 \dot{m}_f Q_R}$$

- The equation compares the mechanical power production in the engine to the thermal power investment in the engine.

5. Thermal Efficiency

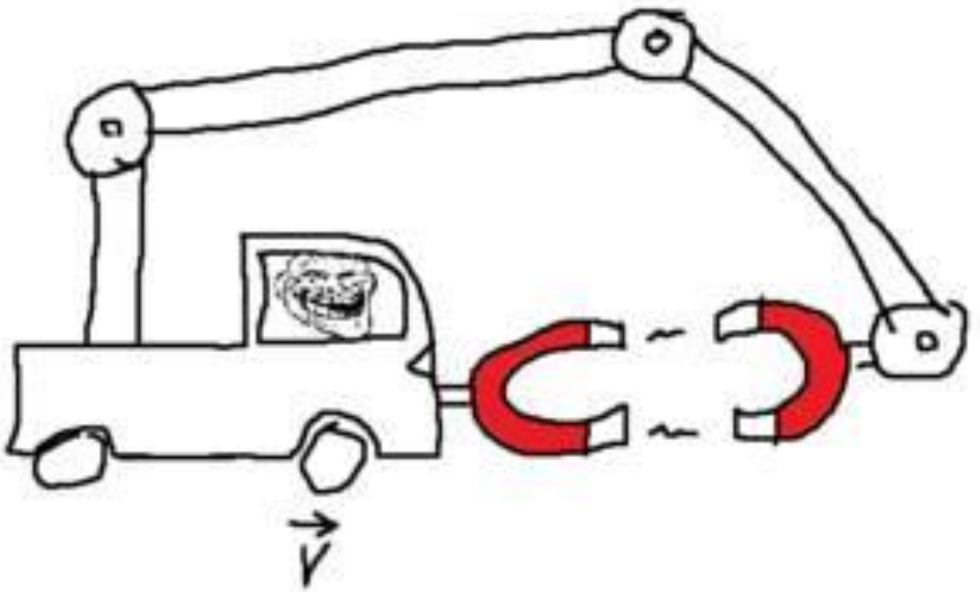
- The rate of thermal energy consumption in an engine and the rate of mechanical power production by the engine are **not equal**.
- Yet we are not violating the law of conservation of energy.
- The thermal energy production in an engine is not usually lost, as it shows up in the hot jet exhaust stream.
- Rather, this energy is wasted (or purged) so that the engine is able to convert it to a useful power.
- This is important to know, or quantify, the inefficiency of an engine, i.e., how much of the energy added (and subsequently purged) is actually being used to generate 'useful' power.
- Therefore, the *lower the exhaust gas temperature*, *the more useful energy is extracted from the combustion gases*, and hence, *the cycle is more efficient* in the thermal context.

5. Thermal Efficiency

- **Regenerative Cycle**
  - The exhaust gas temperature can be lowered by placing a heat exchanger in the exhaust stream to preheat the compressor air prior to combustion.
  - The exhaust gas stream is cooled as it heats the cooler compressor gas and the less fuel is needed to burn to achieve a desired turbine entry temperature.

- **Free Power Turbine (Propeller/Turboshaft)**
  - This creates less wasted heat in the exhaust nozzle; consequently, achieving a higher thermal efficiency than the counterparts without extra shaft power or the heat exchanger.
  - But, ***will our gains outweigh our losses***?

- “Strap this wind turbine to your car and drive forever.”



- Changed to- “Strap this wind turbine to your electric car and stay juiced in park.”

- Still a stupid and unfeasible concept…

5. Thermal Efficiency

- A successful engine does not necessarily have the highest thermal efficiency, but rather its overall system performance and cost is designed to meet the customer’s requirements in an optimum manner.
- The thermal efficiency is bound by the Carnot cycle efficiency (operating between two temperatures) as the maximum.

6. Propulsive Efficiency

- It is the fraction of the net mechanical output of the engine which is converted into thrust power.
- It is denoted by the symbol n_p .

$$n_p = \frac{F \cdot V_0}{\Delta KE} = \frac{F \cdot V_0}{\dot{m}_9 \frac{V_9{}^2}{2} - \dot{m}_0 \frac{V_0{}^2}{2}}$$

$$n_p \approx \frac{\left[\left(\dot{m}_0 + \dot{m}_f\right)V_9 - \dot{m}_0 V_0\right] \cdot V_0}{\left(\dot{m}_0 + \dot{m}_f\right)\frac{V_9{}^2}{2} - \dot{m}_0 \frac{V_0{}^2}{2}}$$

For perfectly expanded nozzle.

$$\Rightarrow \quad n_p \approx \frac{\left[V_9 - V_0\right] \cdot V_0}{\frac{1}{2}\left[V_9{}^2 - V_0{}^2\right]} = \frac{2V_0}{\left(V_9 + V_0\right)} = \frac{2}{\left(1 + \frac{V_9}{V_0}\right)}$$

6. Propulsive Efficiency

- From the final form of the approximate equation, a 100% propulsive efficiency is mathematically possible and will be achieved by engines whose exhaust velocity is as fast as the flight velocity, i.e. $V_9 = V_0$.
- But, will there be thrust?
- Nope!
- Some overspeeding in the jet, compared with the flight speed, is definitely needed to produce reaction thrust in an airbreathing jet engine.
- However, the smaller the increment of velocity rises across the engine, the higher the propulsive efficiency will be.
- Draining the thermal energy from combustion into shaft power can provide a means for achieving small increments, and use it to drive larger mass flow through a fan/propeller.

7. Engine Overall Efficiency

- It is the product of the engine thermal and propulsive efficiencies.
- It is denoted by the symbol, n_0 .

$$n_0 = \frac{\Delta KE}{\dot{m}_f Q_R} \frac{F \cdot V_0}{\Delta KE} = \frac{F \cdot V_0}{\dot{m}_f Q_R}$$

- The overall efficiency of an aircraft engine is therefore the fraction of the fuel thermal power, which is converted into the thrust power of the aircraft.