TURBO MACHINES

BME IV/I

Chapter Six: Aircraft Propulsion

By:
Raj Kumar Chaulagain
Lecturer
Thapathali Campus, TU, IOE

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Chapter overview

- Gas turbine engine parameters
- Performance of jet engines
  - Engine Thrust
  - Specific Thrust
  - Thrust Specific Fuel Consumption (TSFC)
  - Specific Impulse
  - Engine Efficiency
- Thrust variation
- Numerical examples

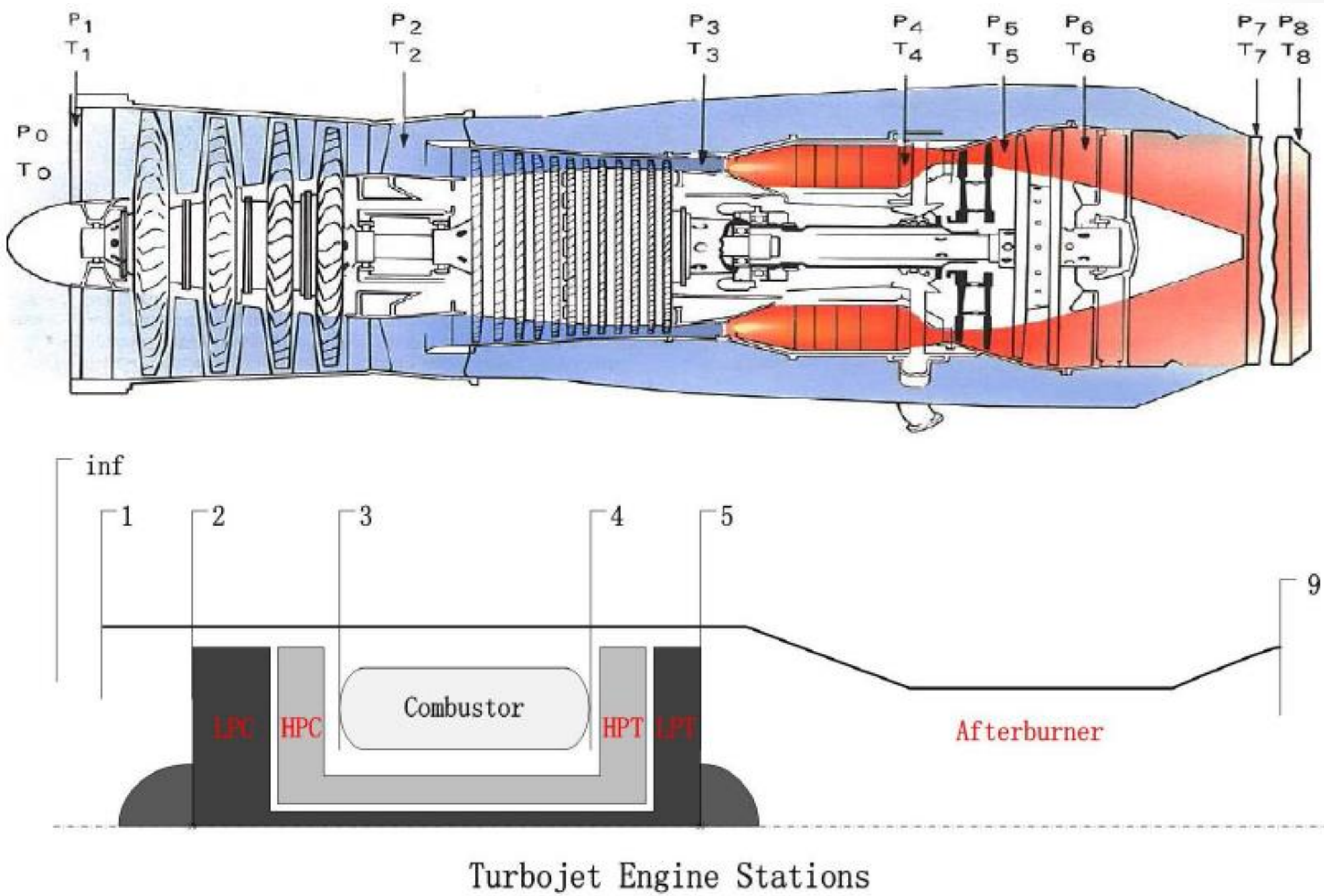
GT ENGINE PARAMETERS

- **Compressor pressure ratio** (*design* parameter): dictate the number and type of compressor stages.
  - The higher the Mach number, the lower the compressor pressure ratio requirement;
  - Above Mach 3, no mechanical compression is needed (ramjet).
- **Compressor air mass flow rate** (*size* parameter).
- **Combustor fuel flow rate/turbine entry temperature** (*temperature limit* parameter): dictate the material and cooling technologies to be employed in the engine hot section, i.e. the turbine and nozzle sections, at the design stage.
- **Fuel heating value** (*ideal fuel energy* parameter)
- **Component efficiency** (*irreversibility* or loss parameter)

Performance of jet engines

1. Engine Thrust
   a. Uninstalled Thrust
   b. Takeoff Thrust
   c. Installed Thrust
2. Specific Thrust
3. Thrust Specific Fuel Consumption (TSFC)
4. Specific Impulse
5. Engine efficiency
   a. Thermal Efficiency
   b. Propulsive Efficiency
   c. Overall Efficiency

CONTD…



P_1 T_1
P_2 T_2
P_3 T_3
P_4 T_4
P_5 T_5
P_6 T_6
P_7 T_7
P_8 T_8
P_0 T_0
inf
1
2
3
4
5
9
LPC
HPC
Combustor
HPT
LPT
Afterburner
Turbojet Engine Stations

CONTD…

- Although the momentum change of the gas stream produces most of the thrust developed by the engine (***momentum thrust***), an additional thrust is produced when the engine operates with the propelling nozzle in a ’choked’ condition.
- This thrust results from the aerodynamic forces which are created by the gas stream and exert a pressure across the exit area of the propelling nozzle (***pressure thrust***).
- Pressure thrust = (P-P**0**) A

Where A = Area of propelling nozzle

P = Pressure at given section

P**0** = Atmospheric pressure

- Momentum Thrust = (WVj)/g

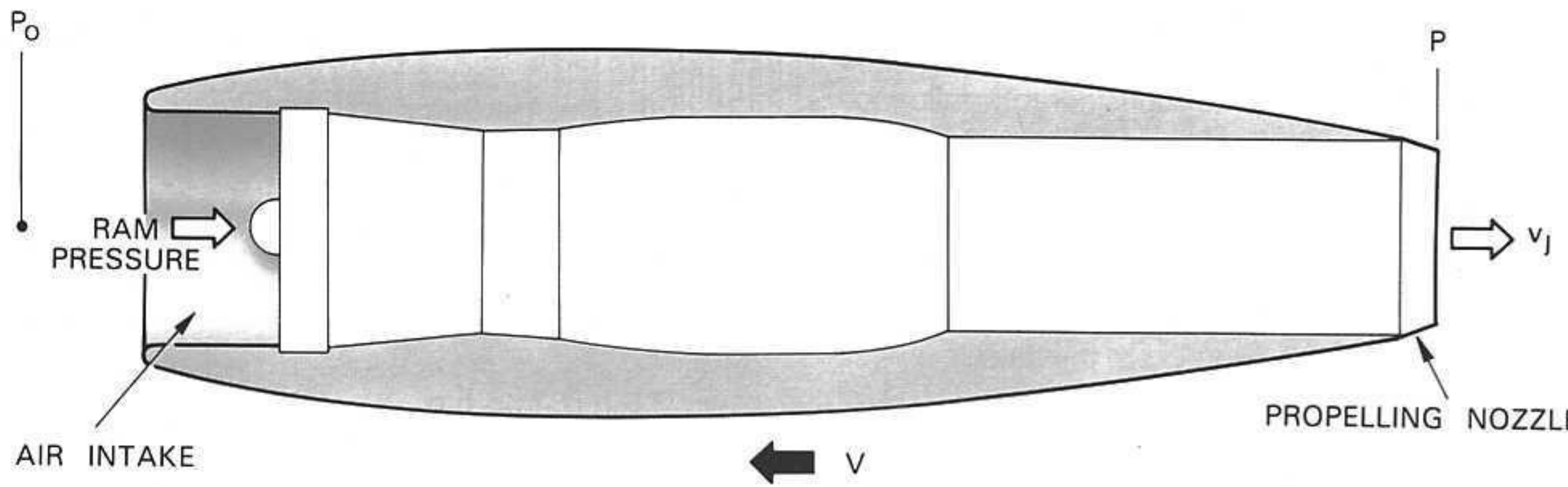
Where, W = mass flow rate, Vj= jet exit velocity

- **Gross Thrust = Pressure Thrust + Momentum thrust**

CONTD…

MOMENTUM DRAG $= \frac{Wv}{g}$ ➡ ⬅ GROSS THRUST $= (P - P_o)A + \frac{Wv_J}{g}$

- ⬅ MOMENTUM THRUST $= \frac{Wv_J}{g}$
- ⬅ PRESSURE THRUST $= (P - P_o)A$



All pressures are total pressures except P which is the static pressure at the propelling nozzle

W	=	Mass of air passing through engine (lb. per sec.)
v_J	=	Jet velocity at propelling nozzle (ft. per sec.)
P	=	Static pressure across propelling nozzle (lb. per sq. in.)
P_o	=	Atmospheric pressure (lb. per sq. in.)
A	=	Propelling nozzle area (sq. in.)
V	=	Aircraft speed (ft. per sec.)
g	=	Gravitational constant 32.2

CONTD…

MOMENTUM DRAG AND NET THRUST

- The momentum drag is the drag due to the momentum of the air passing into the engine relative to the aircraft velocity, expressed as **(WV)/g**

Where W = Mass flow rate

V = Velocity of aircraft

g = Gravitational constant

- ***Net Thrust*** = **Gross Thrust – Momentum Drag**

$$= (P - P_0)A + \frac{W(v_J - V)}{g}$$

Engine Thrust

UNINSTALLED THRUST

- Uninstalled Thrust = momentum of air + static pressure differences
- $$F = \left(\dot{m}_0 + \dot{m}_f\right)v_9 - \dot{m}_0 v_0 + A_9\left(p_9 - p_0\right)$$
  $$= F_{uninstalled}$$

- Ram Drag (momentum drag)
  - Ram drag is simply the consequence of bringing air in the engine with a finite momentum.

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

- Usually, p9≈p0 and neglecting fuel flow, then

$$F = q_m\left(v_9 - v_0\right)$$

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Inlet and outlet pressure conditions

- If p9< p0, the nozzle is **over-expanded** which can happen in *supersonic jets only* (i.e. in convergent-divergent nozzles with area ratio larger than needed for perfect expansion.)

- If p9= p0, 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 p9> p0, the nozzle is **under-expanded** which can happen in *sonic or supersonic jets only* (i.e. with inadequate nozzle area ratio.)

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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.,

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

- For a perfectly expanded (P9=P0) 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.

CONTD…

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.*

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

- These are external parameter comparing to engine.
- Here we focus mostly on the *engine internal performance*, i.e., the uninstalled characteristics, rather than the installed performance.

CONTD…

- 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/mast 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 x *F*.

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., N.s/kg

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

- On test bed, v0 = 0, v9 is specific thrust.
- Non-dimensional specific thrust $= \dfrac{F}{\dot{m}_0 a_0}$

CONTD…

- 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 .

CONTD…

- 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 burning fuel, 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.

CONTD…

- 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.

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

Specific Impulse

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

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

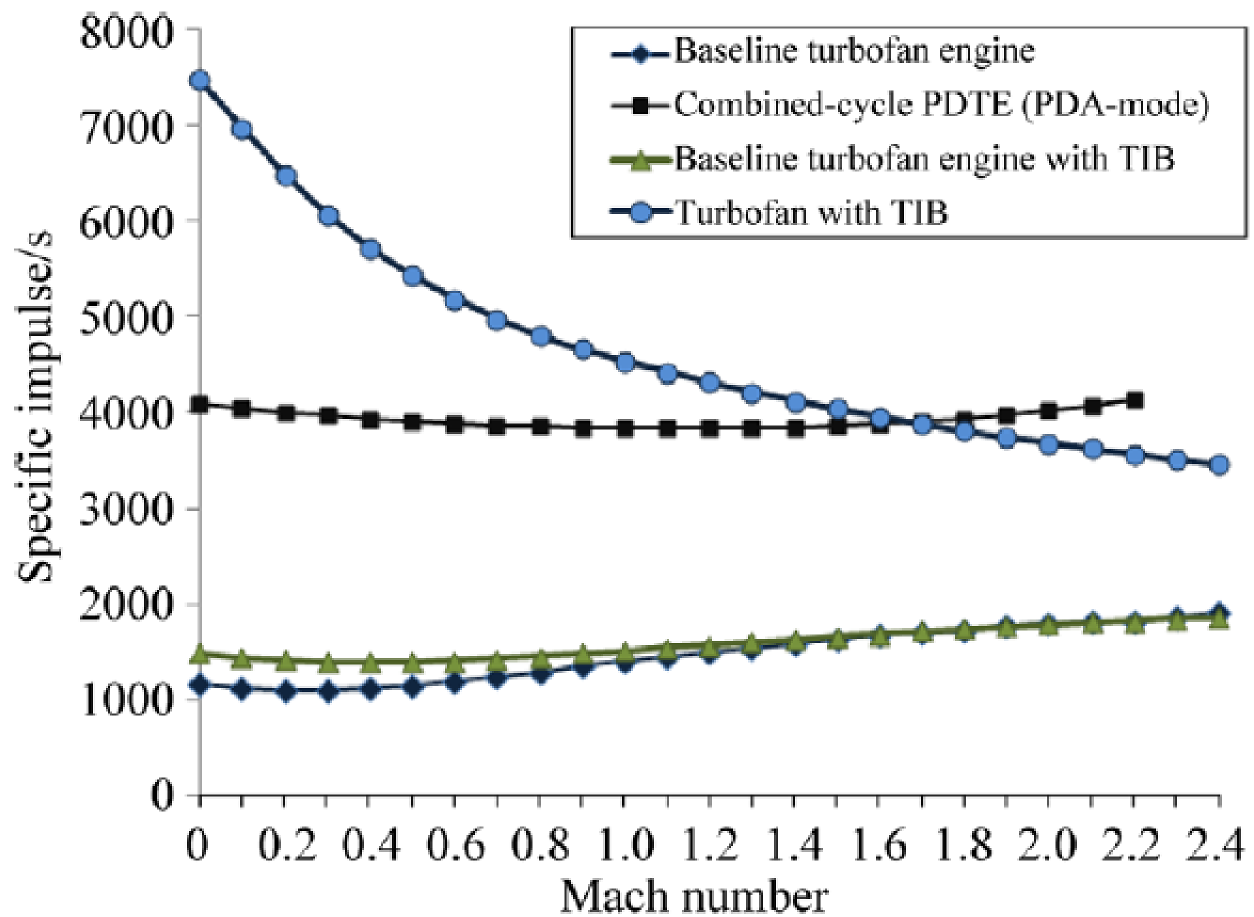
- For a rocket engine,

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

- For an air breathing engine, $\dot{m}_p = \dot{m}_f$
- All propulsions: rockets and air-breathers 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.

CONTD…

Comparison Example



ENGINE EFFICIENCY

- Thermal Efficiency
  - *Burning fuel to produce kinetic energy*
- Propulsive Efficiency
  - *Using kinetic energy of burnt fuel to propel aircraft*

- **Total Efficiency**= Thermal Eff. x Propulsive. Eff.

Prepared by: Raj Kumar Chaulagain, TC, TU, IOE

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

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

CONTD…

- The rate of thermal energy consumption in an engine and the rate of mechanical power production by the engine are **not equal**.
- 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.

CONTD…

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/Turbo shaft)

- 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.

CONTD…

- 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.

CONTD…

PROPULSIVE EFFICIENCY

- The efficiency of conversion of kinetic energy to propulsive work is termed the propulsive or external efficiency and this is affected by the amount of kinetic energy wasted by the propelling mechanism.
- Waste energy dissipated in the jet wake, which represents a loss, can be expressed as $\frac{W(v_J - V)^2}{2g}$

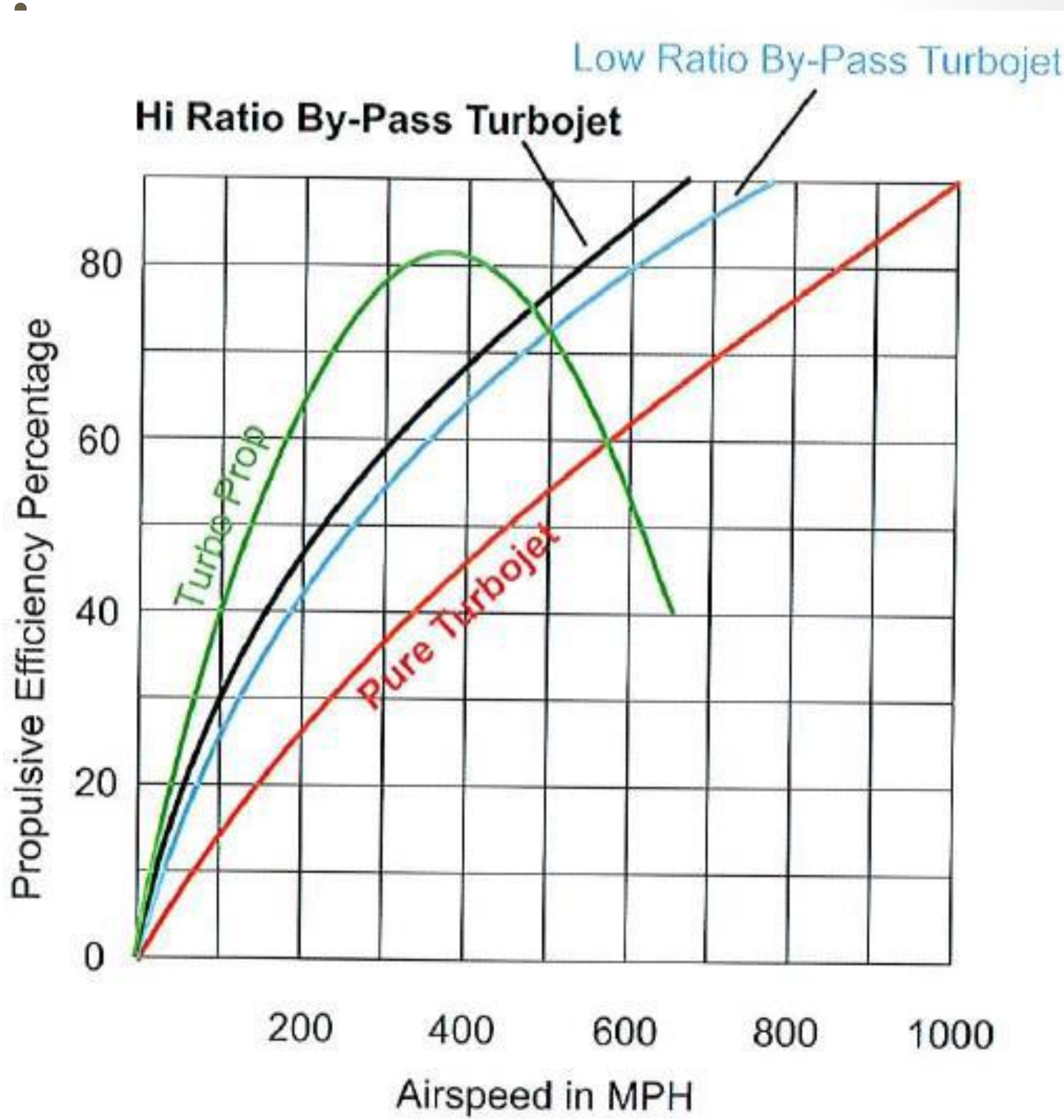
  where (V**J**-V) is the waste velocity.
- Propulsive Efficiency = $\frac{\text{Work done}}{\text{Work done + work wasted in exhaust}}$

$$= \frac{V\left[(P - P_0)A + \frac{W(v_J - V)}{g}\right]}{V\left[(P - P_0)A + \frac{W(v_J - V)}{g}\right] + \frac{W(v_J - V)^2}{2g}}$$

Simplified to : $\frac{2V}{V + v_J}$

CONTD…

- Propulsive efficiency Vs air speed



CONTD…

- 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

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

CONTD…

- 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.
- Some over speeding in the jet, compared with the flight speed, is definitely needed to produce reaction thrust in an air breathing 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.

CONTD…

ENGINE OVERALL EFFICIENCY

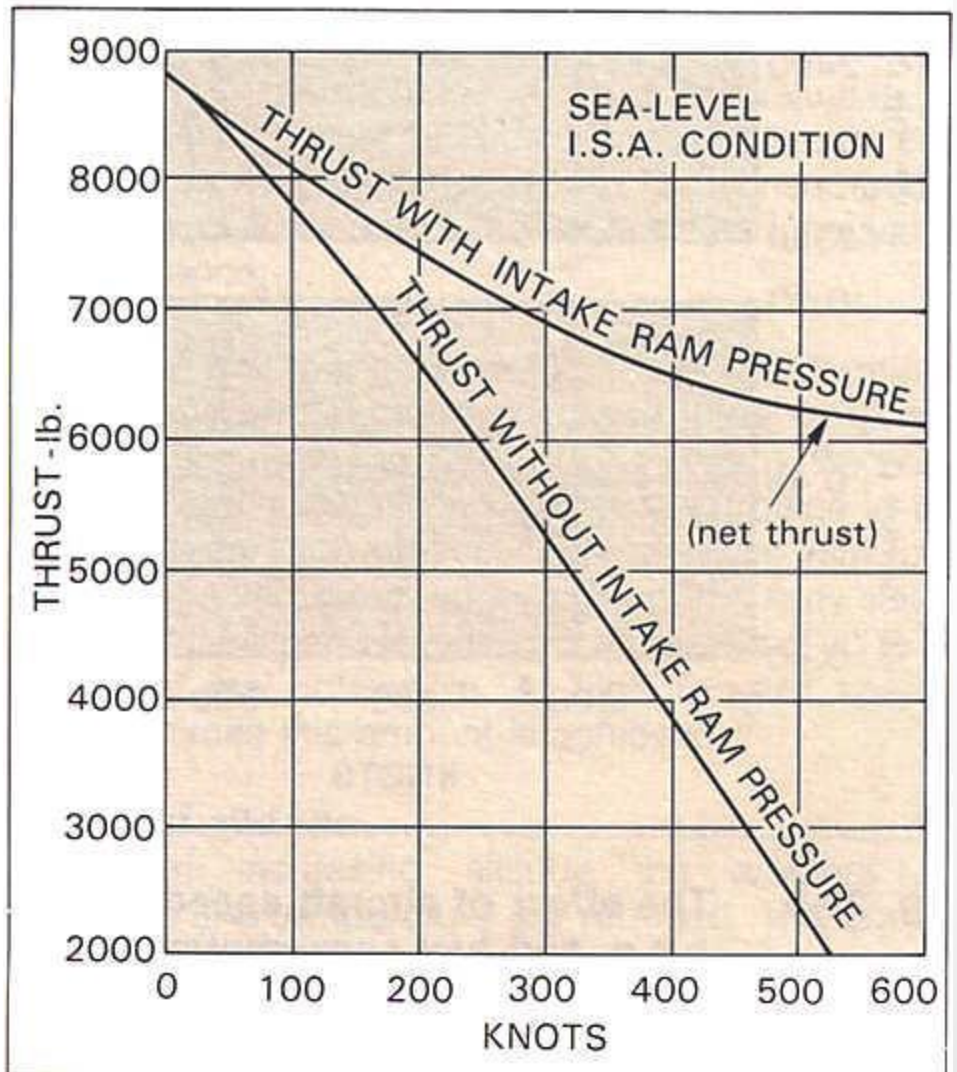
- It is the product of the engine thermal and propulsive efficiencies.
- It is denoted by the symbol, n_0 .

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

- 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.

THRUST VARIATION

- Wrt air speed



The **knot** is a unit of speed equal to one nautical mile (1.852 km) per hour, approximately 1.151 mph.

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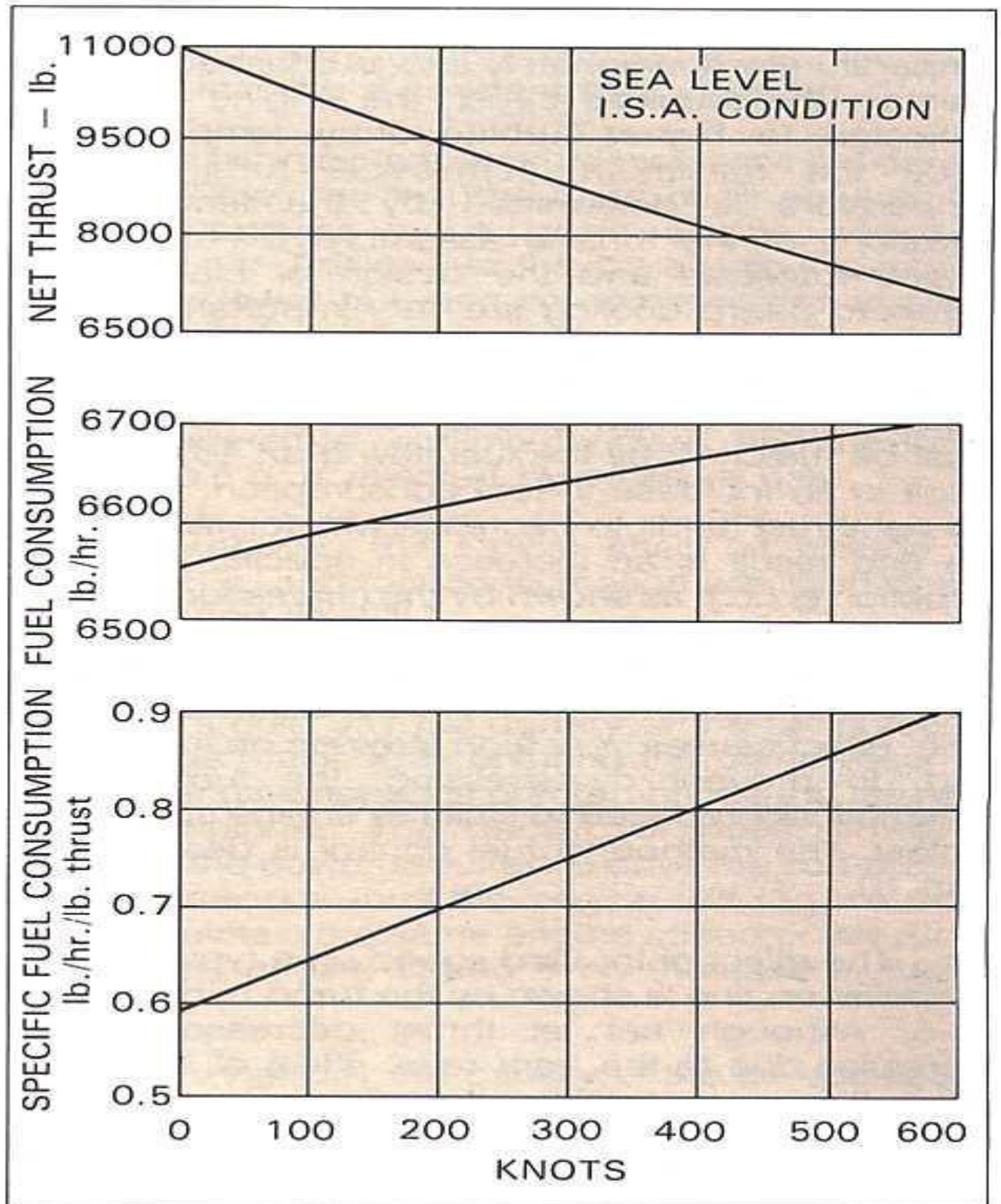
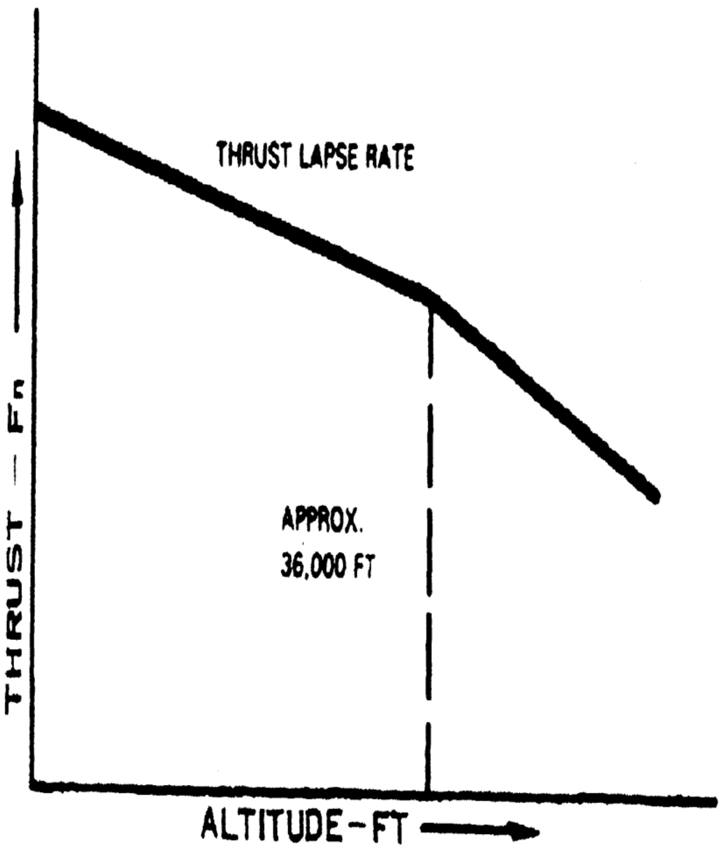
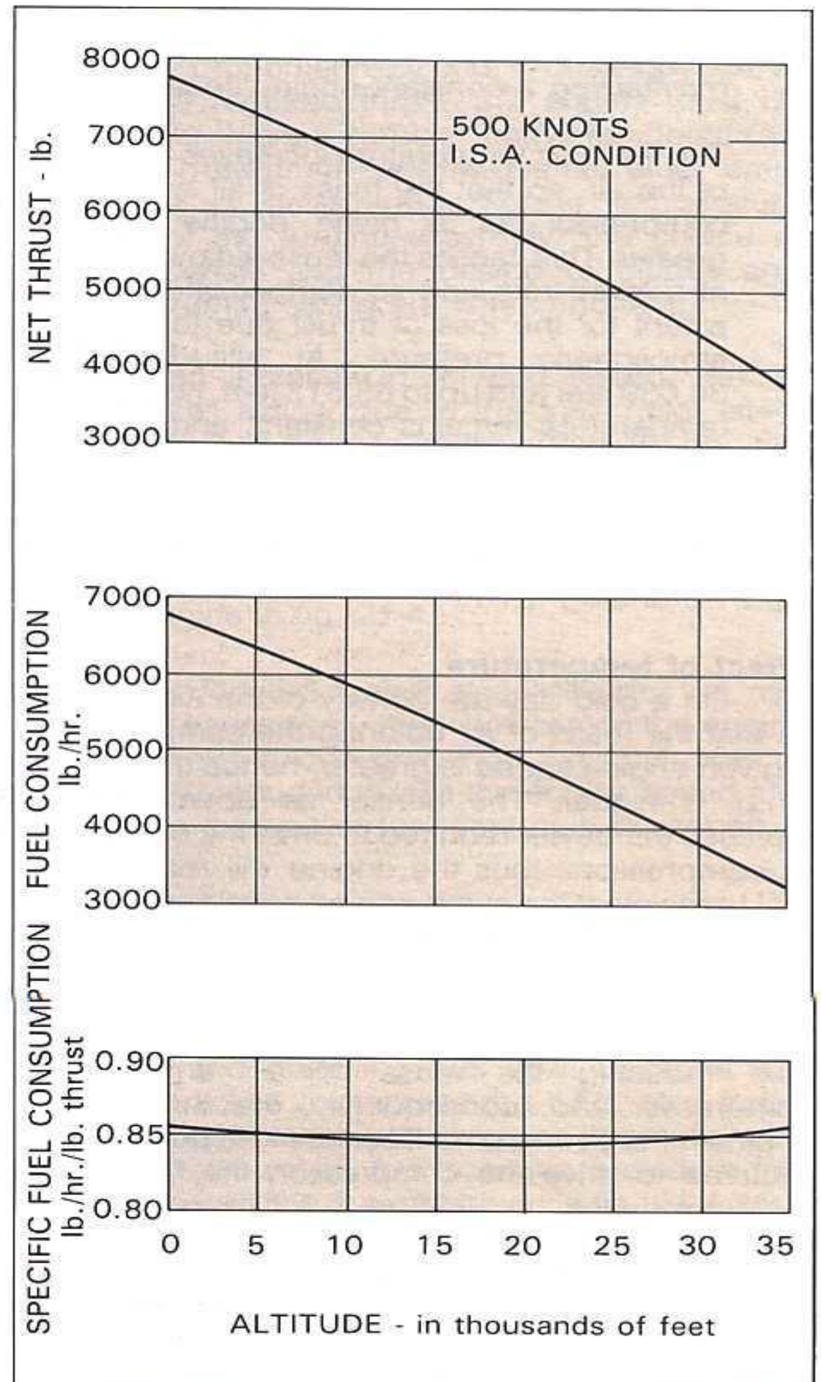
Fuel consumption Vs air Speed



CONTD…

- Wrt altitude





CONTD…

TEMPERATURE (CLIMATE)

- On a cold day, the density of the air increases so that the mass of air entering the compressor for a given engine speed is greater, hence the thrust is higher.
- On a hot day, the reverse will occur.

HUMIDITY

- Because the density of water vapour is less than that of dry air, the mass flow of air entering the engine will be less in a humid climate than in a dry climate.
- The difference is fairly small and, although engine manufacturers will take humidity into account when testing engines, engineers will only take into account altitude and temperature when carrying out power/thrust checks on installed engines.

Numerical examples

Example 1: An air breathing engine flies at Mach M0=2.0 at an altitude where the ambient temperature is T0= - 50 0C and ambient pressure is po= 10 kPa. The air flow rate to the engine is 25 kg/s. The fuel flow rate is 3% of air flow rate and has a heating value of 42,800 kJ/kg. Assuming the exhaust speed is V9= 1050 m/s and the nozzle is perfectly expanded i.e. p9 = p0, calculate:

a) Ram drag in kN

b) Gross thrust in kN

c) Net (uninstalled thrust) in kN

d) Take off thrust in kN

e) Specific thrust

f) TSFC in kg/h/N

g) Thermal efficiency

h) Propulsive efficiency

i) Overall efficiency

CONTD…

V_0=598.84 m/s; V_9=1050 m/s, $\dot{m}_0 = 25\ kg/s$; $\dot{m}_f = 0.03\dot{m}_0 = 0.75\ kg/s$

a) Ram drag, $D_{ram} = \dot{m}_0 V_0 = 14.971\ kN$

b) Gross thrust, $F_g = (\dot{m}_0 + \dot{m}_f)V_9 + (p_9 - p_0)A_9$ since p_0=p_9 there is no pressure thrust.

$\therefore F_g = 27.040\ kN$

c) Net (un-installed) thrust, $F_n)_{un-installed} = F_g - D_{ram} = 12.07\ kN$

d) Thrust specific fuel consumption, $TSFC = \dfrac{\dot{m}_f}{F_n} = 0.2237\ \dfrac{kg/hr}{N} = 62.14\ mg/Ns$

e) Engine thermal efficiency, $\eta_{th} = \dfrac{(1+f)V_9^2 - V_0^2}{2fQ_R} = 0.3026$ or ~30%

f) Propulsive efficiency, $\eta_p \approx \dfrac{2}{1+\dfrac{V_9}{V_0}} = 0.7264$ or ~73%

g) $\eta_{oveall} = \eta_{th} \cdot \eta_p = 0.2198$ or ~22%

CONTD…

Example 2: An aircraft flying at 10km height at a speed of 250m/s. During this, following data were known,

- Propulsion eff.= 0.6
- Overall eff.= 0.2
- Drag on aircraft=6.5kN
- CV of fuel used= 40,000 kJ/kg
- Air density=0.18kg/m3

Find out

a. Jet velocity at exit
b. Volume of air handled by compressor

CONTD…

Solution: V_i (Entry velocity) = 250 m/s (given)

$$\text{Thrust power} = \text{Thrust} \times V_i = 6.5 \times 250 = 1625 \text{ kNm/s} = 1625 \text{ kW}$$

$$\text{Overall } \eta = \frac{\text{Thrust power}}{\text{Heat supplied}}$$

$$\therefore \quad 0.2 = \frac{1625}{m_f \times 40{,}000}$$

where m_f is fuel supplied per second

$$\therefore \quad m_f = \frac{1625}{0.2 \times 40{,}000} = \textbf{0.1805 kg/sec}$$

$$\text{Thrust} = (m_a + m_f)\,V_e - m_a V_i$$

where m_a is the mass of air entering per second

$$\therefore \quad 6.5 \times 1000 = (m_a + m_f)\,V_e - m_a V_i$$

$$6500 = (m_a + m_f)\,V_e - m_a V_i$$

The propulsive efficiency is given by

$$0.6 = \frac{\text{Thrust power}}{\text{Acting K.E.}} = \frac{1625 \times 1000}{\frac{1}{2}\left[\left(m_a + m_f\right)V_e^2 - m_a V_i^2\right]}$$

Solving the equations (a) and (b), we get

$$m_a = 20.0 \text{ kg/sec}$$

and $\quad V_e = 575$ m/sec as m_f and V_i are known

$\therefore$ V_a (Volume of air used in the system)

$$= \frac{m_a}{\rho_a} = \frac{20.32}{0.18} = \textbf{112.9 m}^3\textbf{/sec}$$

THANK YOU !!!