DEPARTMENT OF AEROSPACE ENGINEERING

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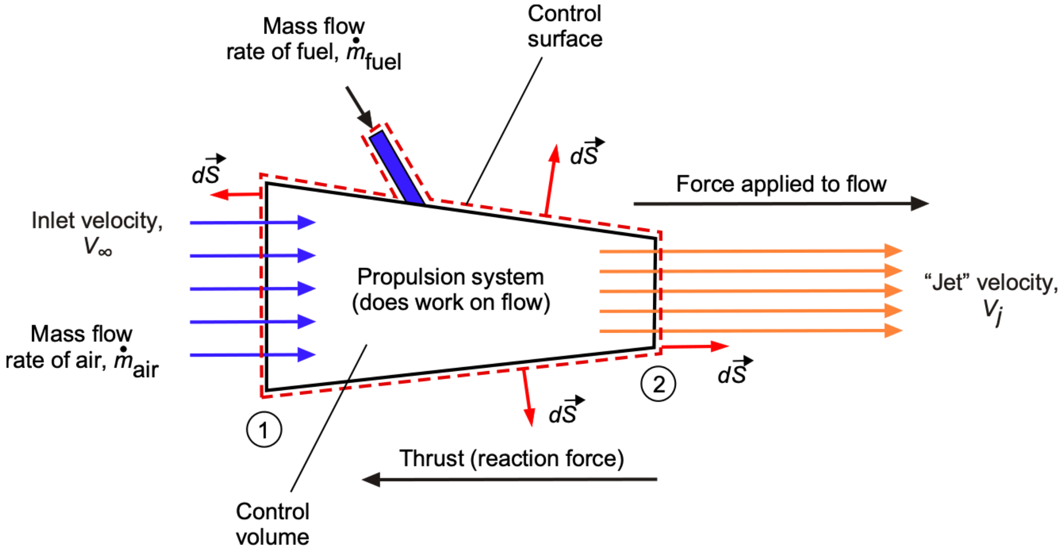
Course	:	**23ASB201 - Aerospace Propulsion**			

UNIT I - INTRODUCTION TO AIRCRAFT PROPULSION

Efficiency Factors in Aircraft Propulsion

Air-Breathing Propulsion Fundamentals

Consider the general propulsive device, as shown by the control volume in the figure below, which moves through the air with an airspeed V_∞. For an air-breathing propulsive device, the air is entrained into the front of the device, which is then compressed and directed to the combustion chambers. Then, the engine works on the air (as a byproduct of the combustion of fuel) to increase its momentum and kinetic energy. Finally, the exhaust is ejected into the slipstream with a higher "jet" velocity V_j. In the case of a rocket engine, there is no inlet velocity, although the operational principles are still the same.



Control volume analysis of a general propulsive device, which works on the air to increase its streamwise momentum and produce a reaction force (thrust).

Assume for the following exposition that there are no external pressure forces and that thrust is produced only by the time rate of change of momentum of the flow. If the mass flow of air into the device is denoted by $\dot{m}_{\text{air}}$ and the mass flow rate of fuel is $\dot{m}_{\text{fuel}}$, then the conservation of momentum applied to the flow gives the thrust produced as

$$T = \left(\dot{m}_{\text{air}} + \dot{m}_{\text{fuel}}\right) V_j - \dot{m}_{\text{air}} V_\infty$$

Now if it assumed that $\dot{m}_{\text{air}} \gg \dot{m}_{\text{fuel}}$ then

$$T \approx \dot{m}_{\text{air}} \left(V_j - V_\infty\right) = \dot{m} \left(V_j - V_\infty\right)$$

i.e., the thrust T is equal to the time rate of increase in momentum of the air as it passes through the propulsive device, and so it is proportional to the increase in velocity of the flow $V_j - V_\infty$.

The increased velocity of the flow also appears as a gain in kinetic energy, which is irrecoverable, i.e., a power loss, as given by

$$P_{rmloss} = \frac{d(KE_{\text{loss}})}{dt} = \dot{KE}_{\text{loss}} = \frac{1}{2}\dot{m}\left(V_j - V_\infty\right)^2$$

It is clear from Eq. that the production of thrust depends on the mass flow rate moving through the device and how much its velocity increases. So, at least in principle, the same amount of thrust can be generated by accelerating a larger mass of flow but at a smaller jet velocity or accelerating a smaller mass of flow at a more significant jet velocity, which affects the efficiency of propulsion.

Quantifying Propulsive Efficiency

Generally, a propulsion system's overall efficiency can be viewed as producing the needed thrust for a given power and the fuel required to produce that power. However, the relative efficiency of the device is essential, i.e., the aerodynamic efficiency of creating a useful propulsive force by doing work in the air.

The efficiency in producing thrust is always related to the kinetic energy of the exit flow from the propulsion system, which is the lost energy per unit time left in the slipstream or wake. Notice that this definition of efficiency does not consider the engine's thermodynamic efficiency or the aerodynamic efficiency of the actual propulsive device used by the engine to do work on the flow.

Relative Efficiency

In terms of quantifying the efficiency of thrust production, consider the useful power supplied by the device (to propel the aircraft forward V_∞), which will be the product of the force produced by the propulsive device and the flight velocity (true airspeed) of the aircraft, i.e.,

$$P_{\text{useful}} = T\,V_\infty$$

This latter equation pertains to a ground-reference frame; the thrust does not work in the frame moving with the aircraft.

The relative propulsive efficiency can now be defined as

$$\eta_p = \frac{\text{Useful power produced}}{\text{Total power expended}} = \frac{T\,V_\infty}{T\,V_\infty + \frac{1}{2}\dot{m}\left(V_j - V_\infty\right)^2}$$

Which recognizes the losses that appear as a gain in kinetic energy in the downstream jet flow.

Recall that based on the conservation of momentum then, the thrust is given by Eq. so substituting in the previous equation gives

$$\eta_p = \frac{T\,V_\infty}{T\,V_\infty + \frac{1}{2}\dot{m}\left(V_j - V_\infty\right)^2} = \frac{\dot{m}\left(V_j - V_\infty\right)V_\infty}{\dot{m}\left(V_j - V_\infty\right)V_\infty + \frac{1}{2}\dot{m}\left(V_j - V_\infty\right)^2}$$

Which, after some simplification, gives

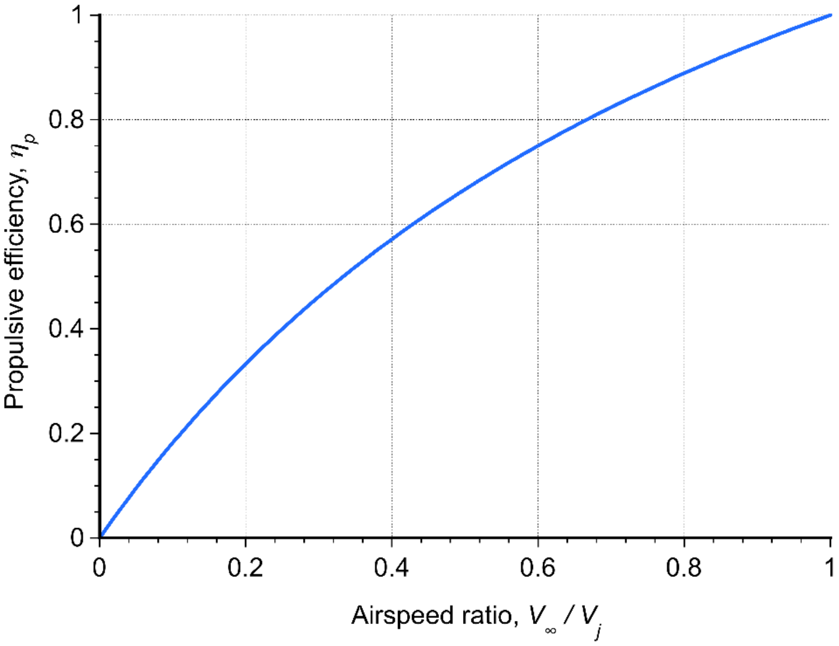
$$\eta_p = \frac{2}{1 + \left(\frac{V_j}{V_\infty}\right)}$$

Where to be meaningful $V_j > V_\infty$. Interestingly, matching the exhaust speed and the vehicle airspeed, i.e., gives the optimum 100% efficiency, at least in theory but not in practice.

The propulsive efficiency can also be written in a perhaps more intuitive form as

$$\eta_p = \frac{2\left(\dfrac{V_\infty}{V_j}\right)}{\left(\dfrac{V_\infty}{V_j}\right)+1} \quad \text{for } \frac{V_\infty}{V_j} \leqslant 1$$

This form reveals that the propulsive efficiency increases with decreasing jet velocity for a given airspeed, as shown in the figure below. This outcome is obtained because the kinetic energy losses become a smaller fraction of the total propulsive power.



The propulsive efficiency of an air-breathing engine increases with increasing airspeed but with diminishing thrust.

Maximizing Propulsive Efficiency

In summary, taking the thrust and efficiency equations together, i.e.,

$$T = \dot{m}\left(V_j - V_\infty\right) \qquad \text{and} \qquad \eta_p = \frac{2}{1+\left(\dfrac{V_j}{V_\infty}\right)}$$

reveals an important outcome regarding the efficiency of thrust production. Notice that a low value for a given thrust and a higher propulsive efficiency can only be achieved by having a significant mass flow rate, through the engine.

Notice also that the thrust equation can be written in terms of specific thrust, as

$$\frac{T}{\dot{m}\,V_\infty} = \left(\frac{V_j}{V_\infty}\right) - 1$$

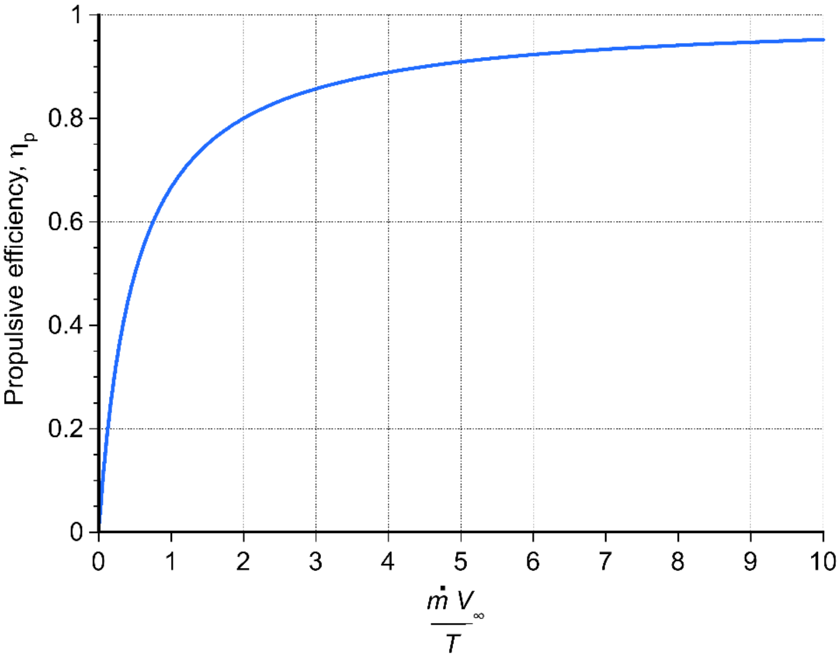
The specific thrust (also related to the specific impulse for rocket engines) is a measure of engine efficiency rather than propulsive efficiency.

Different engines will have different values of specific thrust, but the engines with higher values of specific thrust will be more efficient because they will produce more thrust for a given mass flow rate. Therefore, yet another form of the efficiency equation is

$$\eta_p = \frac{2}{2 + \left(\dfrac{T}{\dot{m}\,V_\infty}\right)}$$

Noting that the grouping is dimensionless.

This result is plotted in the figure below $\dot{m}V_\infty/T$ to emphasize the direct effects of mass flow rate. It will be apparent then that for a given airspeed, the higher the value of the specific thrust and/or the higher the mass flow rate, the better the propulsive efficiency.



The efficiency of thrust production increases with increasing mass flow rate and specific thrust.

Therefore, in general, it can be concluded that it is more efficient to create thrust by accelerating a large air volume at a lower jet velocity versus a lower air volume at a high jet velocity. This is why turbofan engines and propellers, which are “high bypass” devices, have the highest levels of propulsive efficiency. Nevertheless, the efficiency is always less than 100% because of the increased kinetic energy of the exit (jet) flow, an inevitable loss that is a byproduct of creating thrust.

Specific Fuel Consumption

An aircraft’s overall performance characteristics are highly influenced by the engine’s fuel consumption, which can be quantified in terms of *specific fuel consumption* (SFC). The BSFC (*brake-specific* fuel consumption) is the fuel weight used per brake unit of power generated, which is a measure of efficiency, i.e.,

$$\text{BSFC} = c_b = \frac{\text{Weight of fuel consumed}}{(\text{Unit power output})(\text{Unit time})}$$

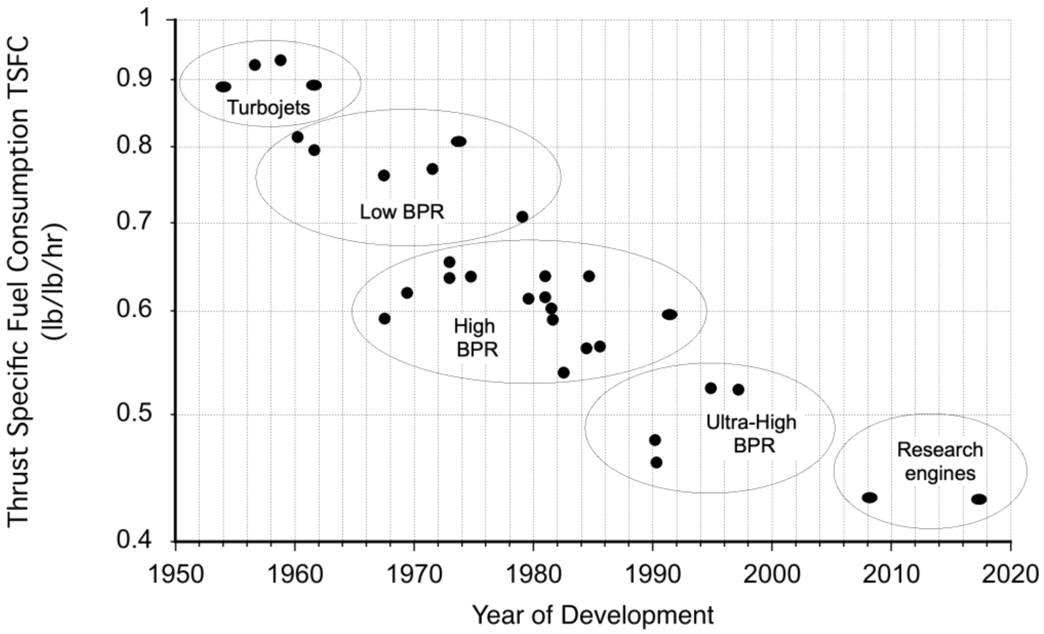
For turboshaft or piston engines, the shaft power produced must be used by a device (such as a propeller or fan) to work on the air, so the propeller or fan efficiency also comes into consideration in determining the overall efficiency of the engine and propeller as a system.

In the case of a thrust-producing engine, the fuel consumption is quantified using *thrust-specific* fuel consumption (TSFC), which is measured in terms of the weight of fuel used per unit thrust per unit time, again a measure of efficiency, i.e.,

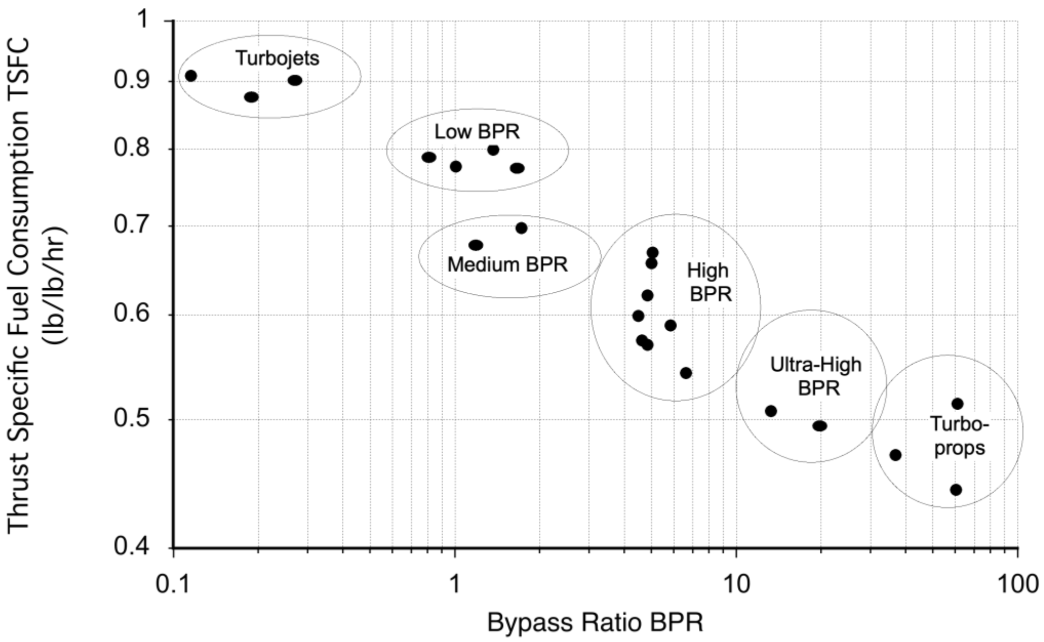
$$\text{TSFC} = c_t = \frac{\text{Weight of fuel consumed}}{(\text{Unit thrust output})\ (\text{Unit time})}$$

Usually, the period for which the TSFC and the BSFC values are quoted is one hour.

Over the decades of their continuous development, the SFC of aircraft engines has improved (reduced) markedly, as summarized in the figure below. Remember that these values measure engine thrust-producing fuel efficiency, so the reductions shown are significant and commensurate with advances in engineering technology in general.



Improvements in subsonic engine performance in terms of thrust-producing specific fuel consumption (TSFC). The values are normalized to a cruise Mach number of 0.8 at ISA standard conditions.



The thrust-producing specific fuel consumption (TSFC) of various types of jet engines and propulsion systems in terms of bypass ratio (BPR).

The efficiency of several propulsive devices is shown in the figure below in terms of their specific fuel consumption, i.e., the fuel used per unit thrust per unit time, which is inversely proportional to propulsive efficiency. Therefore, the higher the efficiency, the lower the specific fuel consumption. Notice that “bypass” increases mass flow through the engine, giving a lower exit or jet velocity. The *bypass ratio* (BPR) is the ratio of the mass flow through the fan relative to the mass flow through the engine's core.

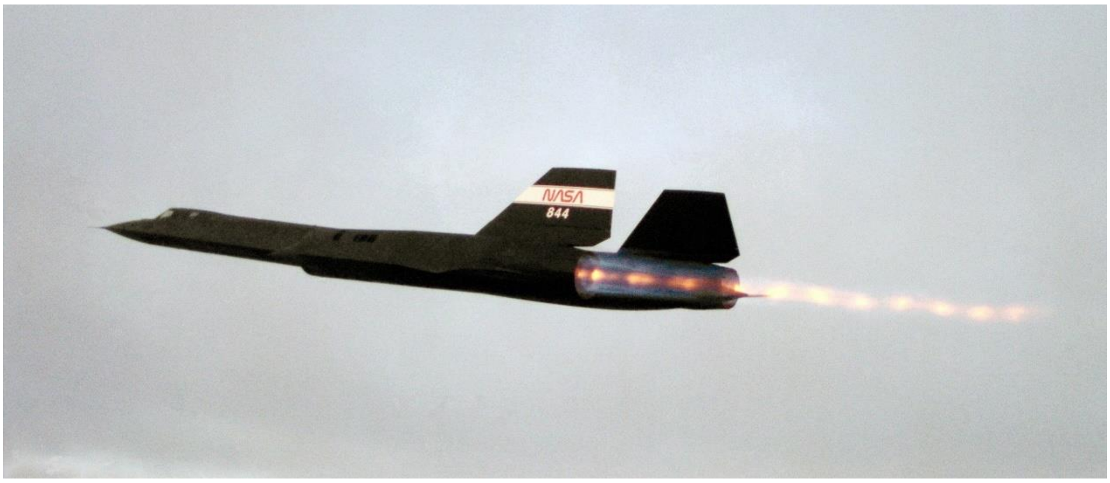
As an example of what has just been concluded in the preceding equations, a turbofan engine (which has a high BPR) has much better fuel efficiency (i.e., lower fuel burn rate) than a turbojet because the fan stage helps to increase mass flow through the engine, but without increasing the net jet velocity (V_j) substantially. A higher BPR also helps to decrease jet noise because of the lower values of V_j, the noise increasing quickly with increasing jet velocity. This characteristic is precisely why high-bypass turbofans are used on most modern airliners rather than turbojets; their efficiency is better than 60%, and they have relatively low noise.

In fact, by similar arguments, a propeller and engine combination has a higher propulsive efficiency (about 70%) because it produces a high mass flow rate through the propeller, and the downstream is relatively small. On a turbojet, V_j is always relatively high, and the propulsive efficiency of this type of engine may be only 20%.

Nevertheless, it is not always possible to have a propulsion system that is well-suited for the flight conditions in which it operates and is also highly efficient. This issue means that engineers designing new aircraft often have to perform studies to decide on the relative benefits of using one propulsion system over another, depending on the cruise speed and flight Mach number of the aircraft and other design factors. Engineers often call these *trade studies*, where the relative merits of one concept are traded off against the relative values of another.

Afterburning

A supersonic aircraft generally requires a turbojet engine with an afterburner, which gives additional jet thrust to propel the aircraft through the high drag conditions during transonic flight, i.e., to go through the "sound barrier" or maintain high supersonic speeds. Afterburning, sometimes called "reheat," is achieved by injecting additional fuel into the jet pipe nozzle, which significantly increases the jet velocity and the thrust T, but also has the disadvantage of very high fuel consumption and low propulsive efficiency. The photograph below shows the SR-71 Blackbird with both engines on full afterburner, which allowed the aircraft to accelerate through transonic conditions and maintain high supersonic airspeeds.



SR-71 Blackbird with the engines on full afterburner. The high-speed exhaust contains numerous shock waves, which appear as “diamonds.”