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DEPARTMENT OF AEROSPACE ENGINEERING

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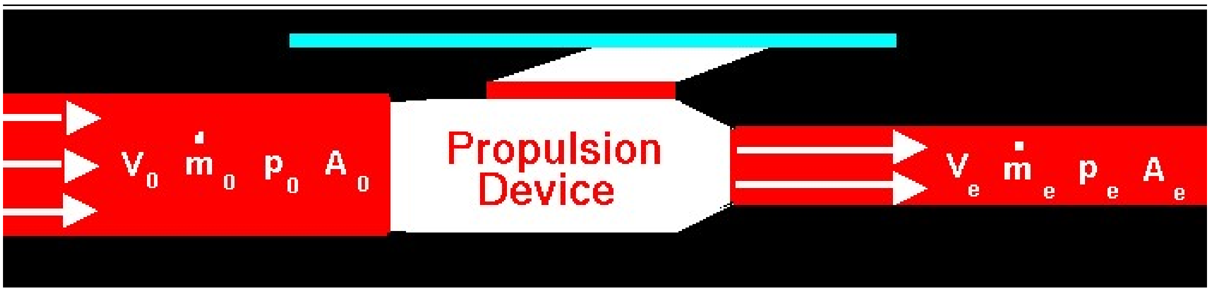
UNIT I - INTRODUCTION TO AIRCRAFT PROPULSION

Thrust Equations and Factors Affecting Thrust

Thrust

Thrust is the force that moves an aircraft through the air. Thrust is generated by the propulsion system of the airplane.



Thrust is a force.

Force = change in momentum with time $\qquad F = \dfrac{([mV]_2 - [mV]_1)}{(t_2 - t_1)}$

$\dot{m}$ = mass flow rate = mass / time

$\dot{m} = r \times V \times A$ where r = density, V = velocity, A = area

If $p_e \neq p_0$: $\quad F = \dot{m}_e V_e - \dot{m}_0 V_0 + (p_e - p_0) A_e$

If $p_e = p_0$: $\quad F = \dot{m}_e V_e - \dot{m}_0 V_0$

How is thrust generated?

Thrust is a mechanical **force** that is generated through the **reaction** of accelerating a mass of gas, as explained by Newton's third law of motion. A gas or **working fluid** is accelerated to the rear and the engine and aircraft are accelerated in the opposite direction. To accelerate the gas, we need some kind of propulsion system. We will discuss the details of various propulsion systems on some other pages. For right now, let us just think of the propulsion system as some machine that accelerates a gas.

Momentum

From Newton's second law of motion, we can define a force **F** to be the change in momentum of an object with a change in time. **Momentum** is the object's mass **m** times the velocity **V**. So, between two times **t1** and **t2**, the force is given by:

F = ((m * V)2 – (m * V)1) / (t2 – t1)

Force

If we keep the mass constant and just change the velocity with time we obtain the simple force equation – force equals mass time acceleration **a**

F = m * a

Mass Flow Rate

If we are dealing with a solid, keeping track of the mass is relatively easy; the molecules of a solid are closely bound to each other and a solid retains its shape. But if we are dealing with a fluid (liquid or gas) and particularly if we are dealing with a moving fluid, keeping track of the mass gets tricky. For a moving fluid, the important parameter is the mass flow rate. Mass flow rate is the amount of mass moving through a given plane over some amount of time. Its dimensions are mass/time (kg/sec, slug/sec, …) and it is equal to the density **r** times the velocity **V** times the area **A**. Aerodynamicists denote this parameter as **m dot** (m with a little dot over the top).

m dot = r * V * A

Note: *The "dot" notation is used a lot by mathematicians, scientists, and engineers as a symbol for "d/dt", which means the variable changes with a change in time. For example, we can write Newton's second law as either*

F = d(mv)/dt or F = (mv)dot

*So "m dot" is not simply the mass of the fluid, but is the **mass flow rate**, the mass per unit time.*

Since the mass flow rate already contains the time dependence (mass/time), we can express the change in momentum across the propulsion device as the change in the mass flow rate times the velocity. We will denote the exit of the device as station "e" and the free stream as station "0". Then

F = (m dot * V)e – (m dot * V)0

A unit check shows that on the right-hand side of the equation:

mass/time * length/time = mass * length / time^2

Pressure

This is the dimension of a force. There is an additional effect that we must account for if the exit pressure **p** is different from the free stream pressure. The fluid pressure is related to the momentum of the gas molecules and acts perpendicular to any boundary that we impose. If there is a net change of pressure in the flow there is an additional change in momentum. Across the exit area, we may encounter an additional force term equal to the exit area **Ae** times the exit pressure minus the free stream pressure. The **general thrust equation** is then given by:

General Thrust Equation

F = (m dot * V)e – (m dot * V)0 + (pe – p0) * Ae

Normally, the magnitude of the pressure-area term is small relative to the m dot-V terms. Let us look at this equation very carefully, for it has some interesting implications.

Design Theory of Engines

We see that there are two possible ways to produce high thrust. One way is to make the engine flow rate (m dot) as high as possible. As long as the exit velocity is greater than the free stream, entrance velocity, a high engine flow will produce high thrust. This is the design theory behind propeller aircraft and high-bypass turbofan engines. A large amount of air is processed each second, but the velocity is not changed very much. The other way to produce high thrust is to make the exit velocity very much greater than the incoming velocity. This is the design theory behind pure turbojets, turbojets with afterburners, and rockets. A moderate amount of flow is accelerated to a high velocity in these engines. If the exit velocity becomes very high, other physical processes become important and affect the efficiency of the engine. These effects are described in detail on other pages at this site.

Gas Turbine Engine

There is a simplified version of the general thrust equation that can be used for gas turbine engines. The nozzle of a turbine engine is usually designed to make the exit pressure equal to the free stream. In that case, the pressure-area term in the general equation is equal to zero. The thrust is then equal to the exit mass flow rate times the exit velocity minus the free stream mass flow rate times the free stream velocity.

F = (m dot * V)e – (m dot * V)0

The first term on the right-hand side of this equation is usually called the **gross thrust** of the engine, while the second term is called the **ram drag**. It is a drag term because it is subtracted from the gross thrust.

Since the exit mass flow rate is nearly equal to the free stream mass flow rate, and the free stream is all air, we can call the mass flow rate through the engine **airflow rate**.

F = (m dot)eng * (Ve – V0)

We can further simplify by absorbing the engine airflow dependence into a more useful parameter called the specific thrust **Fs**. Specific thrust only depends on the velocity change across the engine.

Fs = F /(m dot)eng = (Ve – V0)

General Thrust Equation for Rocket Engines

There is a different simplified version of the general thrust equation that can be used for rocket engines. Since a rocket carries its oxygen on board, there is no ram drag for a rocket engine. The general equation simplifies to:

F = (m dot * V)e + (pe – p0) * Ae

We have to include the pressure correction term since a rocket nozzle produces a fixed exit pressure which in general is different than free stream pressure. There is a useful rocket performance parameter called the specific impulse **Isp**, that eliminates the mass flow dependence in the analysis.

Isp = Veq / go

where **Veq** is the equivalent velocity, which is equal to the nozzle exit velocity plus the pressure-area term, and **g0** is the gravitational acceleration.

Nozzle

For both rockets and turbojets, the nozzle performs two important roles. The design of the nozzle determines the exit velocity for a given pressure and temperature. And because of flow choking in the throat of the nozzle, the nozzle design also sets the mass flow rate through the propulsion system. Therefore, the nozzle design determines the thrust of the propulsion system as defined on this page. You can investigate nozzle operation with our interactive thrust simulator.

FACTORS AFFECTING THRUST:

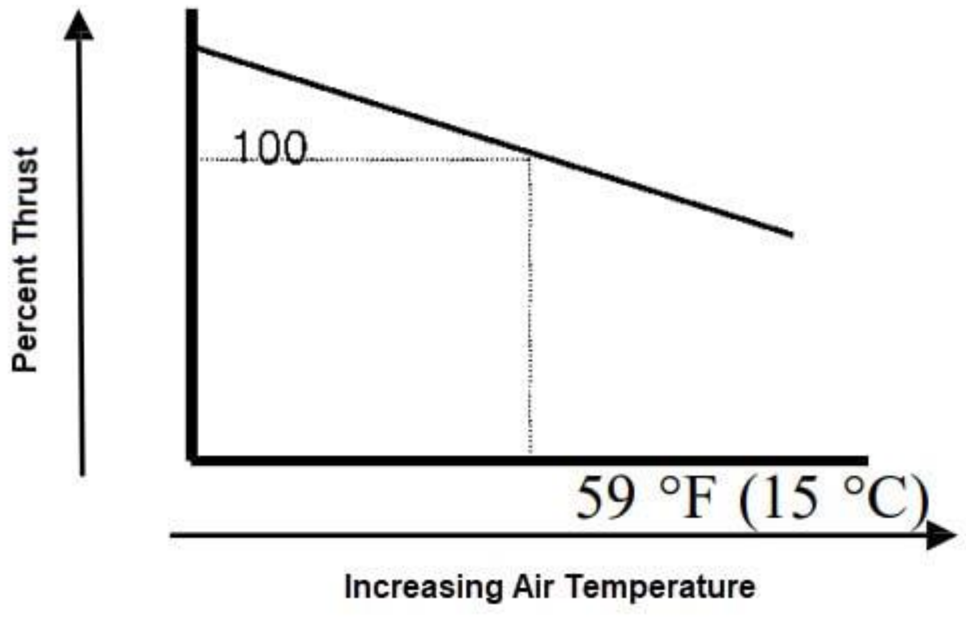
The Factors Affecting Thrust Of A Gas Turbine Engine

The factors affecting the thrust of a gas turbine engine include air density, altitude, airspeed, ram effect, and engine RPM. The effect of these factors is not restricted to any particular gas turbine engine; although a certain engine may be able to compensate for an effect better than another.

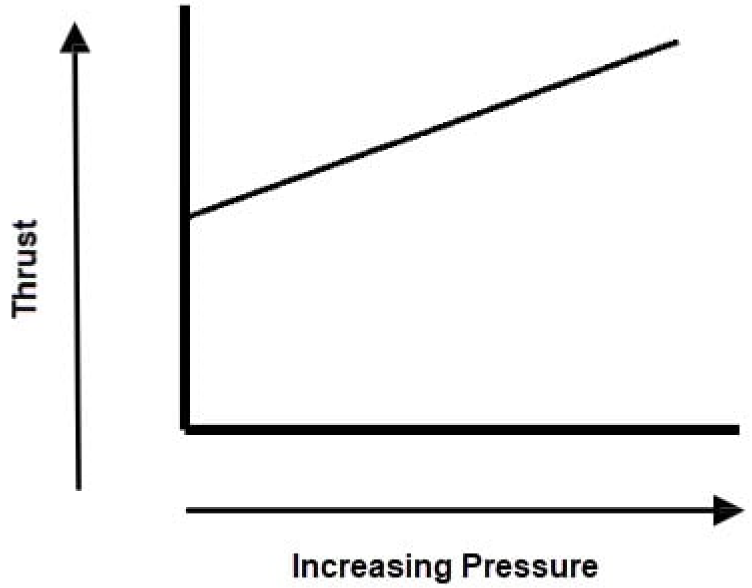
1. Factors Affecting Thrust – Air Density:

Density is the mass of a substance per unit of its volume. According to the thrust equation, if the mass of airflow increases, thrust will increase. If the density of air increases, mass will increase, and therefore thrust will increase. As an aircraft operates at various altitudes and climates, the ambient air temperature and pressure will vary. These factors will affect the density of the air entering the engine, and as a result, will affect thrust.

As **air temperature** increases, air molecules tend to move apart. This results in a density decrease, and a resultant decrease in thrust. An engine operating in the warm temperatures near the equator will produce less thrust than an engine operating in the cold of Alaska. Thrust may vary as much as 20 percent from standard rated thrust on a hot or cold day.



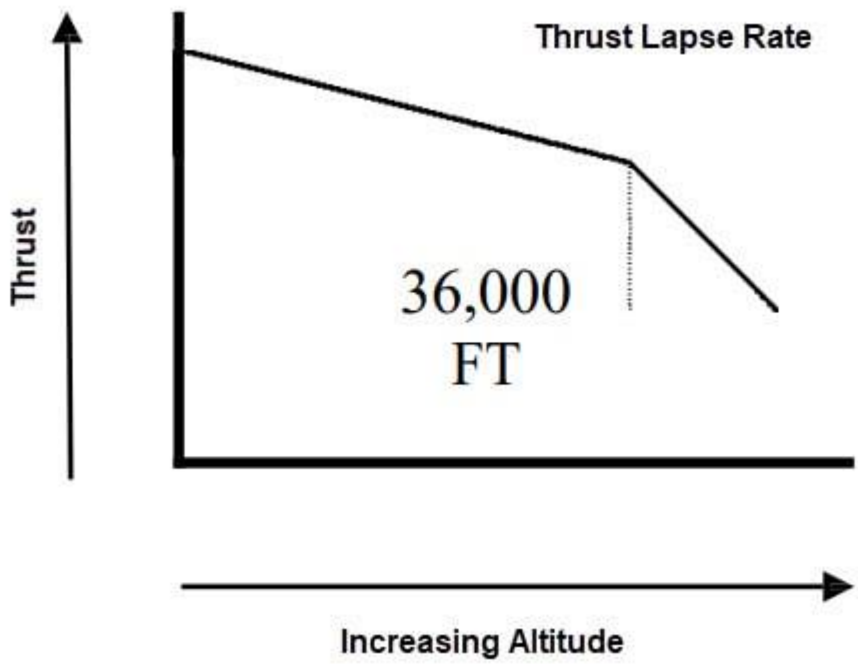
As **air pressure** increases, air molecules tend to move closer together. This increases density, and therefore, thrust increases. For example, an aircraft that flies through the low-pressure eye of a hurricane will produce less thrust than an aircraft operating at normal ambient pressures.



2. <u>Factors Affecting Thrust – Altitude</u>:

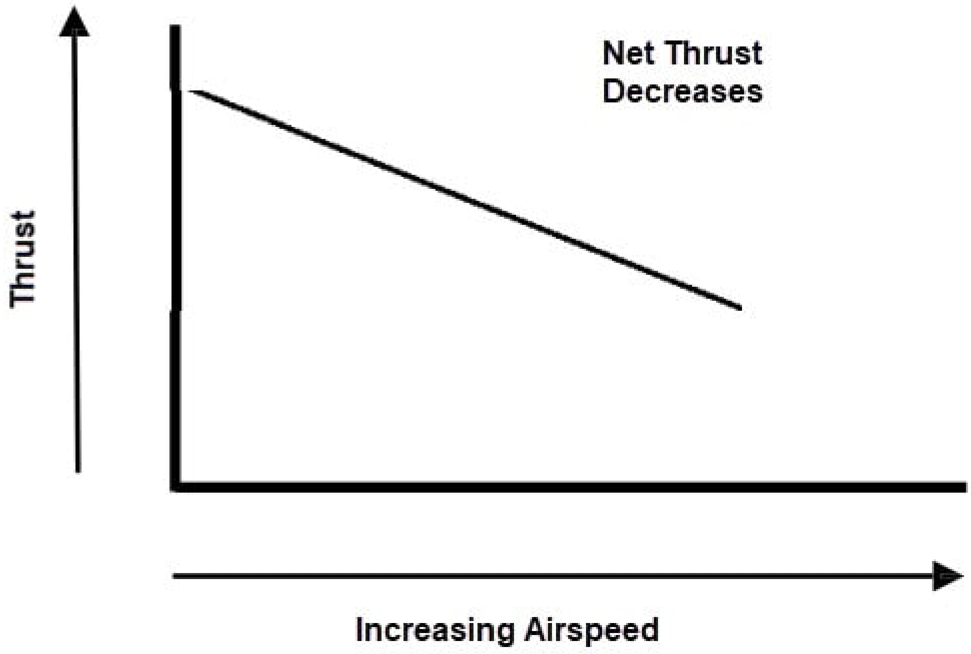
As an aircraft climbs, pressure and temperature will normally drop. From the previous discussion, thrust will decrease with a pressure decrease, and thrust will increase with a temperature decrease. With an increase in altitude, however, the rate of thrust decreases because a pressure drop is greater than the thrust increase resulting from a temperature drop. This means an engine will produce less thrust as it increases in altitude.

At approximately 36,000 feet (beginning of the isothermal layer), temperature stabilizes. As a result, temperature will no longer offset the density decrease due to pressure. Therefore, thrust decreases more rapidly. This altitude is also known as the optimum cruise level. At this altitude, thrust available plus low fuel flow and diminished drag combine to provide optimum performance for many engines.



3. <u>Factors Affecting Thrust – Airspeed</u>:

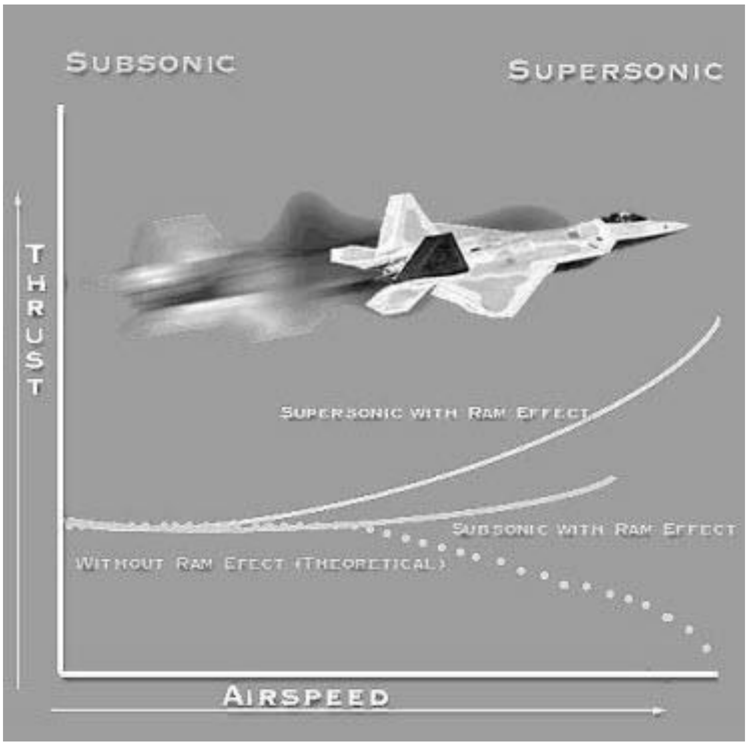
In the thrust equation, the difference between the inlet and exhaust velocities plays a major role in determining the thrust available. As the inlet velocity (v initial) approaches the magnitude of the exhaust velocity (v final), thrust is reduced. Therefore, if the mass of air and fuel is held constant, thrust will decrease as airspeed increases. This decrease in thrust due to an increase in airspeed is theoretical.



4. **<u>Factors Affecting Thrust – Ram Effect</u>:**

If we only consider the change in airflow velocity in the thrust equation, then thrust decreases with an increase in airspeed. Remember, that the thrust equation consists of two variables: mass (m) and acceleration (v final – v initial). As mentioned, the difference between inlet and exhaust velocities decreases as the aircraft increases speed. However, more and more air is being rammed into the inlet, increasing the mass and pressure of inlet air. This offsets the decrease in acceleration and results in a neutral effect or slight increase in thrust at subsonic airspeeds.

This is due to the compressibility of airflow as velocity increases toward the supersonic. As airflow becomes compressible, mass due to the ram effect increases at an increasing rate. The ram effect is especially important to high-performance aircraft due to the exceptionally high mass airflow that occurs at supersonic speeds. This results in a significant increase in overall thrust due to the ram effect at supersonic speeds. For many high-performance fighter aircraft, the ram effect allows excellent high-altitude performance, although air density is low.



5. <u>Factors Affecting Thrust – Engine RPM</u>:

One of the most obvious factors that affects the thrust output is the rotational speed of the engine. With an increase in RPM, there is an increase in thrust. However, at low RPM there is very little increase in thrust with an increase in throttle. At higher rates of revolution, a small increase in throttle setting will produce a large increase in thrust. At the lower settings, fuel consumption is high for the amount of thrust produced. For this reason, gas turbine engines are normally operated at near their maximum RPM.