

CHAPTER 1

AN INTRODUCTION TO GAS TURBINE ENGINES

(Completely Revised)

Objectives

1. This Section contains information about gas turbine engines, their components and systems. The information is presented so that it can be related to the objectives defined in the relevant Skill and Knowledge Specifications (SAKS) for your trade. This Chapter contains an introduction to jet propulsion and current development trends for gas turbine engines which are in use in the Royal Air Force. When you have assimilated this information you should be able to explain:

- The principles of jet propulsion and the working cycle of a jet engine.
- The relevant gas laws and the terminology applied throughout the Section.
- The meaning of thrust and its application.
- The various types of gas turbine engine in use today.

Introduction

2. The conquest of the air by powered flight was ever the aim of man, and a great step forward was made by the Wright Brothers at Kittyhawk, America by their historic flight in 1903. Since this early date, aircraft have developed steadily and, in 1939, aircraft speeds of 464 mph were achieved by production aircraft. Aircraft could climb to 56 000 feet and fly distances up to 7 000 miles non stop. At this time, international records in speed, altitude, and endurance had all been set by Great Britain. In attempts to improve aircraft performance, engines were increased in both size and power output, with various configurations being tried (*ie* various in-line and radial engines with from 7 to 36 cylinders per engine). Superchargers with coolers, water-methanol injection systems and many aids to performance were introduced. However, piston engines and propeller combinations suffered a loss in performance at high forward speeds and high altitudes; clearly a new type of aircraft propulsion unit was needed if aircraft performance was to advance even more; thus the jet engine (gas turbine) was born.

3. It is generally acknowledged that, in Great Britain, Sir Frank Whittle of the Royal Air Force designed and developed the first British gas turbine engine that was suitable for aircraft propulsion. Sir Frank was born in 1907 and he entered the Royal Air Force as an apprentice. As an apprentice he gained a cadetship to Cranwell College and, whilst there, he became interested in the prospect of jet propulsion for aircraft. He produced design drawings for a gas turbine engine and his first engine ran on static tests in 1937. In 1941 the Whittle gas turbine engine powered the Gloster E28/39 aircraft and many of the present-day Rolls-Royce aero engines are developments of Sir Frank's design. Aero gas turbine engines have been the foundation which has made modern high performance aircraft possible.

Principles of Jet Propulsion

4. Jet propulsion is a practical application of Sir Isaac Newton's third law of motion which states: '*For every force acting on a body, there is an equal and opposite reaction*'.

A fireman's hose is an example where reaction is felt. When a powerful jet of water is ejected from a hose, the hose tends to react and move away from the water jet and, so great is the reaction, that sometimes two men are needed to hold the hose and direct the water jet.

5. **Hero's engine.** The earliest known example of jet reaction occurred during the use of a toy called 'Hero's engine'. In 120 BC this toy showed how the momentum of steam issuing from a number of jet outlets could impart an opposite reaction to the jets themselves, and in doing so cause the engine to revolve (Fig 2.1.1). When this principle is applied to aircraft propulsion, the 'body' upon which the force acts is the atmosphere. Air is introduced into the intake duct of the gas turbine engine and then a force is applied to cause the air to accelerate within the engine. The force which accelerates the air reacts in the opposite direction on the engine and moves the engine away from the accelerating column of air in the same manner as the fireman's hose moved away from the water jet.

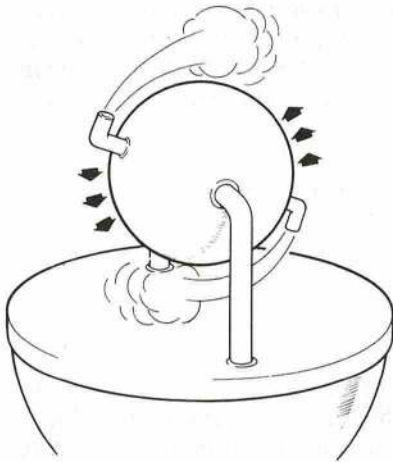
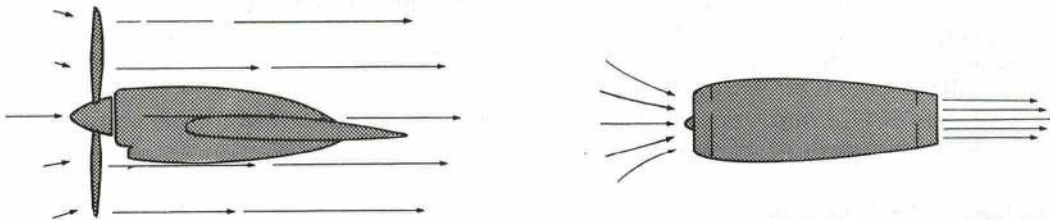


Fig 2.1.1 Principle of Hero's engine

6. Jet reaction is an *internal* phenomenon and it is not, as sometimes assumed, the result of the jet efflux impinging upon the atmosphere. The jet engine is designed to accelerate a stream of air to an exceptionally high velocity and to obtain useful thrust from the reaction. There are many ways of increasing the velocity of the air but, in all cases, the resultant reaction is the propulsive thrust exerted on the engine. The thrust obtained is proportional to the mass of air passing through the engine and to the velocity increase of the mass air flow — *ie* momentum = mass x velocity. Thus, the same amount of propulsive thrust can be obtained by either:

- Accelerating a large mass through a small increase in velocity.
- Accelerating a small mass through a large increase in velocity.

7. **Thrust.** A jet engine produces thrust in a manner similar to that of a piston engine/propeller combination but, whilst the propeller gives a small acceleration to a large mass of air, the turbine engine gives greater acceleration to a smaller mass air flow. This point is illustrated in Fig 2.1.2.



the propeller gives a SMALL acceleration to a LARGE mass of air

the turbo-jet gives a LARGE acceleration to a SMALL mass of air

Fig 2.1.2 Thrust

Application of Principles

8. In addition to Newton's third law of motion, it is necessary to study mass flow of matter, subsonic diffusion (see para 18), Bernoulli's theorem and the gas laws if we are to fully understand how a gas turbine engine produces useful thrust. These are all considered in the paragraphs that follow.

Mass Flow of Matter

9. To understand how matter behaves when moving in a duct it is necessary to consider the mass flow of the matter. Mass flow is defined as the quantity of matter flowing in unit time; the mass flow may be expressed in lb/sec, kg/sec, or in any other convenient units.

10. **Mass flow through a ducted system.** If we investigate what happens when a steady stream of air passes through a steady flow machine, such as a gas turbine engine which is operating at fixed rev/min and air inlet density, we find that the mass flow at any point in the system is of a *constant value*.

11. **Continuity equation.** If we consider the machine to be an open-ended duct (Fig 2.1.3) we find that the mass flow per second will depend on the density of the fluid and the volume flowing per sec:

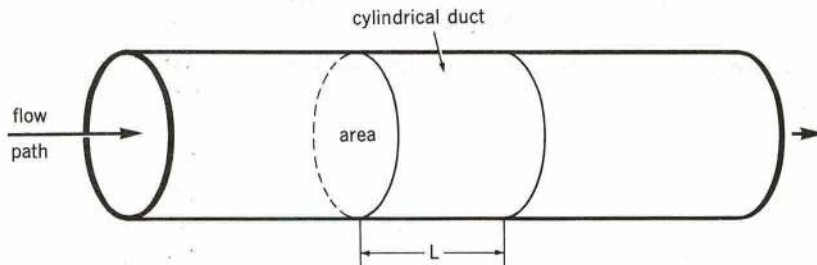


Fig 2.1.3 Steady flow machine

$$\text{Now volume flow} = \frac{\text{Area of duct} \times \text{distance travelled (L)}}{\text{Time (sec)}}$$

But the distance travelled per second = Velocity.

Therefore, *Mass flow* = density \times area \times velocity.

This is known as the 'continuity equation' and it is true for any steady flow system *regardless of changes in the cross-sectional area of the duct*.

12. **Incompressible fluid flow.** Now consider an incompressible fluid as it flows through the duct system shown in Fig 2.1.4. We know that the mass flow is of a constant value and, naturally,

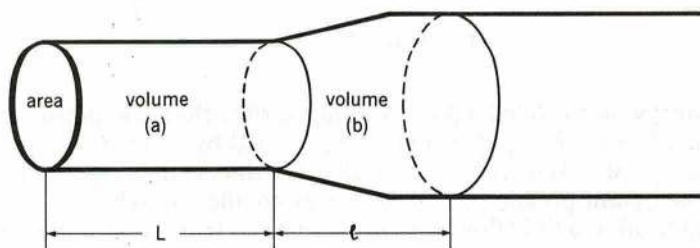


Fig 2.1.4 Divergent duct

as the fluid enters the *larger* cross sectional area it will take up the new shape and the initial volume will now occupy less *length* in the duct. Therefore, in a given time, less distance is travelled and the velocity is *reduced*.

Thus, we conclude that if the mass flow is to remain constant, as it must, an *increase* in duct area must be accompanied by a reduction in flow velocity, and a *decrease* in duct area must bring about an *increase* in velocity; we can express this action as — *velocity varies inversely with changes in duct area*.

Bernoulli's Theorem

13. This theorem can be related to the relationship between *pressure* and *velocity* existing in the air flowing through a duct, such as a jet engine. The theorem states that the total energy per unit mass is constant for a fluid moving inside a duct and that total energy consists mainly of pressure energy and kinetic energy:

- **Pressure energy.** In gas or fluid flow the pressure energy is more often called '*static pressure*' and it can be defined as the pressure that would be felt by a body which was submerged in the medium (gas or fluid) and moving at the same velocity as the medium.
- **Kinetic energy.** This kind of energy is more often called '*dynamic pressure*' and this term is used to define the *extra pressure* created by the movement of the medium. Dynamic pressure is proportional to $\frac{1}{2}$ mass x velocity² (ie $\frac{1}{2}mv^2$).

When the medium (gas or fluid) is moving, the total energy = static pressure + dynamic pressure.

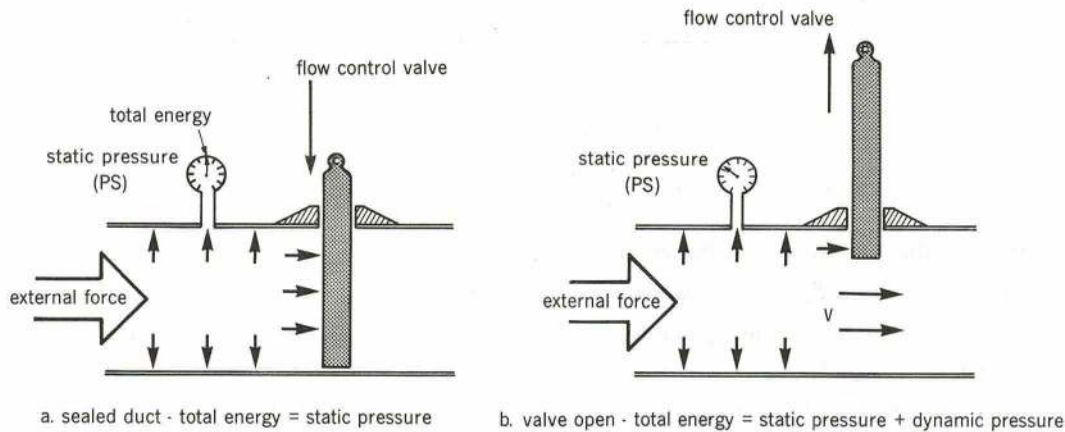


Fig 2.1.5 Static/Dynamic pressure

14. Consider a duct which is filled with an incompressible fluid and pressurized from one end by an external force. The other end of the duct is sealed by a valve which can be opened or closed, and a pressure gauge is fitted into the wall of the duct to indicate the static pressure (PS). With the valve closed, static pressure and total energy are the same (Fig 2.1.5a). However, when the valve is opened to allow a fluid flow, the circumstances change and, although the total energy must remain the same, it now consists of static pressure + dynamic pressure. As the velocity *V* increases, so dynamic pressure *increases* and the static pressure is *reduced* (Fig 2.1.5b).

15. **Total energy.** Total energy can be measured as a ram pressure and is usually called the 'total head' or *pitot* pressure (PT). It is measured by placing a ram tube in the fluid flow. The ram tube must be parallel to the flow with its open end facing the flow (Fig 2.1.6a). A gauge connected into such a tube always records the total head (pitot) pressure regardless of the rate of flow.

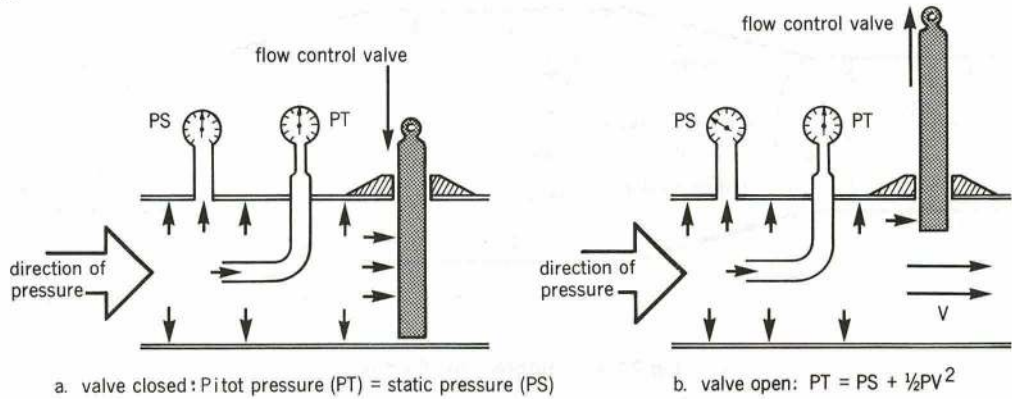


Fig 2.1.6 Pitot pressure/Static pressure

In a situation where there is a no fluid flow, the static pressure (PS) gauge and the total head pressure (PT) gauge will show the same value (Fig 2.1.6a); but, when there is a fluid flow, the total pressure reading remains the same although the static pressure drops (Fig 2.1.6b).

Continuity Equation and Bernoulli's Theorem

16. **Incompressible fluid.** The combined effect of the continuity equation and Bernoulli's theorem produces the effects shown in Fig 2.1.7, when a steady flow of incompressible fluid flows through a duct of varying cross sectional area. This shows:

- Mass flow remains constant as cross-sectional area of duct (and velocity) change.
- Total pressure remains constant, but static pressure (PS) changes as area (and velocity) change.

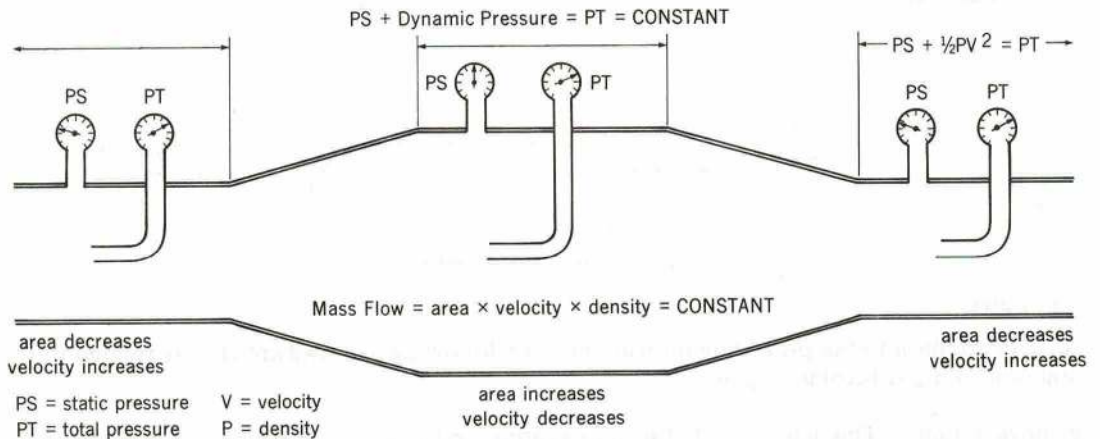


Fig 2.1.7 Incompressible fluid flow

17. **Compressible fluid (atmosphere).** Compressible fluid flow refers to the air flow through a gas turbine engine and, because the air is compressible, flow at subsonic speeds causes a change in the *density* of the air as it progresses through the engine (Fig 2.1.8).

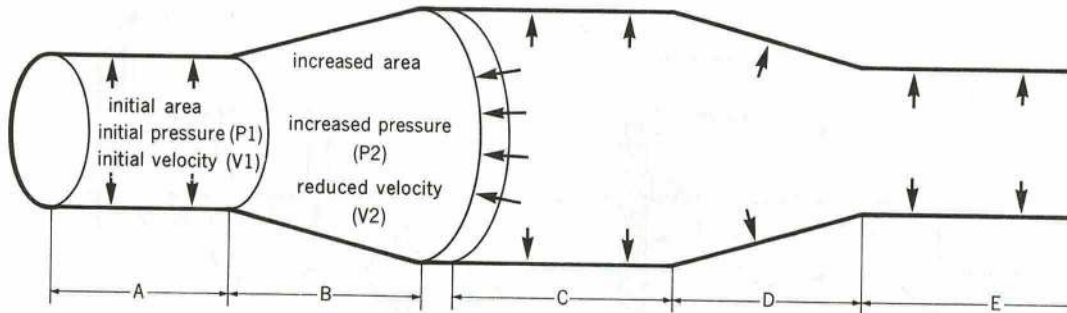


Fig 2.1.8 Compressible fluid flow

The air entering the duct at section A consists of air at pressure (P1) and velocity (V1); then as the air enters the increased area of the duct at B it will spread out to fill the increased area and this will cause the air flow to slow down (continuity equation) and give a change in velocity to V2. The static pressure of the air will increase (Bernoulli's theorem) to become P2 in the wider section of the duct and, because air is compressible, the air density will increase as it is compressed by the rise in pressure in section B of the duct.

18. **Diffuser action.** The flare which increases the area of the duct is known as a diffuser and its shape determines the *rate* of compression and the amount by which the air is compressed. For best results the airflow must remain smooth and, because of this, a most important design feature is the angle of divergence (Fig 2.1.9). When air is compressed by this process it is called *subsonic diffusion* and it is a principle that is used extensively in jet engine design.

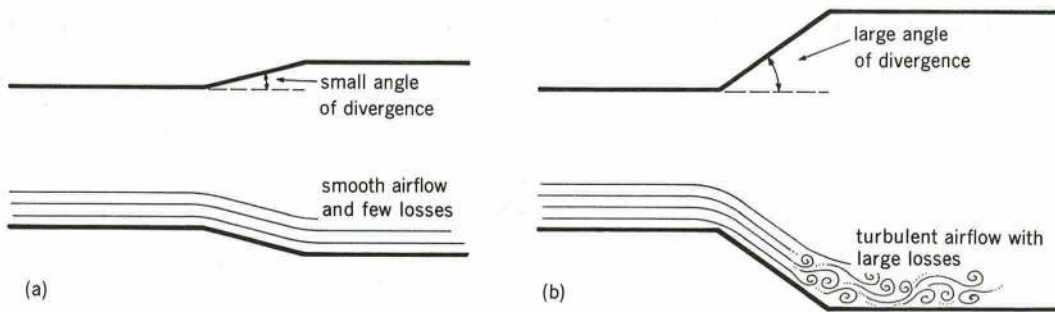


Fig 2.1.9 Angle of divergence

Gas Laws

19. In addition to the preceding information, the following gas laws are closely related to the function of a gas turbine engine:

- **Boyle's Law.** This law is related to temperature and pressure of a gas. It states that if the temperature T remains constant, the volume V of a given mass varies inversely as the pressure P exerted upon it (*ie* $PV = \text{Constant}$).

- **Charles' Law.** This law states that the volume V of a given mass of gas increases by $1/273$ of its volume at 0°C for a rise of 1°C when the pressure P of the gas is kept constant. These laws are now combined in what is called the *ideal gas law*. It gives the relationship:

$$PV = RT \text{ where: } P = \text{pressure}$$

$$V = \text{volume}$$

$$R = \text{a constant}$$

$$T = \text{absolute temperature in K.}$$

The Gas Turbine Engine

20. The gas turbine engine is essentially a heat engine using air as a working fluid to provide thrust. To achieve this, the air passing through the engine is accelerated by heating. This means that the velocity of the air is increased before it is finally emitted in the form of a high velocity jet. In the following paragraphs, we shall see how the various theories and laws are applied to the aero gas turbine. Let us first consider the effect of adding heat to the gas flow.

21. **The effect of adding heat at constant volume.** If a mass of air is heated and its volume cannot change there will be an increase of pressure to accompany the increase in temperature ($PV = RT$). This condition exists in the cylinder of a piston engine.

22. **The effect of adding heat at constant pressure.** If heat is added to a mass of air which is not confined in volume (*eg* not in an enclosed cylinder), its temperature will rise and there will be a related increase in the volume of the gas ($PV = RT$). The pressure will remain approximately constant and this is what happens in the combustion area of a gas turbine engine.

23. **Effects of a convergent duct.** When the area of a duct is reduced this is called *convergent*, and the inlet area is greater than the area at the exit. When air flows through such a duct, it increases in velocity and the static pressure is reduced. In other words, an increase in velocity is accompanied by a drop in pressure; there is also a drop in temperature. How the convergent duct is applied to gas turbines is shown in Fig 2.1.10.

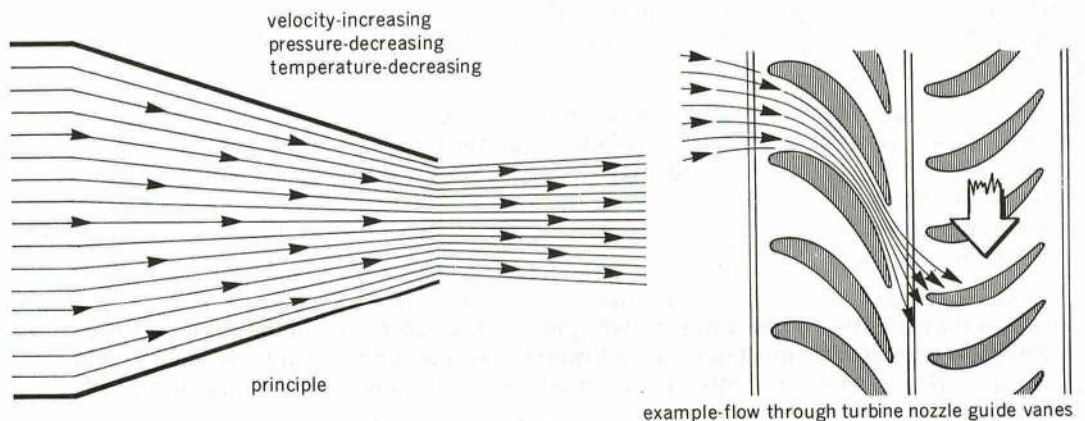


Fig 2.1.10 Convergent duct

24. **Divergent ducts** (see also para 18 and Fig 2.1.9). The divergent duct is used at various points in a gas turbine where velocity is to be *reduced* and pressure *increased*; there is also an increase in temperature. A typical position for a divergent duct is shown in Fig 2.1.11.

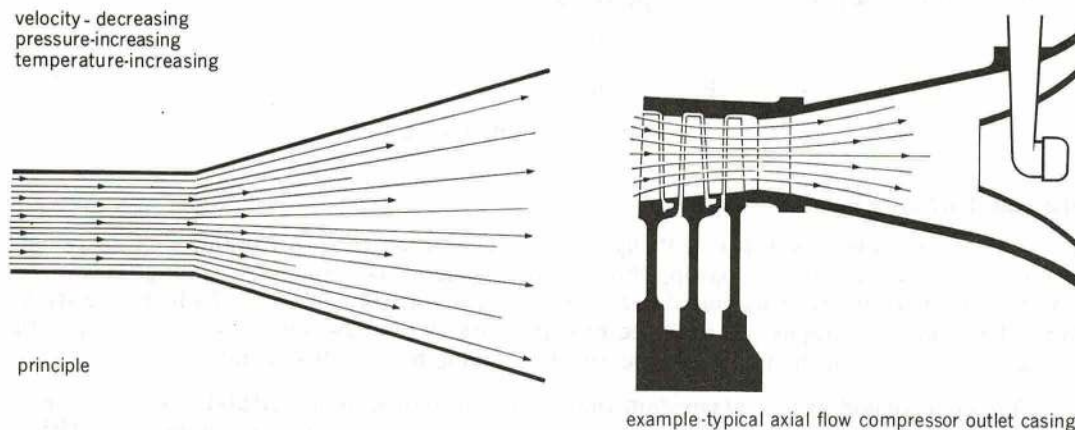


Fig 2.1.11 Divergent duct

Later, we shall see the various changes that occur in velocity and pressure during the passage of an air stream through practical gas turbine engines.

The Working Cycle

25. The working cycle of a gas turbine engine is similar to that of the four stroke piston engine but, in the gas turbine engine, combustion occurs at an almost *constant pressure* whilst, in the piston engine, it occurs at a *constant volume*. Both engine cycles are illustrated at Fig 2.1.12. In the piston engine, the cycle is intermittent, the piston being the component concerned in all four strokes. In contrast, the gas turbine engine has a *continuous* cycle, with a separate compressor, combustion system, turbine, and exhaust system. The continuous cycle, and the absence of reciprocation parts, give a smoother running engine, and enable more energy to be released for a given engine size.

26. It has already been stated that, in the gas turbine engine, combustion occurs at a *constant pressure* with a consequent *increase* in volume; thus, the high peak pressures which occur during combustion in a piston engine are avoided. This allows the use of lightweight, fabricated combustion chambers and low octane fuels in gas turbine engines. On the other hand, the higher flame temperatures require the use of special materials to ensure long life for gas turbine combustion chambers.

27. Since the gas turbine is a heat engine, the higher the temperature of combustion, the greater is the expansion of the gases, and the greater is the efficiency of the engine. However, the combustion temperature must never be allowed to exceed a certain value — namely, that which gives the turbine gas entry temperature for which the turbine assembly was designed.

28. The working cycle upon which the gas turbine engine functions is as follows:

- The air entering the engine is *compressed*.
- Heat is added to the air by burning fuel at a constant pressure, thereby considerably *increasing the volume* of the resulting gas.

- The gases resulting from combustion expand through the turbine, which converts some of the energy in the expanding gases into mechanical energy to drive the compressor.
- The remainder of the expanding gases are propelled through the turbine and jet pipe back to the atmosphere where they provide the propulsive jet.

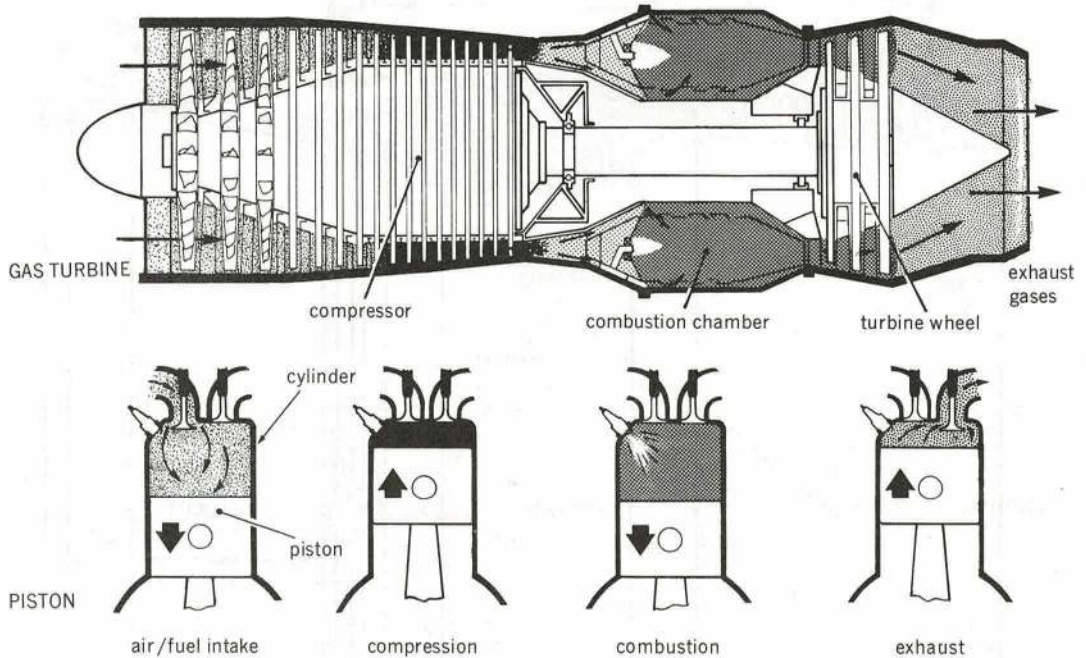


Fig 2.1.12 The working cycle

29. There are three main stages in the engine working cycle during which the changes discussed in para 16 occur:

- **During compression.** Work is done on the air. This *increases* the pressure and temperature and *decreases* the volume of air.
- **During combustion.** Fuel is added to the air and then burnt. This *increases* the temperature and volume of the gas, whilst the pressure remains almost *constant* (the latter being arranged by design in a gas turbine engine).
- **During expansion.** Energy is taken from the gas stream to drive the compressor; this *decreases* the temperature and pressure, whilst the volume *increases*. The rapidly expanding gases are also propelled through the turbine and jet pipe to give a final momentum which is much greater than the initial momentum; it is this *change in momentum* which produces the propulsive jet.

30. **Changes in temperature and pressure.** The changes in temperature and pressure of the gases through a gas turbine engine are illustrated at Fig 2.1.13. The efficiency with which these changes are made will determine to what extent the desired relations between pressure, volume, and temperature are obtained. The more efficient the compressor, the higher is the pressure generated for a given work input — *ie* for a given temperature rise of the gas. Conversely, the more efficiently the turbine uses the expanding gas, the greater is the output of work for a given temperature drop in gas.

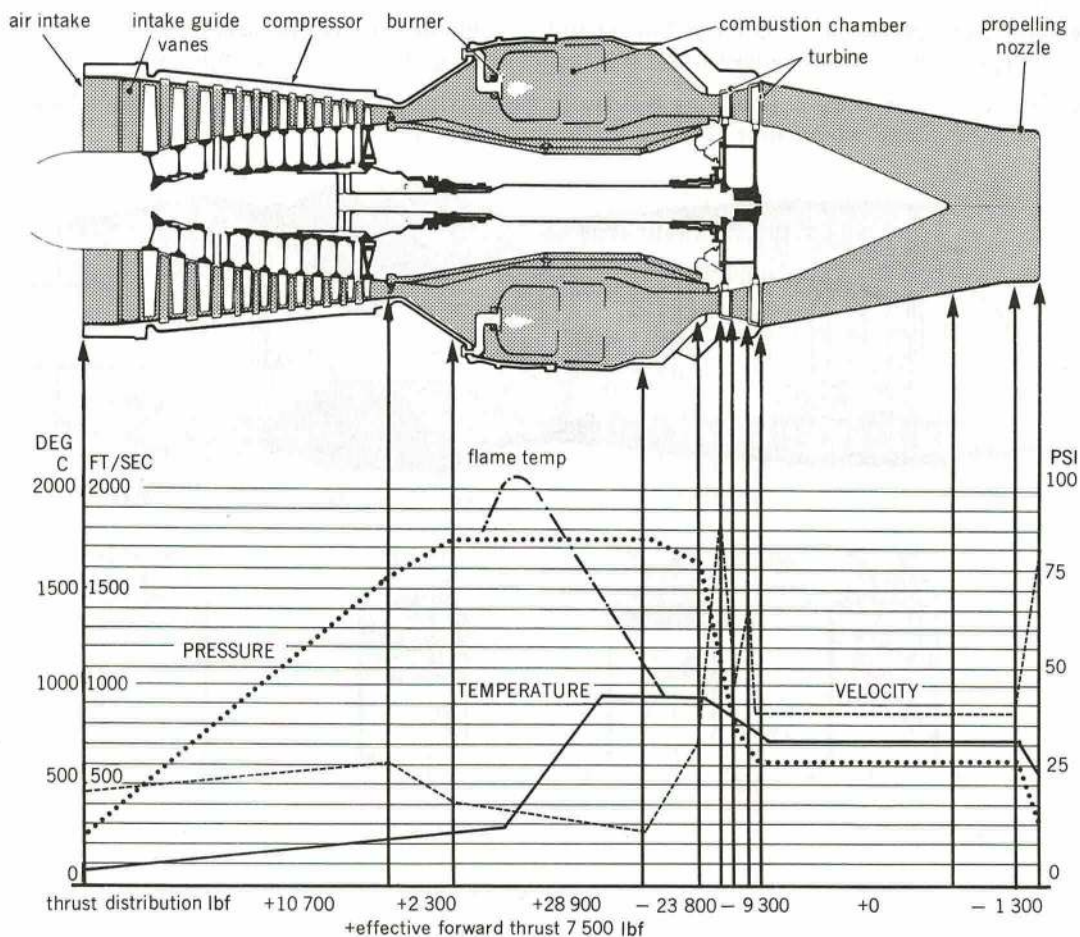


Fig 2.1.13 Changes in temperature, pressure, and velocity

31. **Changes in velocity and pressure.** During the passage of the air (gas) through the engine, aerodynamic and energy requirements demand changes in its velocity and pressure. For example, during compression, a rise in the pressure of the air is required with no increase in its velocity. After the air has been heated, and its internal energy increased by combustion, an increase in the velocity of the gases is necessary to cause the turbine to rotate. Also, at the propelling nozzle, a high velocity is required, for it is the *change in momentum* of the air that provides the thrust on the aircraft. Local *decelerations* of gas flow are also required — for example, in the combustion chambers to provide a low velocity zone for the flame.

32. **How the changes are obtained.** The various changes in temperature, velocity, and pressure are effected by means of the ducts through which the air (gas) passes on its way through the engine. When a conversion from kinetic energy to pressure energy is required, the ducts are *divergent* in shape. Conversely, when it is required to convert the energy stored in the combustion gases to velocity, a *convergent* nozzle is used. The design of the passages and nozzles is of great importance, for upon their good design depends the efficiency with which the energy changes are effected. Any interference with the smooth flow of gases creates a loss in efficiency and could result in component failure because of vibration caused by eddies or turbulence of the gas flow.

Propulsive Efficiency

33. Propulsive efficiency is defined as the ratio of the power available to do useful work in propelling a body to the power supplied — ie:

$$\frac{\text{Power out}}{\text{Power in}} \text{ (expressed as a percentage).}$$

It is always less than 100% because of losses in the system. A propeller-driven aircraft, using a given power, varies its propulsive efficiency with forward speed, and it is also limited by altitude and by blade tip speed. A turbo-jet aircraft, for a given thrust, increases its efficiency with forward speed and the efficiency is not affected by altitude or blade tip speed. The efficiency of each type of engine is illustrated graphically at Fig 2.1.14.

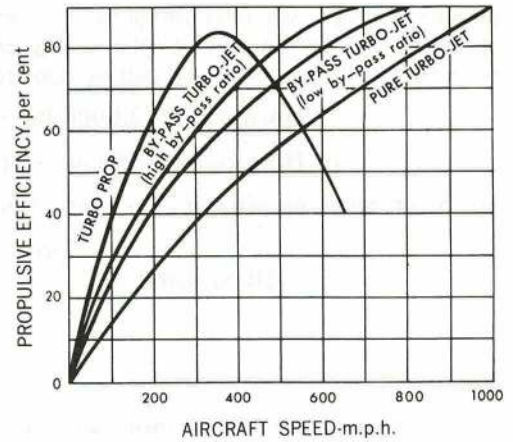


Fig 2.1.14 Propulsive efficiency

34. Fig 2.1.14 shows that the propeller-driven aircraft has a maximum speed of about 600 mph and gives a better propulsive efficiency than the turbo-jet engine up to approximately 500 mph, the efficiency falling off rapidly after about 350 mph. The turbo-jet gives poor efficiency at low aircraft speeds. However, the efficiency steadily improves with aircraft speed and does not fall off with altitude as is the case with a propeller-driven aircraft. Consequently, as the drag of an aircraft lessens with altitude, giving a higher speed from the same thrust and fuel consumption, the turbo-jet aircraft can operate more efficiently at higher speeds and at higher altitudes than the propeller-driven aircraft.

Thrust

35. The thrust derived from a turbo-jet engine is expressed as follows:

$$T = m (V_o - V_i), \text{ where } T = \text{thrust}$$

m = mass air flow

V_o = Velocity of the gases at the nozzle outlet

V_i = Velocity of the air at the intake.

From this expression, it is seen that the amount of thrust obtained depends upon the mass flow passing through the engine and the *difference* between the inlet and outlet gas velocities (momentum). Any rise in mass flow, or a wider divergence in speed, will need a greater force to accelerate the gas and must give a greater reactive thrust.

36. The mass flow through a *static* engine will vary with the speed of the compressor and will be limited by the maximum rev/min of the engine. The velocity difference ($V_o - V_i$) will vary with the heat applied and will be limited by the maximum temperature the engine components can withstand. As an engine *moves forward* with the aircraft, the thrust will fall off because, although the outlet gas velocity V_o remains the same, the intake velocity V_i rises, *so reducing the velocity difference*. This drop in thrust continues as the aircraft speed increases until there is an *increase* in mass flow at the intake. This is known as the '*ram effect*'.

37. **The relation between thrust and power.** Thrust is not power; it is a force, measured in pounds force (lbf); power, on the other hand, is the rate of doing work and is measured in lbf × ft/sec. The power of a turbo-jet engine installed in an aircraft can be calculated only if the

aircraft is *moving*, when the thrust will be overcoming drag (lbf) and moving the aircraft at a certain speed (ft/sec). Thus, the power of a *static* jet engine is *nil*, but the power developed when the aircraft is moving at a constant speed can be defined as:

$$\begin{aligned} \text{Horsepower (33 000 lbf} \times \text{ft/min)} &= \text{Drag (lbf)} \times \text{A/C speed (ft/min).} \\ \text{or Horsepower (550 lbf} \times \text{ft/sec)} &= \text{Drag (lbf)} \times \text{A/C speed (ft/sec).} \end{aligned}$$

However, when an aircraft is moving, thrust equals drag, so that:

$$\text{Horsepower} = \frac{\text{Thrust (lbf)} \times \text{A/C speed (ft/sec)}}{550}$$

Note.

SI metric terms are coming more into use, particularly for modern aircraft. Thus, metres are being quoted instead of feet, kilograms instead of pounds, Newtons instead of pounds force, watts for the unit of power instead of lbf × ft/sec, and so on. For example, the static thrust of a jet engine installed in one modern aircraft is quoted as 23·8 kilo-Newtons (equivalent to 5340 lbf).

Thrust Forces in a Typical Engine

38. Taking an *axial flow type engine* as an example, we shall now follow the thrust forces from inlet to exhaust, *ie* air intake to propelling nozzle, bearing in mind the purpose of the convergent and divergent ducts throughout the engine. These forces are, in effect, gas loads resulting from the pressure and momentum changes of the gas stream reacting on the engine structure and on the rotating components. They are, in some cases, *forward* propelling forces, and in others opposing or *rearward* forces. The amount that the sum of the forward forces exceeds the sum of the rearward forces is known as the *rated thrust* of the engine.

39. If you refer to Fig 2.1.15 you will see that air is induced into the engine and is compressed. The pressure rise produces a large reactive force in a *forward* direction. The air passes through a diffuser — which is another device to convert kinetic energy to pressure energy — and a small reactive force is also exerted in a *forward* direction. The air then passes into the combustion chamber, where it is heated and, in the subsequent expansion, large *forward* forces are exerted on the combustion chamber head and walls.

40. When the expanding gases leave the combustion chambers, they force their way through the nozzle guide vanes where they are accelerated and deflected on to the turbine blades. Due to the acceleration and deflection, together with the subsequent straightening of the gas flow as it enters the jet pipe, considerable drag results. The nozzle guide vanes and the turbine blades are subjected to large *rearward* forces which are also illustrated at Fig 2.1.15. As the gas flow passes through the exhaust system, small *forward* forces may act on the inner cone or bullet, but generally, only *rearward* forces are produced and these are due to the drag of the gas flow at the propelling nozzle.

41. You will be aware that during the passage of the air through the engine, changes in its velocity and pressure occur. For instance, where a conversion from velocity (kinetic) energy to pressure energy is required, the passages are divergent in shape, similar to that used in the compressor diffuser already mentioned in para 24. Conversely, where it is required to convert the energy stored in the combustion gases to velocity, a convergent passage or nozzle, similar to that used in the turbine, is employed. When the conversion is to velocity energy, drag loads or *rearward* forces are produced; where the conversion is to pressure energy, *forward* forces are produced.

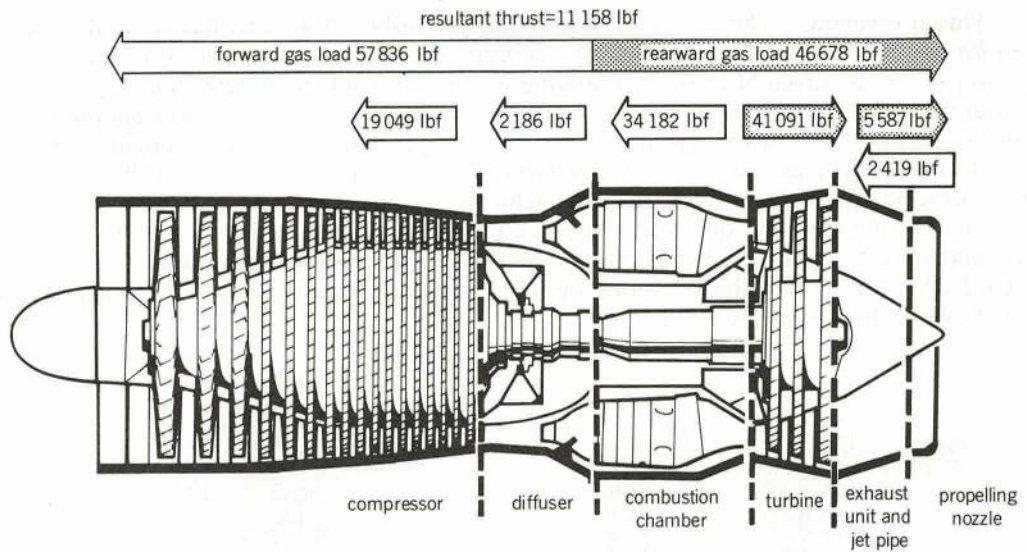


Fig 2.1.15 Thrust forces in an axial flow type engine

Variations in Application of Thrust

42. **Thrust augmentation.** The maximum basic thrust obtained from a turbo-jet engine is dependent on the limiting temperature of the turbine. However, the basic thrust of the engine can be augmented by after-burning or re-heat. With re-heat, fuel is injected into the airstream between the turbine and the jet pipe propelling nozzle, utilizing the unburned oxygen in the exhaust gas to support combustion. The resultant increase in the temperature of the exhaust gas gives an increased velocity to the jet leaving the propelling nozzle and, therefore, increases the engine thrust. The principles of after-burning are illustrated at Fig 2.1.16.

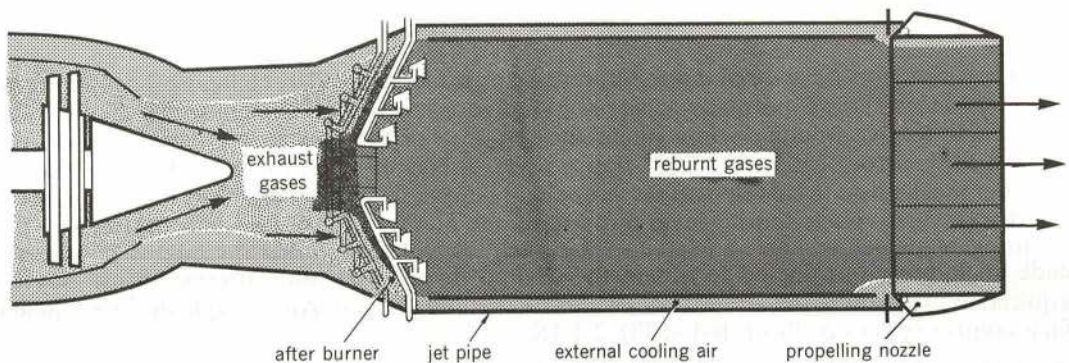


Fig 2.1.16 Reheat principles

43. **Thrust reversal.** The use of high-performance turbo-jet aircraft has created an urgent need for new methods of slowing down the aircraft quickly on landing. This is required so that the aircraft can be brought to rest on landing within the available length of existing runways without the excessive use of wheel brakes or the use of braking parachutes. The simplest way of achieving this is to *reverse the direction* of the exhaust gas stream, thus using engine power as a deceleration force. This system can also be used to reduce speed in flight, thus allowing a rapid rate of descent. Basically, reverse thrust is achieved by directing the gas stream in a *forward* direction. On the selection of reverse thrust, pneumatically operated doors rotate to uncover ducts and close the normal gas stream exit. Deflector vanes then direct the gas stream in the forward direction so that the jet thrust opposes the aircraft motion. Two methods of thrust reversal are indicated at Fig 2.1.17.

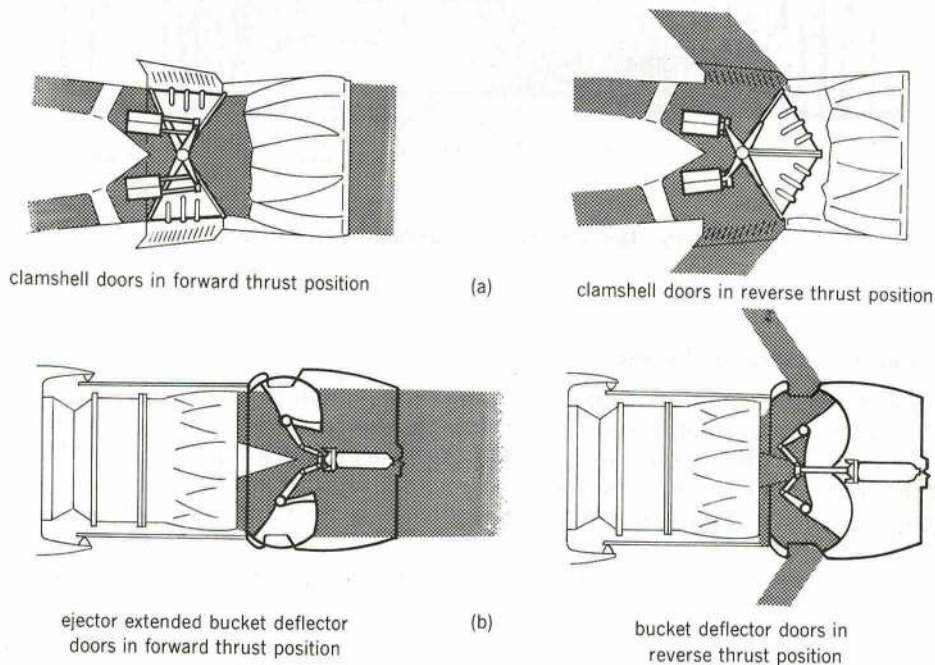


Fig 2.1.17 Thrust reversal

44. On turbo *propeller-powered* aircraft, reverse thrust is obtained by changing the pitch of the *propeller* blades. This is normally achieved by a hydro-mechanical system which changes the blade angle to give braking action under the response of the power or throttle lever in the aircraft. Movement of the throttle or power lever directs oil from the control system to the propeller mechanism to first fine off the propeller blade angle to zero, and then to coarsen off in negative (reverse) pitch. During lever movement, the fuel flow to the engine is trimmed by the throttle valve which is interconnected to the pitch control unit so that the engine power and blade angle are co-ordinated to obtain the desired thrust. Maximum reverse thrust may be required to manoeuvre the aircraft backwards after rolling to rest. An example of the propeller pitch control system is illustrated at Fig 2.1.18.

45. **Lift thrust (deflection and vectoring).** Vertical take-off and landing (VTOL) or short take-off and landing (STOL) are desirable characteristics for any type of aircraft, provided that the normal flight performance is not unreasonably impaired. Until the introduction of gas turbine engines for aircraft propulsion, this was not possible and, in fact, VTOL could only be achieved by a helicopter. Early in 1941 however, the late Dr A A Griffiths, then Rolls-Royce

Chief Scientist, envisaged the use of a jet engine to provide lift thrust by changing the direction of the propulsive jet. In 1947 a lightweight jet engine was designed by Rolls-Royce primarily for missiles and, from this engine, the first lift jet was developed for V/STOL application.

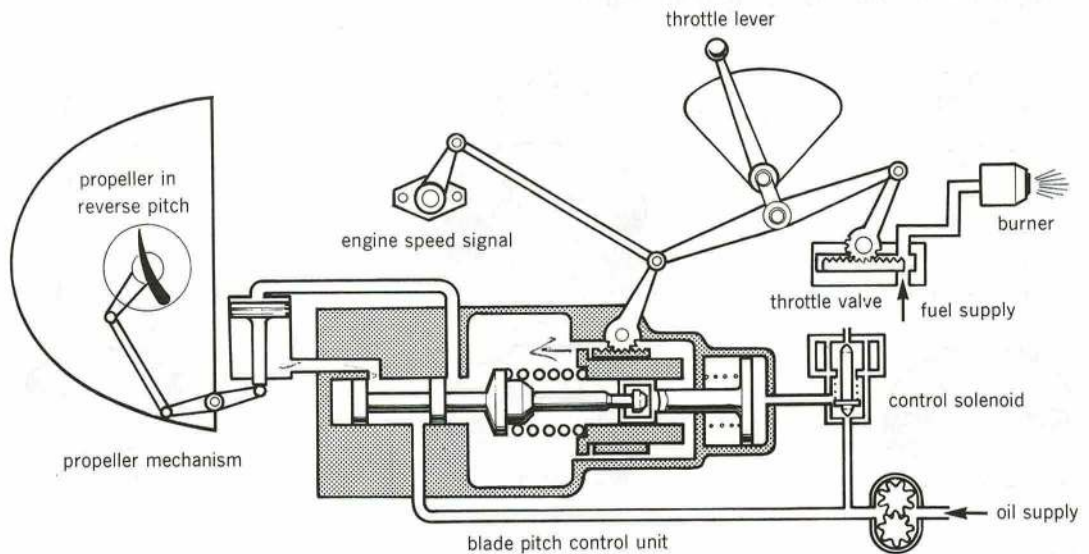


Fig 2.1.18 Use of a propeller for thrust reversal

46. **Methods of obtaining jet lift.** There are several ways in which jet lift can be obtained:

- Deflecting the exhaust gases (lift/cruise engine).
- Using specially designed lift jets or driving a lift fan from the engine.
- By mechanical swivelling of the engine.
- By using vectoring nozzles to vary the thrust angle of the exhaust gases.
- By installing additional lift fans in the wings or fuselage of the aircraft.

47. The various methods outlined above are described briefly in the following sub-paragraphs:

a. **Lift-cruise engine.** With this method, the engine is primarily for *forward* propulsion, but the thrust is capable of being 'deflected' by a 'switch-in' deflector and nozzle system for lifting purposes. An *additional* lift system will normally be required for VTOL. The deflection is achieved by using a device known as a switch-in deflector or diverter, to redirect the exhaust gases; or a deflector system consisting of two or four swivelling nozzles. The diverter consists of a heavily-reinforced door which lies flush with the jet pipe wall when the engine is operating in forward thrust. When deflected thrust is selected, the door moves to blank off the conventional propelling nozzle, thus directing the exhaust gas and so enabling intermediate braking and lift positions to be selected. The deflector door causes a negligible loss in performance, since it lies flush with the wall of the jet pipe in the normal forward thrust position. The four-nozzle deflector system would be used on a *by-pass* engine, the exhaust gases being divided and ducted through two nozzles and the by-pass air through similar nozzles. Each can be rotated through approximately 150° . During forward flight, both the twin and four nozzle systems incur a performance loss due to the exhaust gases being continuously deflected through the nozzles. An illustration of the types of thrust deflector nozzles, together with an illustration of the 'switch-in' deflector system, is shown in Fig 2.1.19.

b. **Lift-jet and lift-turbofan.** The lift-jet or lift-turbofan engine is designed primarily to produce vertical thrust during the take-off and landing phase of a V/STOL aircraft. The engine is mounted vertically and must be lightweight and simple in design because it is used in conjunction with other propulsion units.

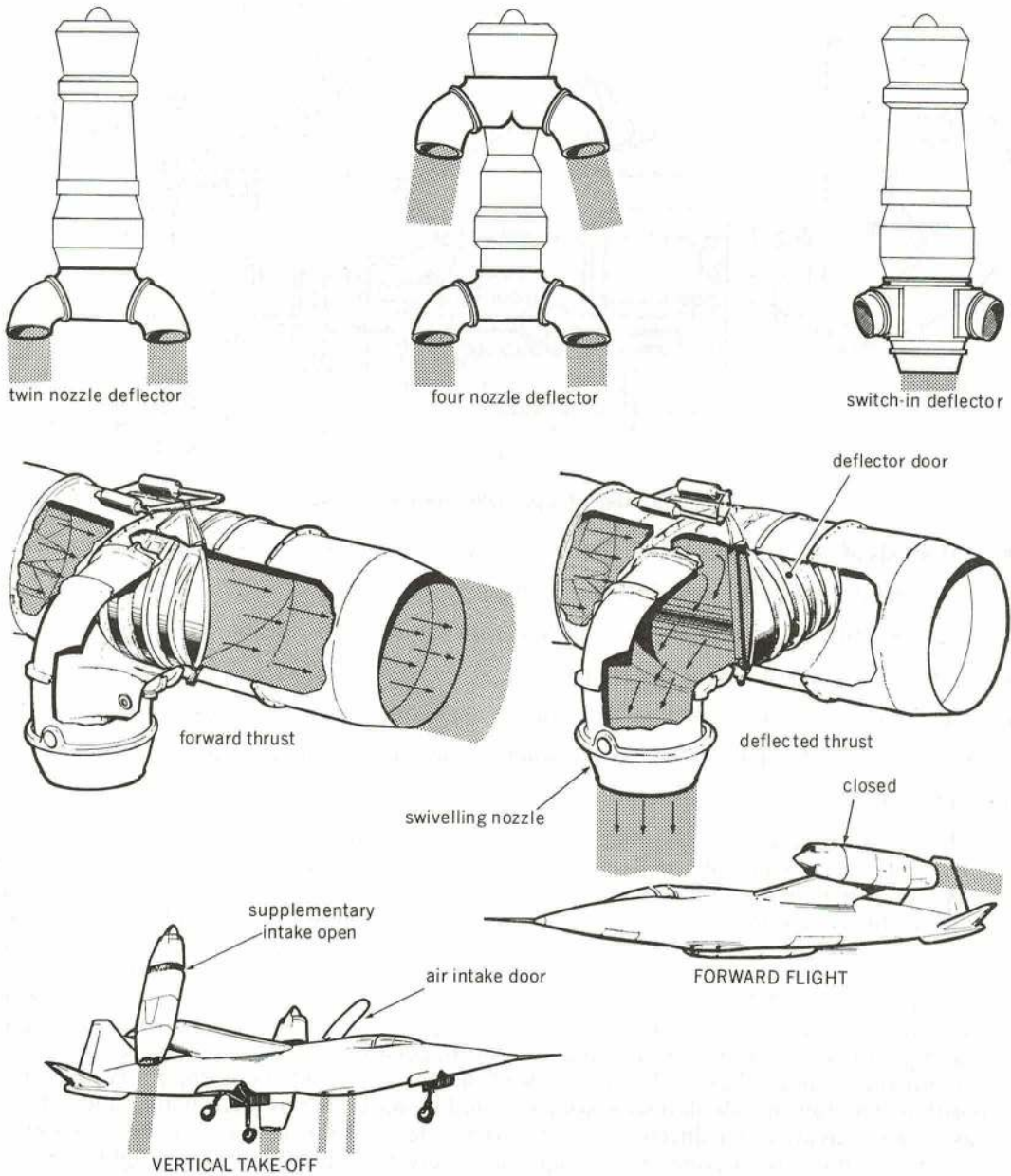


Fig 2.1.19 Thrust deflector nozzles and swivelling engines

c. **Swivelling engines or pods.** This method consists of having propulsion engines which can be *mechanically* swivelled through approximately 110° to provide vectored thrust. In addition, one or more lift-jets or lift turbofans may be installed to provide supplementary lift-thrust during the take-off, transition and landing phases; these additional units are also capable of deflecting the thrust. An example of obtaining jet lift by swivelling the propulsion engines is also indicated in Fig 2.1.19.

d. **Lift/thrust engine.** With this method, the engine is designed to give both vertical thrust (lift) and forward propulsion. The exhaust gases are angled by rotating vectoring nozzles to provide forward, vertical or reverse thrust for V/STOL operating. A four-nozzle or a twin-nozzle deflector system with swivelling nozzles may be used to deflect or vector the exhaust in a similar manner to that of the lift/cruise engine (Fig 2.1.19 refers).

e. **Lift-fan.** The lift-fan, or ducted fan, principle of achieving VTOL consists of a gas turbine engine, or engines, driving fans mounted in the wings or fuselage. The fans are remote from the power unit(s) and are driven mechanically or by air or gas. They operate with a large airflow at low velocity and produce a high propulsive efficiency. This method would appear suitable for low-speed aircraft with extended hover requirements.

Gas Turbine Development

48. There has been a great deal of development on gas turbine engines since the Whittle gas turbine engine first appeared. This engine was fitted with a single-sided centrifugal compressor, which had a low compression ratio (about 4:1). To increase this, it would have been necessary to increase the diameter of the compressor and, therefore, the frontal area. This would, in turn, have increased the weight considerably. Although the two-sided centrifugal compressor was an improvement, similar penalties could not be avoided. The demand for greater power output, efficiency and flexibility led to further improvements in design, particularly by Rolls-Royce with the axial flow, single and twin spool type compressors, the turbo-fan engine (including the RB series), up to the present RB 211 engine.

49. Although we shall be discussing the components of the turbine engine in Chapter 2 of this Section, it can be stated that all gas turbine engines have an intake assembly, a compressor assembly, a combustion assembly, a turbine assembly and an exhaust assembly. Although the basic principles of each component remain the same, the path of the air through the engine varies according to the design. A straight flow system is usual as it provides an engine with a small frontal area and is suitable for use of by-pass and ducted fan principles. We shall now introduce common types of gas turbine engine.

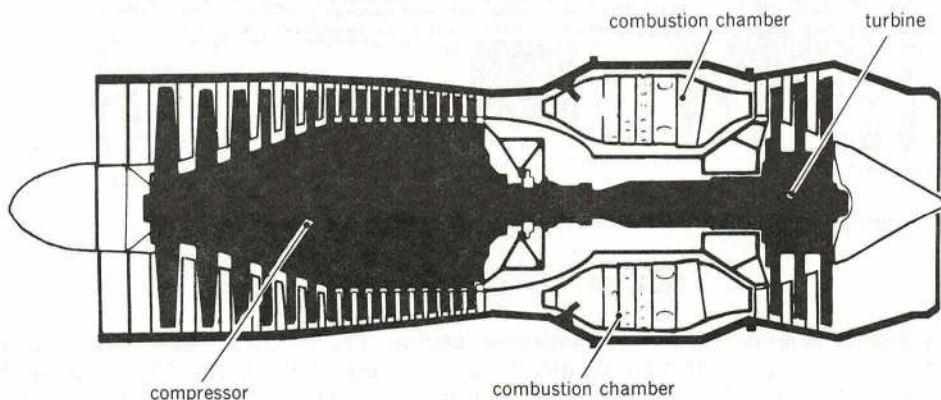


Fig 2.1.20 Single spool axial flow engine

a. **Single spool axial flow compressor engine.** This engine replaced the centrifugal type already mentioned because of the disadvantages of a low compression ratio, high specific fuel consumption and large frontal area. The axial flow engine with its various stages of compression in the same casing (the Avon Mark 1 engine made by Rolls-Royce had 12 stages of compression) gave higher compression ratios and a considerable improvement in performance and lower fuel consumption, as well as a smaller frontal area. This engine is illustrated at Fig 2.1.20.

b. **Twin spool axial flow compressor engine.** This engine has a compounded compressor assembly in which the compressors are driven by separate turbines, through co-axial shafts; the only connection between the two rotating assemblies is the gas stream. This allows each half of the compressor to be run at its most efficient speed. The low pressure assembly rotates at a lower rev/min and accepts air from the intake and passes it to the high pressure drum, resulting in higher pressures and increased stability. The advantages to be gained are:

- Higher compression ratio.
- Better airflow stability.
- Lower specific fuel consumption.
- Greater flexibility in operation.
- Reduction in the possibility of 'stall' and 'surge'.
- More rapid acceleration possible.
- Easier starting.
- Greater power at altitude.

The twin spool axial flow compressor engine is illustrated at Fig 2.1.21 and is suitable for the turbo-propeller combination.

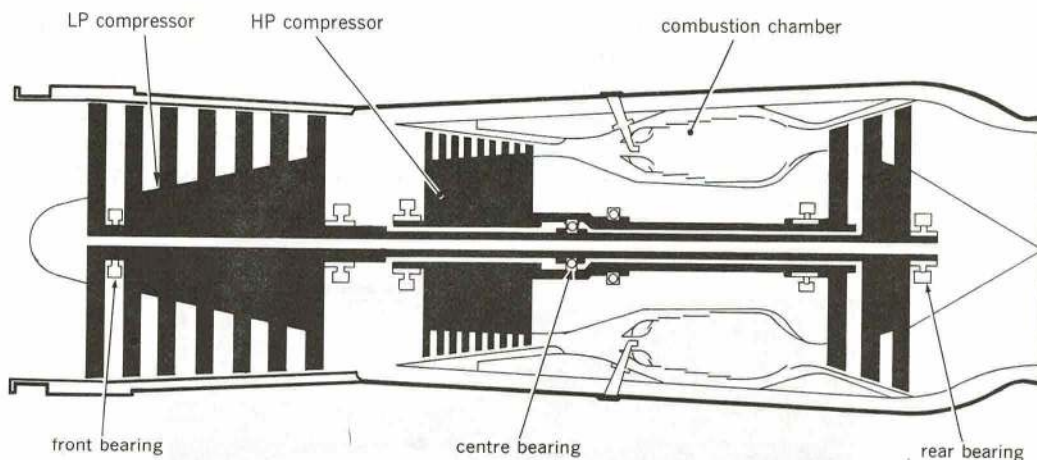


Fig 2.1.21 Twin spool axial flow engine

c. **By-pass twin spool axial flow compressor engine.** The by-pass engine was developed to permit the use of higher turbine temperatures to obtain higher thrust. About half of the low pressure air is passed through the annular by-pass duct surrounding the high pressure compressor assembly and combustion system to rejoin the hot gas stream *after* the turbine. This results in higher combined flow of cooler, slower gases to atmosphere. The advantages to

be gained in addition to those mentioned at para 37b are:

- Higher propulsive efficiency.
- High thermal efficiency.
- Better power/weight ratio. (Smaller, lighter high pressure compressor, combustion system and turbine).
- Reduced fire risk and heat loss.
- Reduced noise level.
- Greater thrust yield from reheat.

The by-pass twin spool axial flow compressor engine is illustrated at Fig 2.1.22a.

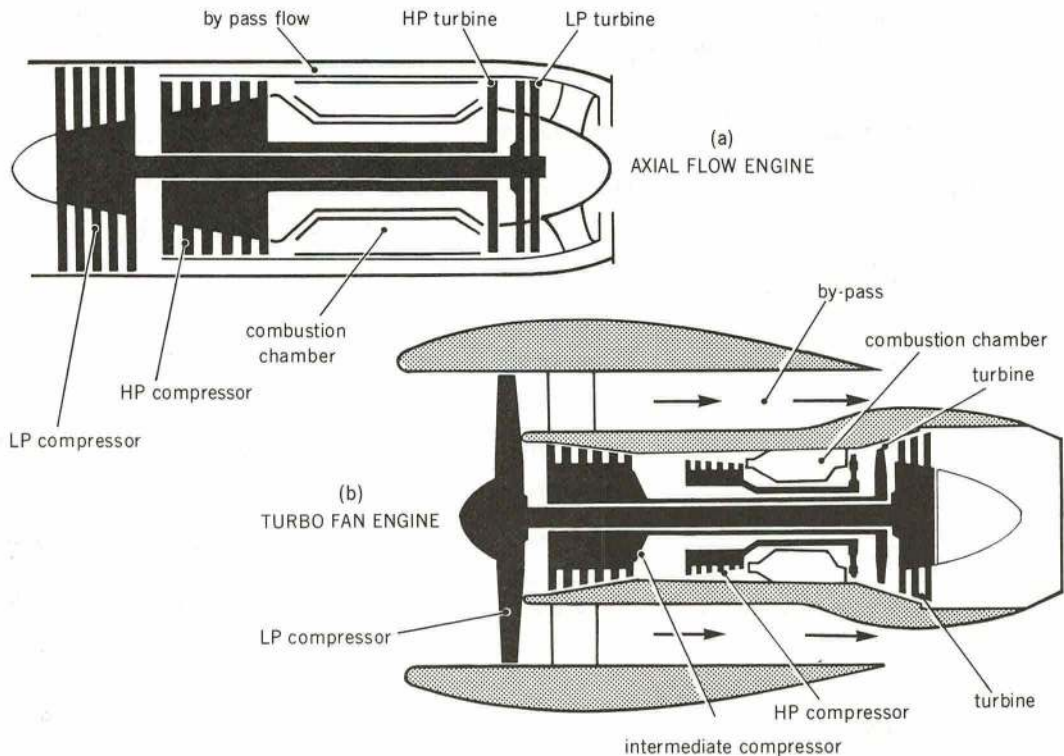


Fig 2.1.22 By pass axial flow and turbo fan engines

d. **Turbo-fan engine.** This is a high-ratio by-pass engine with a large diameter front fan driven by the low pressure turbine, and operating within a cowl to provide a separate low velocity, high-mass air flow; the air is ducted to flow concentrically with the hot jet and does not mix in an exhaust unit as in the medium by-pass engine. The front fan may have more than one stage and the by-pass ratio is 3:1 or more. As the high pressure compressor is required to pass only a proportion of the total mass flow, both the compressor and combustion system are of smaller and lighter construction than those engines already mentioned at *b* and *c*. An illustration of a turbo-fan engine is at Fig 2.1.22b.

50. Some turbo-fans have three concentric shafts with an *intermediate compressor* (as fitted to the Rolls-Royce RB178-51, the Rolls-Royce/Turbomeca RB172 Adour, the Rolls-Royce RB203-01 (Trent) and the Rolls-Royce RB211). The advantages to be gained are as for the by-pass engine mentioned at para 37c, but with greater propulsive efficiency and much lower specific fuel consumption (SPC) due to the large mass flow and lower jet velocities.

Conclusion

51. We have now discussed briefly the principles of jet propulsion, the working cycle and some of the gas laws and terminology which will be used throughout further Chapters in this Section. We have also introduced the various uses of thrust as a propulsive force and some of the modern gas turbine engines.

52. The Whittle engine formed the basis of the modern gas turbine engine. Since its inception, it has been developed (mainly by Rolls-Royce) to provide some well-known engines, fitted into the aircraft shown in the following table.

Name of Engine	Type of Engine	Aircraft
Derwent	Turbo-jet	Meteor
Avon	Turbo-jet	Hunter, Canberra, Lightning
Olympus	Turbo-jet	Concorde
Dart	Turbo-prop	HS 748
Proteus	Turbo-prop	Brittania
Spey	Turbo-fan	Trident, Phantom
Conway	Turbo-fan	VC 10, Victor
Pegasus	Turbo-fan	Harrier
Adour	Turbo-fan	Jaguar

The *turbo-shaft* type of engine is fitted to Helicopters and marine craft (eg Gnome).

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