PART 1 : SECTION 3

CHAPTER 2

COMPRESSORS

Introduction

1. Two types of compressors are used in gas turbines, one in which the flow of air is radial (outwards from the centre), and the other in which it is axial (parallel to the compressor shaft). The radial compressor is similar to the supercharger in a piston engine, except that it is larger, to deal with up to 100 lb. (1,250 cu. ft.) of air per second. The radial type is termed a centrifugal compressor, and the axial type is known as an axial compressor. Either type, or a combination of both, may be used in gas-turbine engines, and each has its advantages and disadvantages.

2. Compressor design is mainly an aerodynamic problem, some of the principal factors affecting the performance being the aerofoil section of the blades, the blade pitch angles, and the length/chord ratio of the blades. Another important detail is the clearance between the blade tips and the shroud around them. Compressibility effects within the compressor can have a marked effect on the performance.

3. A compressor must satisfy a number of requirements to realize maximum efficiency :—

(*a*) It must provide the required pressure rise.

(*b*) Compression must be effected with the least possible loss, as the greater the loss the greater the power absorbed from the turbine.

(*c*) It must be aerodynamically stable over the operating range of r.p.m.

(*d*) The tip speed of the impeller should not approach too closely to sonic speed, a speed of ·9M at any point on the radius being preferable.

4. Compressor design is in most engines a compromise between high performance over a narrow band of r.p.m. or moderate performance over a wide band of r.p.m. Consequently, although it is possible for the compressor to be designed so that very high efficiency is obtained at the highest power, any deviation from the design conditions may cause serious changes in the aerodynamic flow conditions and so a loss of efficiency and unstable conditions within the engine. As the flow varies with operating conditions, it is usual to compromise and design for a lower efficiency, giving greater flexibility of performance and the retention of the highest possible performance over a wider range of r.p.m.

Centrifugal Compressors

5. The single-stage centrifugal compressor unit consists of three main components: the compressor casing, which embodies the air inlet guide vanes and outlet ports, the compressor (sometimes called the *impeller*), and the diffuser. The main features of this unit are briefly :—

(*a*) For a given useful capacity and pressure ratio it can be made comparatively small in size and weight.

(*b*) As the motion is purely rotary, the impeller can be accurately balanced.

(*c*) A reasonable efficiency can be maintained over a substantial range of operating conditions.

(*d*) It is very robust.

(*e*) It is relatively simple to manufacture.

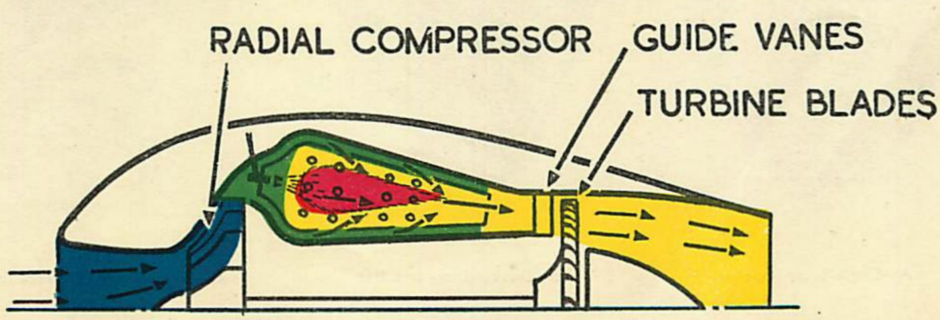

Fig. 1. Effect of Compressor Type on the Shape of the Engine.

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6. **Airflow.** Air enters the air intake at atmospheric pressure and temperature, passing into the eye (centre) of the impeller, which is designed to admit the air without excessive velocity. The air is picked up by the rotating vanes of the impeller and, owing to centrifugal force and depending on the rotational speed, leaves the periphery of the impeller at approximately right angles to its entry at an increased velocity. On leaving the impeller-vane passages, the air acquires, in addition to its radial velocity, a tangential velocity which represents about half the total energy acquired during its passage through the impeller. The air then passes through the diffuser where the velocity energy is converted to pressure energy, so that the pressure is increased and the velocity decreased. Work is done by the compressor in compressing the air, and, since the process of compression involves adiabatic heating, a rise in temperature results.

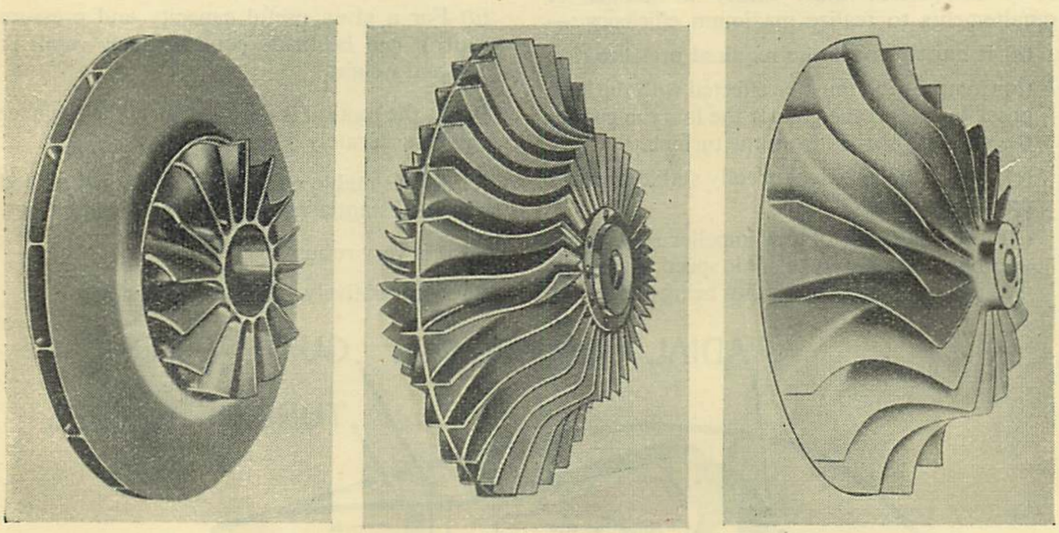
7. Apart from losses, the temperature rise across the compressor depends on the amount of work done, and this in turn depends broadly on the tip velocity of the impeller and the total air inlet temperature. The usual centrifugal compressors have a pressure ratio of approximately 4·5 to 1 with an adiabatic efficiency in the region of 80%. It must be appreciated that with ideal compression there are no losses, but, as with most other practical machines, there are losses due to friction, turbulence, and shock, and these increase with the rate of flow through the impeller. Consequently the effective pressure rise is reduced, and a constant pressure ratio with varying flow is not obtained for a given tip speed. Therefore it follows that :—

(*a*) The pressure obtained from an impeller is less than the theoretical value, and depends on r.p.m. and diameter, and varies with the mass of air flowing through it.

(*b*) The work capacity of an impeller at a given speed is less than the theoretical value.

(*c*) The temperature rise depends mainly on the work capacity of the impeller and on frictional losses, but is independent of the pressure rise.

8. **Compressors.** There are two main types of compressor in general use for centrifugal compressors : the single entry (Fig. 2A) and the double entry (Fig. 2B). A third type, known as the shrouded single entry, has been used and is illustrated in Fig. 2C. The single entry compressor consists of a disc having integral radially disposed vanes. When the compressor is



A—Single-Entry Impeller

B—Double-Entry Impeller

C—Single-Entry Shrouded Impeller

Fig. 2. Typical Centrifugal Compressors.

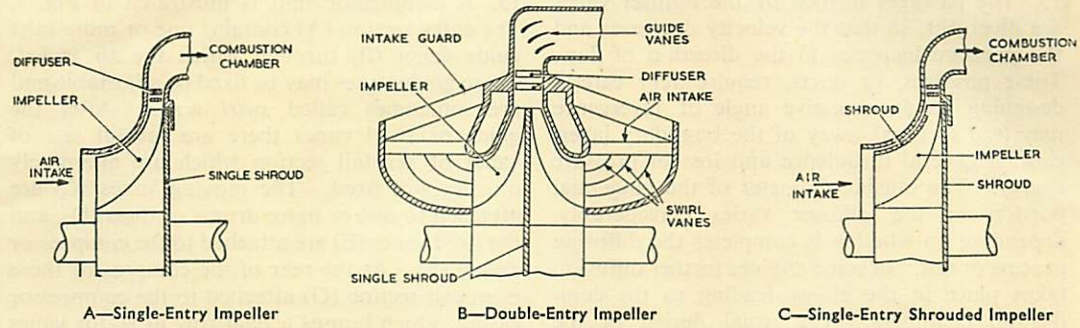


Fig. 3. Diagrammatic Arrangement of Centrifugal Compressors.

assembled in its casing (Fig. 3A), these vanes form divergent passages, which turn the incoming air so that it is discharged radially from the compressor tip into the diffuser vanes. At high tip speeds the velocity of the air relative to the vane at entry approaches the speed of sound, and it is essential for maximum efficiency that there is the minimum shock (compressibility effects) at entry. On most compressors, therefore, the pick-up (air entry) portions of the vanes are curved and then blended into the radial portions at the tip, the curvature being so adjusted that the sections of the vanes in planes normal to the axis of rotation are truly radial. There are consequently no secondary bending stresses in the vanes from the effects of rotation alone, and, from the stress point of view, the loads that arise from imparting angular motion to the air are negligible.

9. The centrifugal compressor is a highly stressed component. Vibration arises mainly from the pressure concentration around the leading edge of the vanes. As each vane passes a diffuser tip it receives an impulse, the frequency of which is a product of the number of vanes and the r.p.m. If this frequency should coincide with the natural frequency of a part of the compressor, resonance occurs and vibration develops ; thereafter a process, which begins with the failure of the internal structure of the material, may spread until centrifugal stresses are high enough to tear the material, causing structural failure.

10. The double entry compressor (Fig. 3B) is similar to the single entry, but has radial vanes on both sides of the disc. Air enters at each side, and is delivered radially to a common diffuser. The single entry shrouded compressor (Fig. 3C) would appear to be more robust, owing to the outer shrouded portion strengthening the vanes and consequently reducing the tendency for the vanes to vibrate.

11. Balancing is an important operation in compressor manufacture, and any out-of-balance forces must be eliminated to prevent the serious vibration that might otherwise develop at the high speeds at which the compressor operates.

12. **Diffuser System.** The object of the diffuser is to convert the velocity energy of the air leaving the compressor to pressure energy before it passes into the combustion chambers. The diffuser (Fig. 4) may be formed integral with the compressor casing, or bolted to it. It consists of a number of tangential vanes, the inner edges of which are parallel to the direction of the resultant airflow from the rotating compressor, the passages between the vanes being proportioned so that the air pressure attains the requisite figure on entry to the combustion chambers.

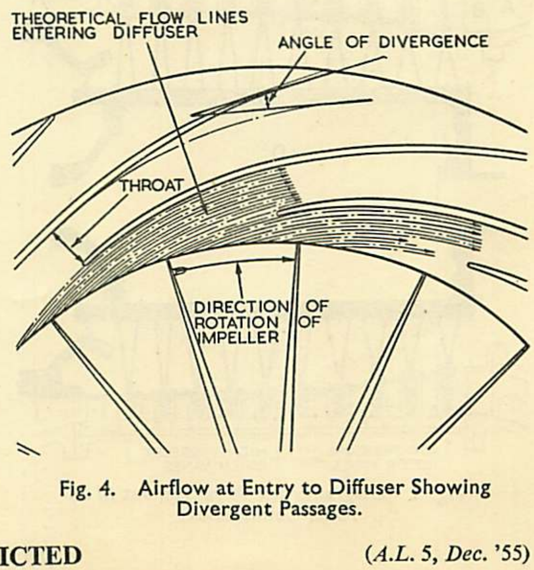


Fig. 4. Airflow at Entry to Diffuser Showing Divergent Passages.

13. The passages formed by the diffuser vanes are divergent, so that the velocity decreases and the pressure increases in the direction of flow. These passages, or ducts, require very careful designing, as an excessive angle of divergence may lead to break-away of the boundary layer, causing general turbulence and loss of pressure energy. The outside diameter of the tangential portion of the diffuser varies considerably, depending on whether it completes the diffusing process or not. In some engines further diffusion takes place in the elbow leading to the combustion chambers. The usual design of the diffuser passages is such that the area increases very gradually for the first inch or two from the throat, the rate of increase being stepped up during the later stages of expansion. The clearance between the tips of the diffuser vanes and the compressor tips is an important factor, because if placed too close together, the tips may set up aerodynamic buffeting impulses which are communicated to the compressor, causing unsteady flow and possibly initiating dangerous vibration. The usual clearance is about an inch.

Axial Flow Compressors

14. The design of an axial flow compressor is based on the conversion of kinetic energy into static pressure energy through the medium of rows of rotating blades (rotors) which change the whirl velocity of the air, and alternate rows of stationary diffusing vanes (stators) which convert the kinetic energy to pressure energy.

15. A compressor unit is illustrated in Fig. 5. The entry section (A) contains one or more inlet guide vanes (B) through which the air is fed. These guide vanes may be fixed or adjustable and are sometimes called *swirl vanes*. After the guide or swirl vanes there are several sets of vanes of aerofoil section which are alternately moving and fixed. The moving vanes (C) are attached to one or more drums or discs (D), and the fixed vanes (E) are attached to the compressor casing (F). At the rear of the compressor there is an exit section (G) attached to the compressor casing, which houses a final row of stator vanes (H) and air straightener vanes (J). One or two additional sets of stator vanes may be fitted before the first row of compressor vanes to improve entry conditions and so raise the compressor efficiency.

16. The foregoing description covers a general type, but various other arrangements are used according to the particular purpose of the engine. A typical design is illustrated in Figs. 6 and 7.

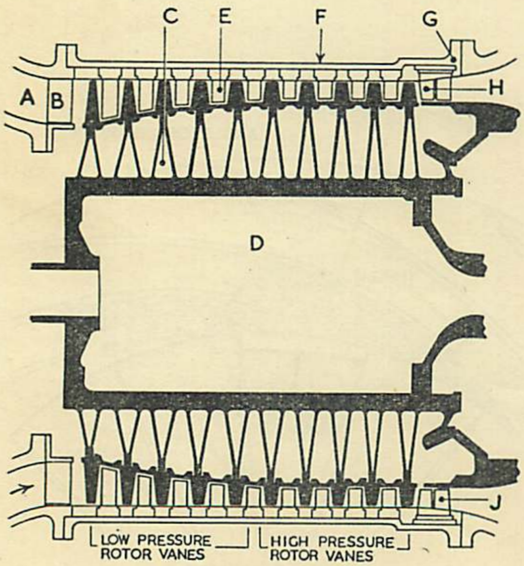


Fig. 5. Diagrammatic Arrangement of an Axial Compressor.

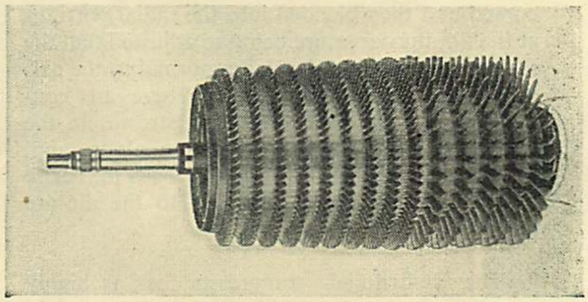


Fig. 6. Axial Compressor Rotor showing Aerofoil Section of Vanes.

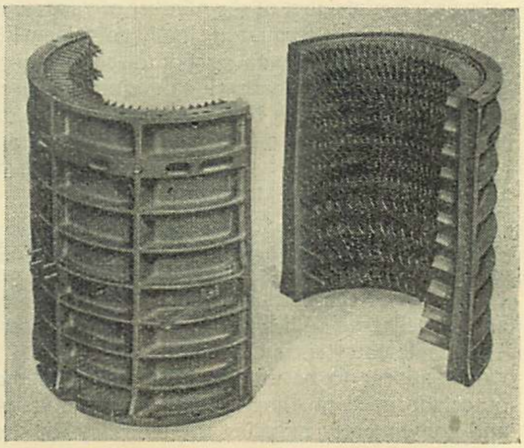


Fig. 7. Compressor Casing and Stator Vanes.

17. **Compressor Rotor.** The rotors and stators vary in length according to the pressure stage, the longest vanes being at the low pressure or entry stage. To compress and transfer the large amount of air required, and to obtain a smooth flow with the minimum of harmful characteristics, the vanes are of aerofoil section. Since the compressor is to a great extent analogous to a propeller, and to an aircraft wing, the accumulated data from test results on aerofoil sections have been of value in compressor design.

18. **The Curved Vane.** The necessity for the curved vane can be more readily appreciated if two points on a rotating uncurved vane are considered, one near the tip and the other near the root. In an uncurved vane the section at both points has the same angle relative to a plane through the axis of rotation, but the root point has a lower rotational speed and therefore a different angle of attack. To obtain the optimum angle of attack at each point over the whole length of the vane, the angle of the tip section must be reduced and that at the root section increased. The vane must therefore be curved so that the *angle of incidence* of all sections decreases from root to tip giving a constant *angle of attack* during rotation, as with a propeller.

19. **Vane Research.** Theory alone cannot determine how an aerofoil or vane will perform in a stream of air ; consequently resort must be made to experiment. The important experiments usually take two forms, the first being a study of the airflow around the vane section by the simple expedient of placing a single vane in a wind tunnel and measuring the air deflection and other characteristics over a range of angles of attack, in a manner similar to that used when testing wing aerofoil sections. In the second method a series of vanes are arranged at a specified pitch, and the airflow between and around the vanes is studied ; this arrangement is known as a cascade.

20. Cascade data are usually measured at the centre of the arrangement so as to obtain comparative results as free as possible from wind tunnel effects. It will be appreciated, however, that the results obtained are not fully representative of the conditions in a compressor. The main features peculiar to compressors which have to be taken into consideration in practice are :—

(*a*) Surface eddies which appear as trailing vortices at the root and tip of the vanes, caused by boundary-layer effects through the stages.

(*b*) Radial clearances between the vane tips and the compressor casing.

(*c*) Axial clearance between rows of vanes.

(*d*) Turbulence of the wakes from preceding vane rows.

Although it is possible to design a vane which has an ideal section, it is not always possible to use this vane since manufacturing limitations may ultimately decide the design that can be used.

Airflow through an Axial Compressor

21. Air enters the compressor through guide vanes provided to ensure a correct angle of entry to the first row of rotating vanes, where it is picked up and accelerated during its passage across the moving vanes, leaving at a greater velocity than at entry. Owing to the angle of incidence and the rotation of the vanes the air leaves the vanes at some new angle. The air then flows over the first row of stator vanes, and is again changed in direction and velocity, ready for the next stage of rotating vanes. There is now a fixed lift and drag force for each row of vanes. Increasing the lift is equivalent to turning the air through a greater angle and consequently achieving greater changes of velocity, and thus greater pressure increases. The increase in lift is accompanied by an increase in drag, which reduces the velocity increase, and also the pressure at delivery. As the turning angle of the air is limited by the maximum lift coefficient of the aerofoil section used, it follows that the maximum compression ratio is also a function of the lift coefficient.

22. Each row of stators acts as a diffuser for converting into pressure the kinetic energy of the air leaving the preceding rotating row of vanes, and also as nozzles for guiding the air into the next row of rotating vanes. There is a limit to the amount of diffusion and the angle through which the air can be turned ; if this is exceeded, high losses result owing to blade stalling.

23. After passing through the final row of rotating vanes, the air passes through a final stage of stator vanes and, in some engines, a row of straightener vanes. These provide any further diffusion necessary and give the best conditions for entry of the air to the combustion chambers.

24. **Reverse Flow.** In some axial-flow engines the airflow through the compressor is in a forward direction (towards the front), parallel to the axis of the rotor. Fig. 8 illustrates a typical airflow diagram in an engine of this type.

25. The main features of the axial compressor are :—

(*a*) High efficiency and therefore a lower fuel consumption at a given power. A compression ratio of up to 7 to 1 without serious loss of efficiency is possible with this type of compressor. (This compares with 4·5 to 1 realized by the centrifugal compressor.)

(*b*) A smooth airflow into the combustion chambers is assured.

(*c*) As the motion is purely rotary, the rotor can be accurately balanced.

(*d*) As large mass airflows can be catered for, an axial compressor is more suitable for use in high-powered engines.

Surging

26. Surging is instability of flow, a simple explanation of which follows. Assume that a compressor is discharging into a container, and as the result of some outside force there is a reduction of mass flow into the compressor. This causes the local pressure in the compressor to fall, and the air or gas in the container tends to blow back into the compressor. When this happens, the flow is reduced and the pressure therefore tends to rise. When, or soon after, maximum pressure has been reached a surge may begin, the air surging to and fro through the passages of the compressor instead of giving a steady stream of air in one direction. The surging can become strong enough to produce a vibration, which is transmitted to the aircraft. Surge is evident by rapid oscillation of delivery, accompanied by audible indications ofinstability, varying from a muffled rumbling noise to an abrupt explosion and vibration. From the foregoing it can be appreciated that a compressor is designed for a certain range of flows which may be fairly broad at low pressure ratios but reduced at high ratios.

Axial Compressor Surging

27. The mechanism of surging in an axial flow compressor is rather complicated, but it is generally taken that there are two kinds of surge, one at low speed and one at high speed. In addition, once surging has begun, stable conditions can only be obtained by throttling back. Surging is caused by a decrease in the mass airflow, accompanied by a decrease in the axial velocity and the stalling of the complete compressor. With an increase in the angle of attack of the vanes, the flow pattern changes and it becomes more difficult for air to follow the contour of the vane ; the air then breaks away from the surface behind the leading edge and the vane stalls with a sudden deterioration in compressor efficiency.

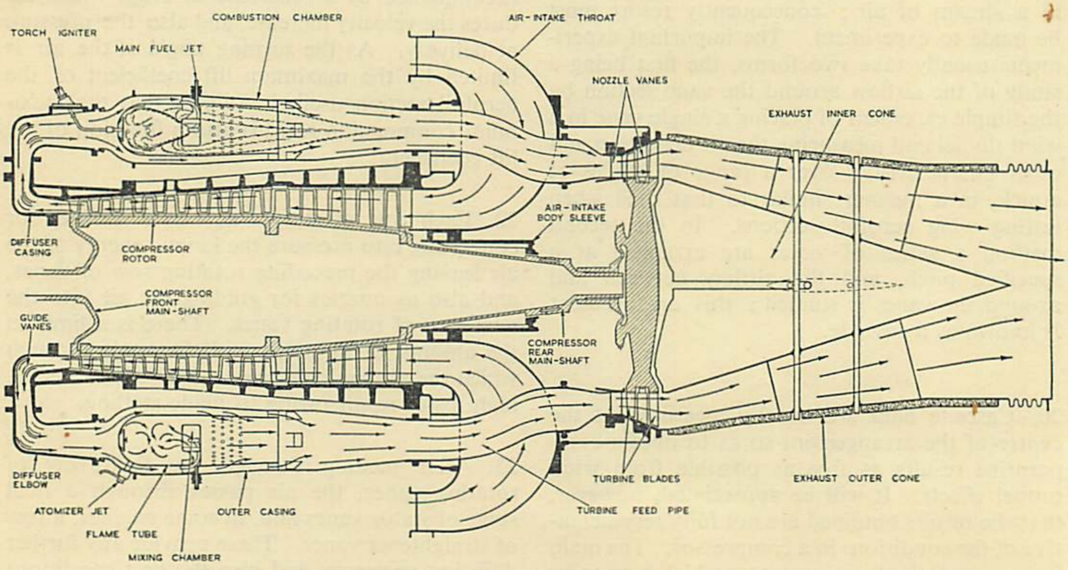


Fig. 8. Airflow Diagram of Reverse-Flow Axial Compressor.

28. With a reduction in mass airflow at low r.p.m., the angle of attack of the first low-pressure stages is greater than that of the high-pressure stages, so that the low-pressure stages are the first to stall, the succeeding stages not necessarily being affected ; this is often indicated by an audible rumbling and a higher than normal j.p.t. With a further reduction in mass flow, caused either by reducing the I.A.S. or an attempt to accelerate the engine, the remaining stages stall in succession, unless the first-stage stall so disturbs the airflow that a general breakdown and surge occur. At high speed the angle of attack of all stages is about the same, so that at stalling conditions all stages are affected simultaneously and the engine surges without any warning. The vanes may be unstalled by throttling fully back, but in some engines it may be necessary to stop the engine.

29. As surging is caused by a reduction in mass flow from the optimum figure, similar effects and a subsequent stall may be caused by a limitation of the mass flow through the combustion chambers or turbine. This may be particularly troublesome when starting, as the sudden ignition of fuel causes a choking effect, which momentarily reduces the mass flow and consequently sets up stalled conditions. A similar condition arises following a sudden acceleration from idling speed. The tendency to surge is generally overcome by careful attention to the vane design, and by the introduction of such devices as variable-incidence inlet guide vanes (swirl vanes), and pressure-operated air release valves at certain stages in the compressor, to bleed off excess air.

30. Compressor surge imposes very severe vibrations and excessive temperatures on the engine and should therefore be avoided or minimized. It is also accompanied by a falling off of thrust (falling r.p.m.), and an increase in fuel consumption. The severe vibrations associated with this condition make it very easy to identify ; the more violent surge is accompanied by a "bang" loud enough to be startling.

Variable Position Guide Vanes

31. When variable-incidence inlet guide vanes are fitted, they are automatically set to the closed position during starting and at low r.p.m., but are moved to the open position as the r.p.m. rise, either progressively, or completely at a preset r.p.m. In the closed position they give a swirl to the incoming air so that the angle of attack of the low-pressure blades is kept moderate and stalling is thereby avoided. In the open position they admit the maximum quantity of air.

32. The air release valves (bleed valves) automatically permit air to be bled off from certain critical points when pressures are at a particular level, thus allowing a higher total mass flow through the compressor, and reducing the mass flow through the combustion system and turbine. In some engines the air release valves operate in conjunction with the variable-incidence inlet guide vanes.

Twin-Spool Engines

33. One other method of avoiding flow troubles at high-pressure ratios is to have the compressor mechanically split into two halves, each half having its own turbine and operating independently of the other (Fig. 9). Such an engine is termed a *twin-spool* engine. The low-pressure spool runs at a lower r.p.m. than the high-pressure spool and so the onset of compressor stalling at low r.p.m. is avoided. Further, the high-pressure half, running at higher r.p.m., prevents the last stages operating at large negative angles of attack. While the low-pressure rotor runs at a lower r.p.m. than the high-pressure rotor, its speed rises with the reduction of density at altitude. As a result, the rate of decrease in thrust with altitude is less than that of a single-shaft engine of the same sea-level output.

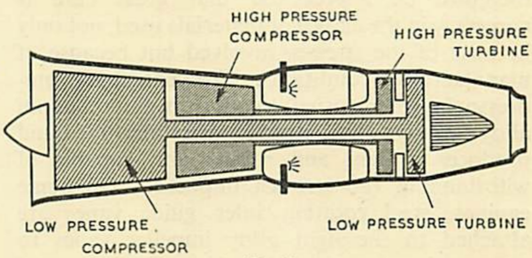


Fig. 9.

Diagrammatic Arrangement of a Twin-Spool Engine.

Icing of Compressors

34. Experience has shown that the centrifugal compressor is particularly resistant to the effects of ice and snow. Because of the high working r.p.m. and temperature, ice will not usually adhere to an impeller in a quantity sufficient to affect the efficiency to any great extent, and it has been demonstrated that large pieces of ice may pass through the compressor causing only slight superficial damage. Any ice which forms on the intake usually breaks up and dissolves when

passing through the compressor. However, the formation of ice on axial flow compressors can become a hazard, since this type of compressor is more susceptible to damage from ice owing to the delicate vanes, and the appreciable loss of power and over-heating which occur when the intakes are partially blocked by ice.

Fouling of Compressors

35. Both axial and centrifugal compressors are subject to a deterioration of performance as a result of dirt on the surfaces of the rotating vanes and the stationary components surrounding them. The solid matter is inducted with the air and may tend to adhere to the inner surfaces of the compressor, but not in sufficient quantities to become serious. If, however, the solid matter is accompanied by oil in suspension, the resulting build-up of the deposit affects the performance. The loss of efficiency is greater in the axial compressor, as the vanes are more sensitive to the airflow pattern than those of the centrifugal compressor. This deposit can be removed by periodically passing a solvent through the intake during a ground run, so avoiding the alternative of dismantling the engine.

Materials

36. Compressors operate at maximum speeds varying from 7,000 r.p.m. to 18,000 r.p.m. with top speeds approaching sonic speed. It can therefore be appreciated that great care is necessary in the choice of materials used, not only because of the stresses involved but because of manufacturing conditions. The centrifugal compressor impeller is usually made from an aluminium alloy forging. This alloy is easily machined and produces a light and robust unit capable of withstanding the stresses imposed. On some engines, steel rotating inlet guide vanes are attached to the light alloy impeller vanes to ensure adequate strength against the impact of any small foreign bodies drawn through the air intake.

37. Axial compressor vanes are usually made from steel stampings, each vane being machined to close limits of weight, and having a high standard of finish in order to maintain a stable airflow and to prevent cracks.

38. Temperature problems do not arise in a compressor, as the temperature is limited to that arising from adiabatic compression and reaches a maximum of about 200°C. If higher temperatures had to be used, light aluminium alloys would no longer be satisfactory as this material loses much of its strength properties at a temperature slightly above 200°C.

Comparison of Axial Flow and Centrifugal Flow Compressor Engines

39. **Power.** For a given temperature of the air entering the turbine, the power output of a gas-turbine engine is a function of the quantity of air handled. The axial flow engine can handle a greater mass of air per unit frontal area than can the centrifugal type.

40. **Weight.** From the viewpoint of unit weight of structure to unit thrust, most axial flow engines deliver a given thrust for a slightly lower weight, *i.e.* it has a better power/weight ratio.

41. **Efficiency.** The efficiency of each component of a gas-turbine engine shows up in the fuel consumption. The centrifugal compressor may reach an efficiency of 75 to 80% up to pressure ratios as high as 4 : 1. Above this pressure ratio, efficiency drops off at a prohibitive rate. The axial flow compressor may have an efficiency of 80 to 90% over a wide range of compression ratios. Therefore it can be seen that the centrifugal compressor engine is not as economical in terms of fuel used per pound of thrust per hour (specific consumption).

42. **Design Simplicity.** Since the centrifugal compressor is of considerably simpler design than the axial flow, this factor dictated its use in the early history of gas-turbine engines ; much more was known of this type of impeller as a result of its long use in supercharged piston engines. In small power units where high efficiency is not essential, the centrifugal type enjoys an advantage. Simplicity, of course, in any size of engine means low initial cost.

43. **High-Altitude Operation.** Satisfactory combustion at altitudes of about 70,000 ft. may be practical only with the high compression ratios obtainable from an axial flow compressor.

44. **Application.** The power of the centrifugal compressor engine can be increased only by enlarging the diameter of the impeller and thus increasing the diameter and frontal area of the fuselage or nacelle. The power of the axial flow engine, on the other hand, can be increased by using more stages in the compressor without a marked increase in diameter. In nacelle and wing installations the centrifugal type is at a serious disadvantage because of its larger diameter.

45. It is all-important that the drag of high-speed aircraft is kept low, and the axial flow engine is especially well suited to these aircraft by reason of its smaller diameter ; the high efficiency and small diameter of the axial flow engine favours its installation in medium- or long-range aircraft, the greater weight and cost of the unit being offset by gains in fuel economy. Since the gas-turbine driven propeller (turbo-prop) shows the greatest promise in long-range high-altitude transport aircraft, the axial flow compressor is used almost exclusively in the development of the turbo-prop installation.

46. Irrespective of the type of compressor, about 100 B.H.P. is required to deliver one pound of air per second to the combustion chambers. Since this rate of flow gives roughly 50 lb. of thrust, the compressor of a unit developing a thrust of 5,000 lb. requires in the region of 10,000 B.H.P. to drive it. In the light of these figures it is interesting to recall one of the earlier projects of Campini, an Italian designer. At that time turbine blade materials able to withstand the operating temperatures necessary for even a moderate efficiency were still undeveloped, so Campini decided to drive the compressor with a 900 H.P. piston engine located in the air intake. His aircraft first flew in 1940 and was widely publicized after flying from Milan to Rome. But it was not a success, having a top speed of little more than 170 knots and taking 53 minutes to climb to 13,000 feet. It is easy to see that, with such a low power available for compression, the thrust developed could not be very high. Even had the project showed more promise, it would still have the disadvantages, compared with a turbine-jet, of greater weight, complication, and vibration.

Compressorless Jets

47. Mention must be made of two types of jet engines in which no mechanical compressor is used. The first is the intermittent pulse duct, the propelling agent of the German V.1 flying bomb (Fig. 9). Once this type of unit is launched and given an initial speed, the pressure rises in the divergent air intake. The pressure rise causes a grid of flap valves to open, admitting the air to the combustion chamber, where it is mixed with fuel sprayed from several rearward facing nozzles. As soon as there is enough air to support combustion, the mixture is ignited by the hot combustion chamber walls (except initially), the resultant sudden internal pressure rise closing the valves so that the expanding gases escape at a high velocity rearwards. Pressure in the combustion chamber then falls quickly to below atmospheric, the flap valves reopen and the cycle is repeated at a frequency of about 45 times per second.

48. **The Ram Jet.** The other type of compressorless jet engine is the ram jet or athodyd (short for aero-thermo-dynamic-duct), a divergent/convergent duct in which fuel is burned continuously in the middle at the widest part. After having been given a high initial airspeed of about 500 knots the intake produces a pressure rise large enough to enable flight to be maintained, but as ram effect is small at these relatively low speeds efficiency is very low also. The higher the speed the greater the pressure rise, with consequent greater efficiency. The ram jet is expected to power certain types of missiles flying at speeds of from 1·5 M. to 4 M. at sea level. It can also be used to provide a source of power when fitted to the rotor tips of helicopters ; in this way the necessary high operating speed can be obtained on an aircraft which itself has low flying speeds.

49. The reheat method of thrust augmentation is basically a ram jet operating in the jet pipe of a turbo-jet engine. The "ram" is supplied by the normal jet stream. Reheat equipment is sometimes called a turbo-ramjet.

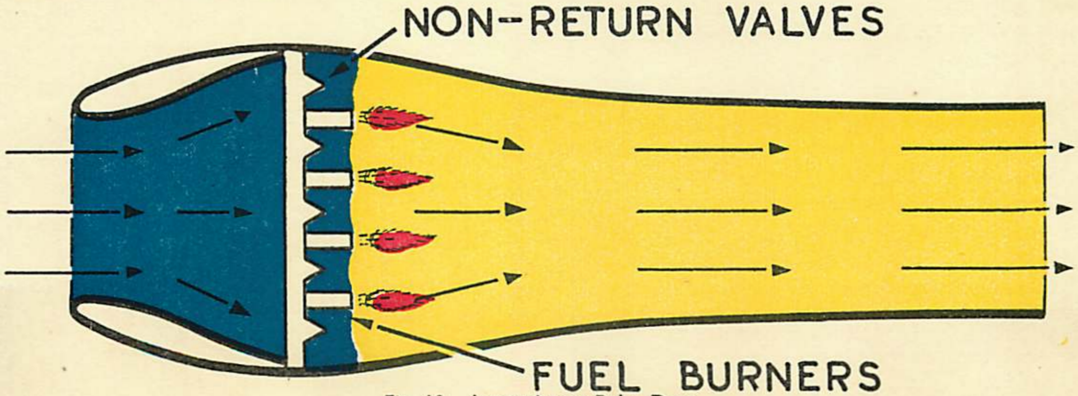


Fig. 10. Intermittent Pulse Duct.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