PART 1 : SECTION 3

CHAPTER 4

COMBUSTION SYSTEMS

Introduction

1. The function of the combustion chamber is to burn a mixture of air and fuel steadily and produce a steady stream of gas at a uniform temperature. The main requirements of a combustion chamber are :—

(*a*) High combustion efficiency.

(*b*) Reliability.

(*c*) Low pressure-loss.

(*d*) Non-sensitivity to grade of fuel.

(*e*) Ability to operate efficiently over the range of pressures, inlet temperatures, and air/fuel ratios required.

(*f*) Satisfactory rich and weak mixture flame-extinction limits.

(*g*) Uniform temperature and velocity distribution at the entrance to the turbine.

(*h*) Simplicity of control.

(*j*) Ease and cheapness of manufacture.

Types of Combustion Chambers

2. There are two main types of combustion chambers (sometimes called combustion cans) used in gas-turbine engines :—

(*a*) Multiple chambers arranged around the circumference of the engine body.

(*b*) The single, annular chamber.

3. **Multiple Combustion Chambers.** Although the multiple chamber arrangements as fitted to various engines are basically similar, there is considerable variety in detail, particularly in the methods of mixing the fuel and air and obtaining the desired amount of turbulence. Multiple combustion chambers (6 to 14 in number) may be arranged for direct or reverse flow according to design requirements. The principal advantage of the reverse flow system is that the total engine length is reduced ; this is most useful when using an axial compressor.

The Direct Flow Combustion Chamber

4. Fig. 1 shows a combustion chamber which consists of an air-casing carrying a torch-igniter used for starting (only fitted to certain chambers), an inter-connector and a fuel drain. In the air-casing is a flame tube, located concentrically, consisting of two parts, the primary portion and the main tube. The primary portion, at the forward end of the flame tube, is composed of an outer cap and a double end-plate, or colander, carrying the swirl assembly. The airflow from the compressor is separated at the outer cap into primary and secondary flows ; the primary flow being concerned mainly with combustion and the secondary with cooling. About 65% of the primary air flows over the outer cap and through the annular space between the flame tube and the outer casing. The remaining 35%

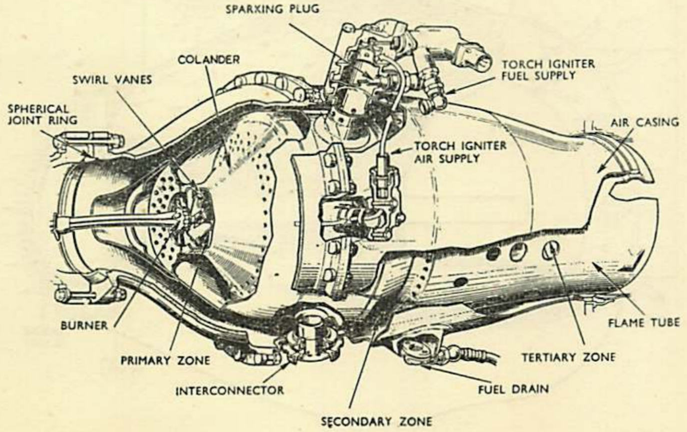

Fig. 1. Direct-Flow Combustion Chamber.

flows through the orifice of the outer cap, a small amount passing through the holes in the colander and then along the inner walls of the flame tube, serving to prevent the flame from impinging on the wall of the tube and reducing the tendency to form carbon. The remainder of the 35% passes through the bore of the colander and then through the annulus formed between it and the burner-jet holder. In the annulus is the swirl assembly which is provided with a number of swirl vanes that impart a rotary motion to the air entering the primary combustion zone. This action produces a strong vortex which causes a "back flow" of air towards the burner (because of the deep low-pressure core of the vortex), and thus prevents flame extinction by the high-velocity airflow.

5. The main portion of the flame tube is cylindrical, having a gradual taper to the rear. A number of holes are provided to admit the secondary air passing along the annular space on the outside of the flame tube ; this portion of the tube is known as the secondary zone. A further series of holes are provided toward the rear of the tube for the admission of additional air ; this portion is termed the tertiary zone. These zones overlap, the air being admitted gradually and continuously over practically the whole length of the flame tube.

6. Combustion is completed within the first one-third of the length of the secondary zone, the remainder of the zone constituting a dilution and mixing chamber. The annular space between the flame tube and the air-casing is continued to the end of the air-casing. The space keeps an insulating layer of cool air between the flame tube and the air-casing.

7. With multiple combustion chambers, only two torch igniters are usually provided since the chambers are inter-connected and ignition in one chamber is propagated instantaneously to the others. The inter-connectors join the adjacent air-casings and flame tubes, so that in addition to propagating the flame they also equalize the pressure in all chambers.

The Annular Combustion Chamber

8. The annular combustion chamber (Fig. 2) surrounds the main body of the engine and is open at one end to the compressor and at the other end to the turbine. Within the annular chamber is an annular flame tube, similar in section to the multiple tube type. At the compressor end is a supporting plate for a series of up to about 20 burners, which inject the fuel down-stream into the flame tube. In some engines the burners are arranged to inject the fuel up-stream ; in these types the spray from the burners is not diffused in a wide angle as with the down-stream type, since some degree of penetration of the incoming air is required. The air is metered and made to swirl by suitably arranged holes in the front plate.

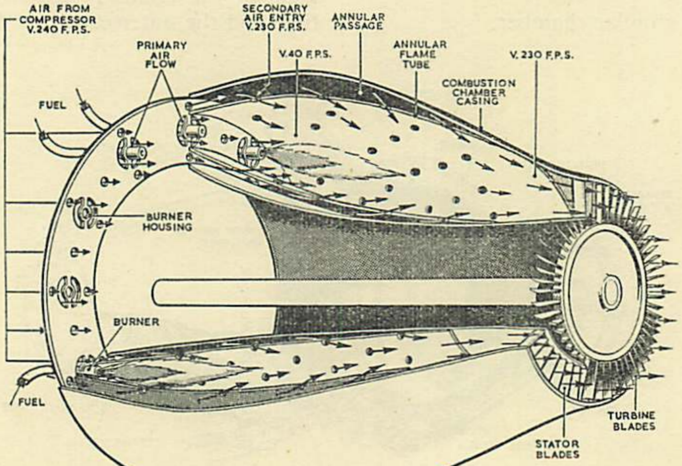

Fig. 2. Annular Combustion Chamber.

9. The annular chamber forms a continuous sheet of hot gas which flows from the primary zone to the turbine ; the design is similar to the multiple-chamber system in that the primary air supports combustion in the high-temperature turbulent zone, and secondary and tertiary air cools the gas before entry to the turbine. The main advantages of this system are :—

(*a*) The total chamber area exposed to the gas is reduced, resulting in a reduced pressure loss.

(*b*) Instead of a series of outlets to the nozzle guide vanes, a continuous sheet of gas at uniform temperature over the whole area is obtained, resulting in a better pressure and flow distribution into the nozzles.

(*c*) Ease of servicing.

(*d*) Simplicity of manufacture.

(*e*) Smaller overall diameter when used with an axial flow compressor.

10. **"Cannular" Combustion Chamber.** A development of the annular combustion chamber is the cannular chamber which uses a series of individual flame tubes within the main annular chamber. This has the advantage of having more rigid control of the primary and other airflows—poor distribution of the fuel and air being a common defect of the true annular arrangement.

Fuel Injection and Vaporization

11. Two distinct principles have been evolved for the injection and vaporization of the fuel. One principle is based on the injection of a finely divided (atomized) fuel into a turbulent airstream, the mixture then being vaporized and burnt. The other is based on pre-vaporization and mixing of the vaporized fuel with an airstream before entering the combustion zone. The various types of atomizers and burners are described below. Vaporization (vapour combustion) systems are described in paras. 38 to 41.

Swirl Atomization

12. Most British gas-turbine engines use swirl-type atomizers which operate on the familiar principle of a water sprinkler. Essentially, a swirl atomizer consists of a small cylindrical or conical cavity into which a number of streams of fuel enter almost tangentially. Owing to their direction of entry into the cavity, a vortex is set up and the swirling fuel leaves from a single orifice on the axis of the cavity in atomized form.

13. The underlying principle of vortex flow is that the tangential velocity of the fluid increases towards the centre with an accompanying pressure drop, with the result that the path that any given particle tends to follow when it leaves the orifice is peculiar to its position and different from every one of its neighbours. The fluid tries to leave the orifice in the form of a hollow cone and, were it not for the restraining effects of viscosity and surface tension, would resolve itself into a cloud of particles of little more than molecular size. Viscosity and surface tension hold the liquid together, particularly at low pressures when the swirl energy available for disintegration is small.

14. Fig. 3 shows what happens at the orifice of a typical swirl atomizer as the pressure is increased. At the lowest pressures the fluid leaves as a mere trickle, slightly modified by its original tangential entry. At a slightly higher

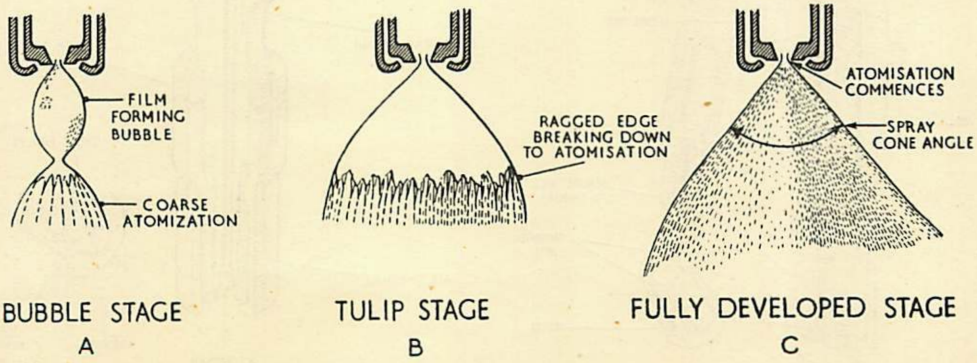

Fig. 3. Stages of Atomization.

pressure the effect of the tangential velocity causes the fluid to form a hollow cone on leaving the orifice, but the viscosity draws the fuel together as a continuous film which later comes together again forming the so-called *bubble*. At a still higher pressure the film no longer re-forms as a bubble, but starts to break up at the edges, forming what is known as the *tulip*. As the pressure is increased further the tulip shortens, atomization occurring nearer and nearer to the orifice, and over the optimum working range the fuel emerges in the form of a multiplicity of tiny droplets almost as soon as it leaves the final orifice.

Types of Burners

15. The function of a burner is to inject fuel in a readily ignitable form into the flame tubes of the combustion chambers. Four types of atomizing burners are used :—

(*a*) Lubbock.
(*b*) Simplex.
(*c*) Duplex (Duple).
(*d*) Spill.

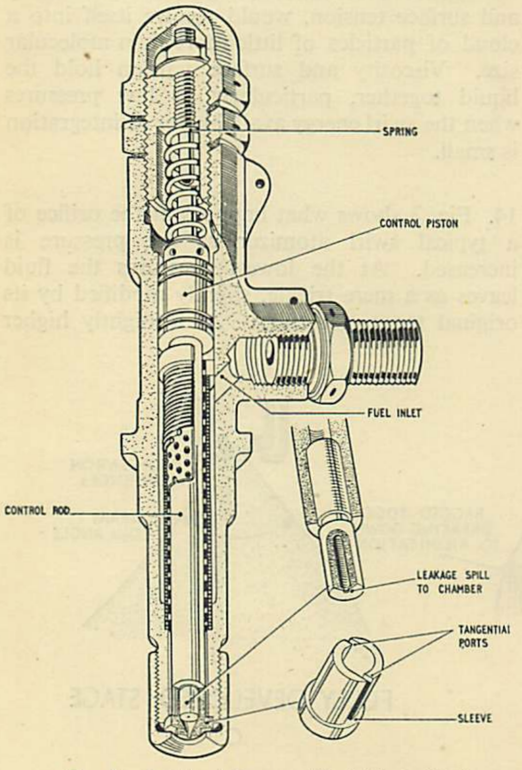

Fig. 4. Lubbock Burner (Variable Orifice)

16. **Lubbock Type Burner.** In this type (Fig. 4) the area of the tangential slots through which the fuel enters the swirl chamber is controlled. As the pressure in the fuel line increases, the effective area of the slots, and therefore the amount of fuel discharged, are both increased. This action pressurizes the fuel lines at low flows without raising the maximum pressure requirements to any great extent ; and it gives good results. Some trouble was, however, experienced with sticking of the piston that operates the variable area slots, particularly if the fuel filtering was not of the highest order. This difficulty resulted in the adoption of a simple swirl-type atomizer.

17. **Simplex Type Burner.** This consists of a simple swirl chamber and atomizing orifice (Fig. 5). The area of the orifice is fixed, the flow through the burner being proportional (inherently)

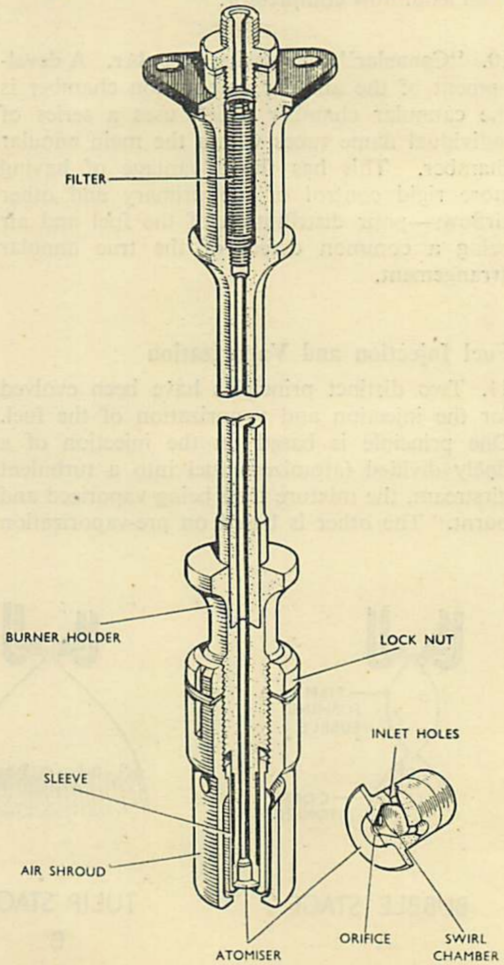

Fig. 5. Simplex Burner.

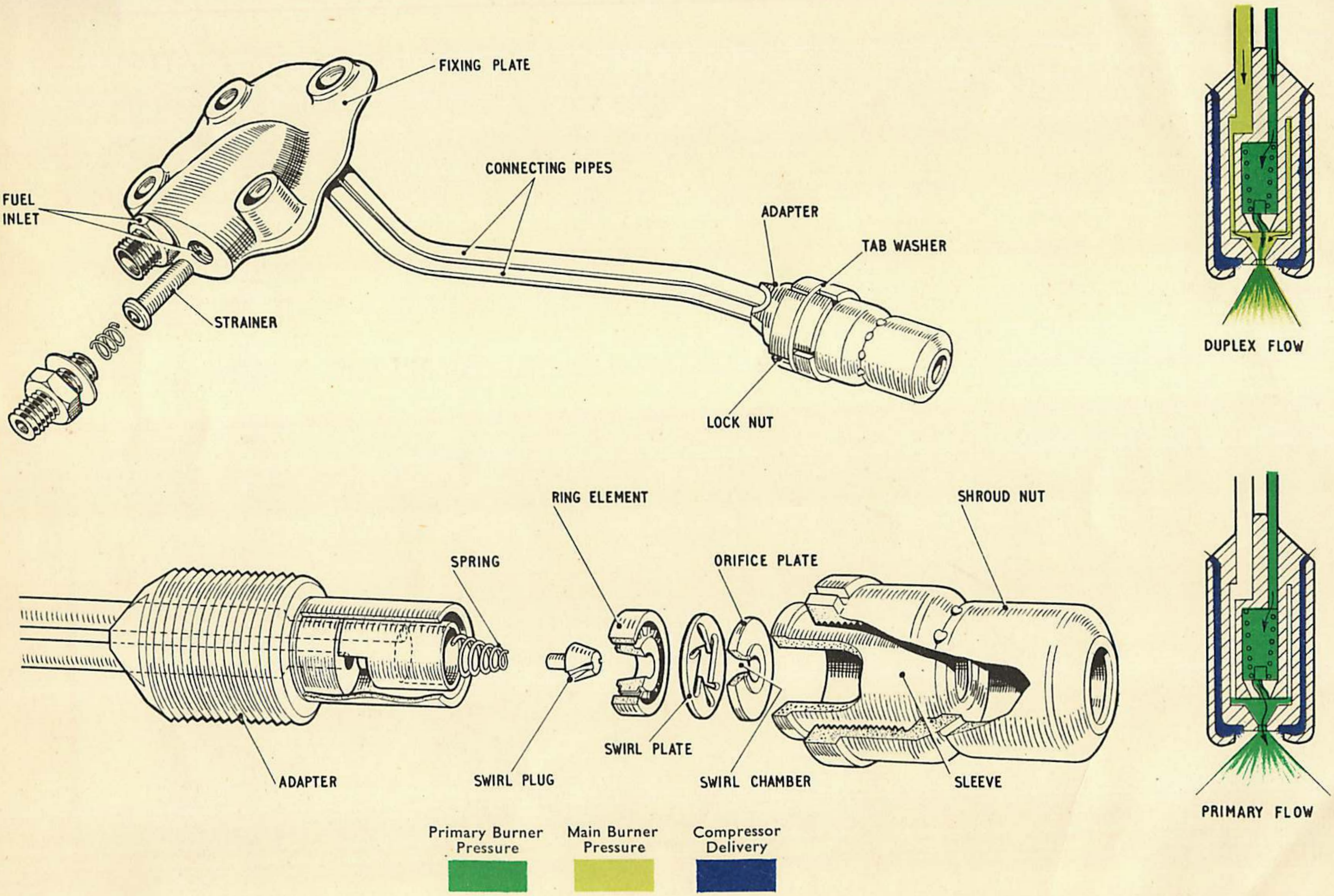

Fig. 6. Duplex I Burner

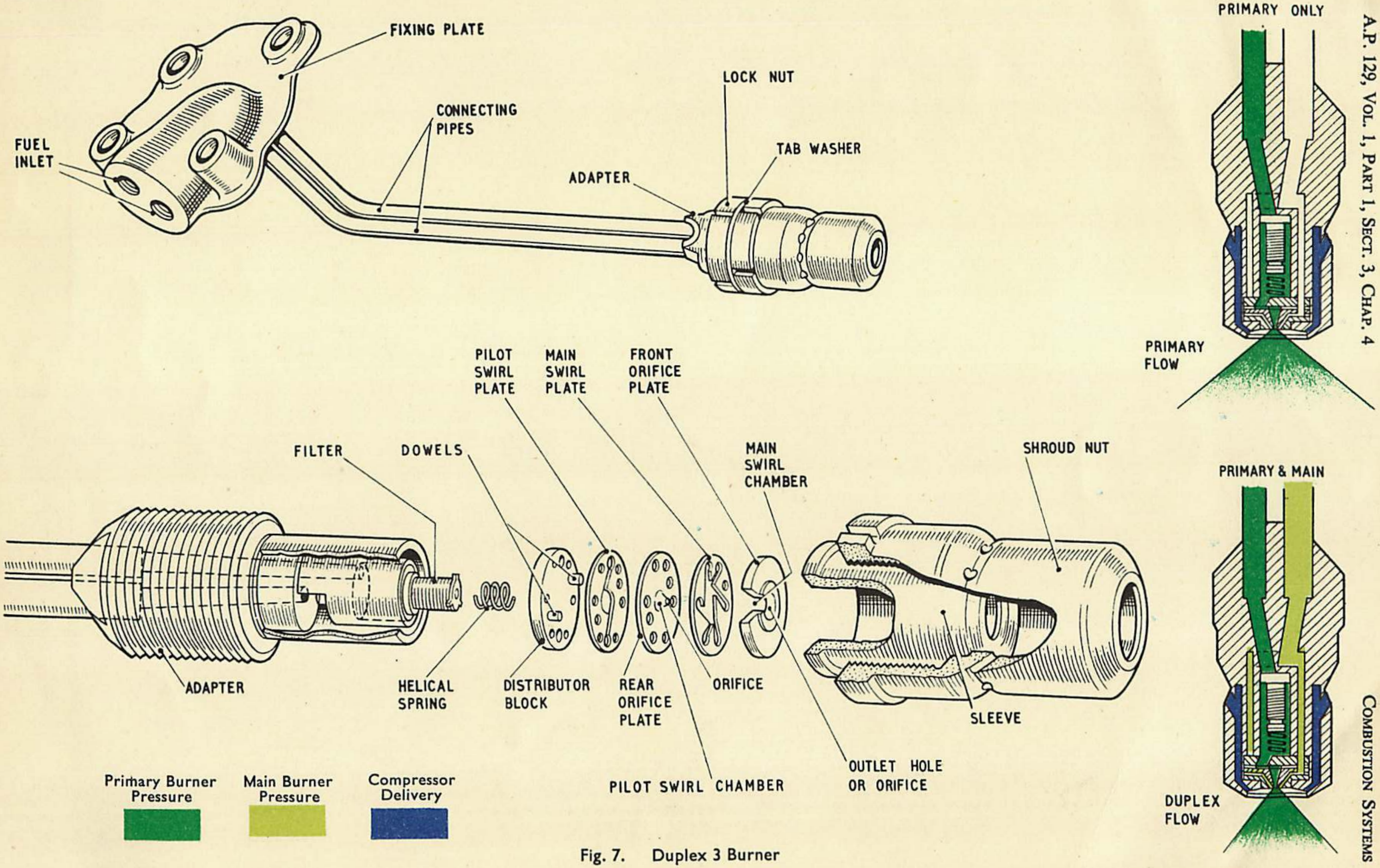

Fig. 7. Duplex 3 Burner

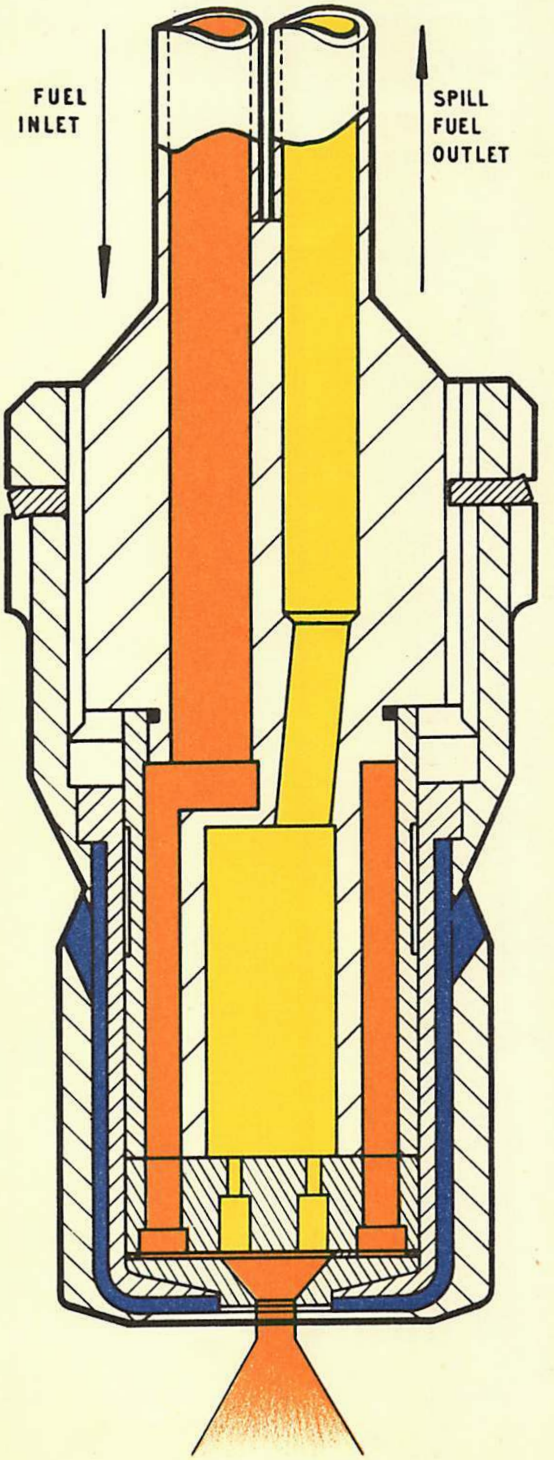

Fig. 8. Spill Burner

to the square of the pressure drop across it. Thus for a flow range of, say, 10 : 1, the burner has a pressure drop variation of 100 : 1. This means that if the minimum pressure for effective atomization is 30 lb./sq. in. the pressure needed to give a maximum flow is 3,000 lb./sq. in. The pumps available on very early engines were unable to supply such high pressures, so the Lubbock burner was devised to overcome the square law effect.

18. **Duplex or Duple Type.** Duplex burners, as their name implies, use two sets of atomizers—one for low flows, and both for high flows—as a means of defeating the square law.

(*a*) In systems using the Duplex 1 (Fig. 6), two pipelines (manifolds), the primary and the main, lead fuel to the ring of burners, each burner having a single swirl chamber and orifice. At idling speeds and at high altitude a pressurizing valve permits the fuel to pass only along the primary manifold ; this is adequate for the low flows required under these conditions. At higher flows and pressures the pressurizing valve opens to allow fuel to the main manifold as well, thus giving a combined flow down both manifolds. Under both sets of conditions the fuel passes through the single swirl chamber and orifice in the burner. In this way the Duplex burner can give effective atomization over a wider flow range than the Simplex for the same maximum burner pressure. Also, efficient atomization is obtained at the low flows necessary at high altitude. The pressurizing, or *splitter* valve, is remote from the burners and can be made common to all the burners.

(*b*) The Duplex 2 burner has a pressurizing valve for each burner, and has consequently only one feed pipe for each burner. With these burners a flow distributor is necessary to ensure that all the burners pass the same quantity of fuel.

(*c*) Duplex 3 burners (Fig. 7) have co-axial swirl chambers and orifices for both the primary and main flows. Otherwise the Duplex 3 is similar to the Duplex 1.

19. **Spill Type.** The spill burner (Fig. 8) can be described as being a Simplex burner with an additional passage from the swirl chamber for spilling fuel away. With this arrangement it is possible to supply the fuel to the swirl chamber at a continuous high pressure. As the fuel flow rate decreases with altitude or reduction in r.p.m., surplus fuel is spilled away from the swirl chamber, leaving less to pass through the atomizing orifice. Since the swirl chamber is designed to convert the fuel pressure energy into the kinetic energy needed for atomization, the constant high-pressure supply to the spill burner (even at extremely low flows into the combustion chamber) ensures that there is efficient atomization of the fuel at all times. A spill-burner system involves a modification of the fuel system used with the other types of atomizing burner. A means has to be provided for removing the spill flow under any particular set of operating conditions. This involves the use of a second pump and suitable controls for the starting and stopping sequences of the engine.

20. **Advantages of the Duple Burner over the Simplex Burner.**

(*a*) Better atomization of fuel is obtained at low fuel flows, thereby improving engine control and relighting characteristics at altitude.

(*b*) The lower fuel pressure required for maximum flow reduces possible fire risk.

(*c*) The accumulator and the minimum burner pressure valve are unnecessary.

(*d*) It is easier to fit new burners.

Torch Igniters

21. The torch igniter is used on early engines for initial ignition of the fuel/air mixture ; normally two are fitted to each engine. It consists of an igniter body, a combined electro-hydraulic valve and atomizer, and igniter plug. The igniter body holds each part in relation to the other, so that a spray from the atomizer and a spark from the igniter plug are brought together within a mixing chamber enclosed by an air shroud, so producing an intense flame.

22. **Operation.** During starting, the torch igniter is supplied with low-tension and high-tension current and with fuel under pressure from the torch-igniter feed-pump. The L.T. current energizes a solenoid which lifts an armature and needle-valve, permitting fuel to flow under pressure to the atomizer from which it issues to be ignited by the high intensity spark between the electrodes of the igniter. The flame propagates directly into the spray zone of the combustion chamber main burner and burns continuously during the starting cycle, giving ample time for the engine to light up and become self-sustaining. At the end of the starting cycle, which lasts about 30 seconds, the torch igniter is automatically de-energized. The possibility of a successful relight is reduced above about 25,000 feet.

High-Energy Ignition Units

23. High-energy ignition units supply a hotter spark than the torch-igniter type and are used in most engines. Each engine has two igniters which are operated from the normal 24-volt D.C. supply, and relighting may be possible up to altitudes of 55,000 feet and at temperatures between −50° C. and +100° C. However, at altitudes above about 35,000 feet, the chances of a successful relight are reduced. The maximum height for best relighting results varies between aircraft types and is given in Pilots' Notes for the type.

Working of the High-Energy Igniter

24. An induction coil (Figs. 9 and 10), operated by a trembler mechanism from the 24-volt D.C. aircraft supply, repeatedly charges a reservoir capacitor through a high-voltage rectifier. The rectifier prevents a discharge back into the coil windings while the capacitor voltage builds up to a value of about 2 kV., at which point the sealed discharge gap breaks down. The capacitor then discharges through the sealed discharge gap, a choke, and the engine igniter plug, which are all connected in series. The capacitor is then recharged and the cycle is repeated at a frequency of not less than one discharge per second. The discharge can be heard as a cracking or loud clicking noise.

25. Discharge resistors are connected across the reservoir capacitor to ensure that stored energy is dissipated if the capacitor is left in a charged condition when the unit is not in use. The safety resistors across the output circuit prevent the voltage building up if the unit should be accidentally switched on while the igniter plug lead is disconnected. The choke controls the duration of the discharge to give the best ignition properties.

Igniter Plug

26. The igniter plug used in this system differs in appearance and function from the standard sparking plug. The electrode end of the igniter plug is integral with the central electrode, insulator and outer metal housing, the latter being earthed. The discharge is initiated by a slight electrical leakage across the surface of the insulator from the central electrode to earth, which provides a low resistance path for the capacitor discharge. In practice it is found that a heavily carboned igniter plug gives a better spark than a clean igniter, by causing a more positive initial leakage.

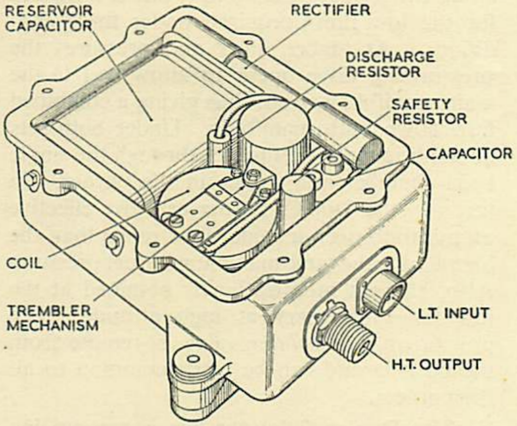

Fig. 9. High-Energy Ignition Unit.

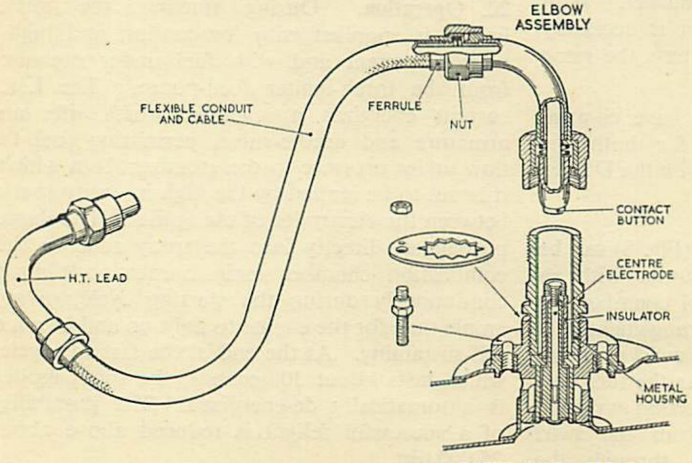

Fig. 10.

High-Energy Ignition—

Igniter Plug Assembly.

Position of Igniter

27. The position of the igniter is such that the electrodes protrude into the fuel injection zone just outside the high temperature area. Once the mixture is ignited, the flame is self-sustaining within the limits of the working range of air/fuel ratios.

Mixing the Air and Fuel

28. Since the rate of combustion is governed by the temperature, it is inefficient to mix all the air with the fuel in one stage ; this would give an air/fuel ratio of 60 to 70 : 1, resulting in a final temperature of only about 800° C. which would give practically no reaction. If, however, the air/fuel ratio is around 18 : 1, a combustion temperature of about 1,500° to 1,600° C. results, and consequently a better reaction is obtained. Although the theoretical air/fuel ratio is usually assumed to be 15 : 1, the practical ratio is generally 18 : 1 to ensure good mixing and minimize carbon formation due to excessive cracking of the fuel. The importance of the primary zone into which the requisite proportion of the total air is admitted can now be more readily appreciated.

29. A proportion of the total primary air passes through the swirl vanes which give it a vortex motion having the highest velocity near the centre. This high whirl velocity at the centre of the swirl produces a low static pressure at this point ; consequently there is a reverse flow of air back into the central core of incoming air (Fig. 11). This flow reversal is a valuable stabilizing feature of swirl because, once ignition has taken place, the flame is continually being fed back to the burner orifice, thus shortening and concentrating the flame.

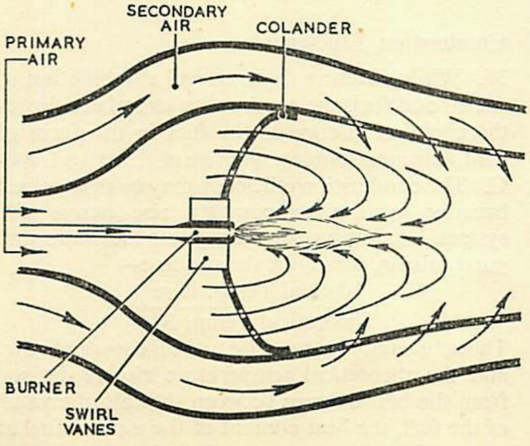

Fig. 11. Airflow Reverse with Swirl.

30. The remainder of the primary air passes through the holes in the colander, where it meets the fuel spray at about right-angles to the spray cone (Fig. 12), thus causing the desired amount of turbulence. Controlled turbulence is a very effective method of combustion control, since it has been established that a thorough stirring together of the air and fuel is a distinct advantage in ensuring the fine mixing necessary for rapid and uniform flame propagation.

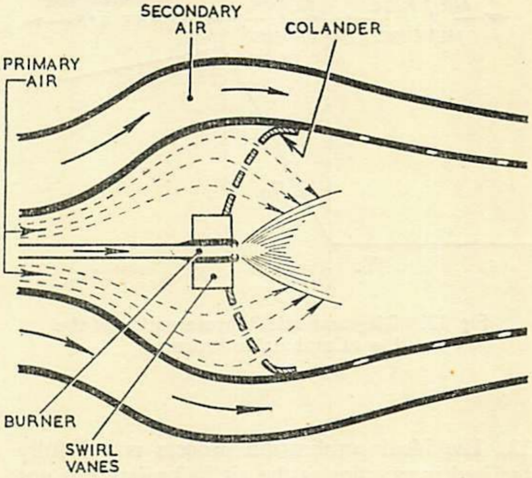

Fig. 12. Distributed Turbulence.

Combustion Process

31. The ideal combustion process may now be considered, for which purpose it must be assumed that a flame front exists as shown in Fig. 13. Upstream of this flame front the unburnt and atomized (not fully vaporized) air/fuel mixture is moving downstream at a velocity V_1 and a temperature T_1. In order to effect ignition, the temperature of the mixture must be raised to T_g to vaporize the fuel. This is done by conducting some of the heat of combustion from the existing flame front back to the unburnt mixture at plane A. When the fuel is vaporized, burning begins, heat is released, and the gas temperature increases further until it finally reaches T_2, the combustion being complete at plane B. The whole reaction, therefore, occurs between planes A and B. Between T_1 and T_g the fuel droplets are vaporizing and starting the preliminary stages of reaction. The period between the start of vaporization and the final reaction is known as the ignition lag.

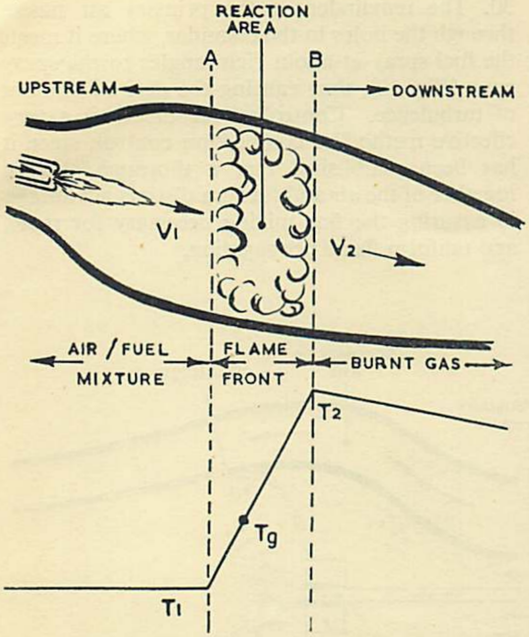

Fig. 13. Diagrammatic Representation of the Ideal Combustion Process.

32. The ideal combustion process is not fully realized in practice as the air/fuel mixture is not homogeneous, so that some of the mixture will not burn and is consequently still liquid after the main reaction has taken place. This results in combustion continuing downstream of plane B, where the tertiary air is admitted. In its early stages, the main burning rate is generally assumed to be slow, increasing in speed as the droplets vaporize and mix with the initial hot products, then finally slowing down. Of the total droplets injected, some may only be either partly vaporized, or cracked and remain unburnt. Any unburnt fuel ejected from the jet-pipe burns externally on contact with atmospheric air producing a torch flame (torching). This flame indicates incomplete mixing.

Factors Affecting Flame Extinction

33. Combustion control and air/fuel ratios are important factors in the prevention of flame extinction. There appear to be two types of extinction, one due to a rich and the other due to a weak mixture. With an increase in mixture strength the gas temperature increases, until a maximum temperature is reached. This maximum temperature is reached at a certain mixture ratio, dependent on the engine design. For a given set of conditions the system can burn up to a limiting air/fuel ratio, but beyond this figure the combustion efficiency falls. With the approach of the limiting condition, combustion becomes unstable, the flame length fluctuates, and pressure variations arise, finally resulting in complete extinction of the flame.

34. The weak mixture extinction is mainly due to low fuel flow, *i.e.* less than is required for existing engine conditions. This is most likely to occur when the engine is throttled back rapidly to the idling position at high air-speed.

Secondary and Tertiary Air

35. Since a normal maximum flame temperature of 1,500° to 1,600°C. is necessary to obtain the required heat-rise and satisfactory thermal efficiency, some arrangement must be provided to reduce this temperature before the gas flow reaches the turbine, as the turbine material is limited to a temperature of about 800° C. The reduction in temperature is effected by the entry of the secondary and tertiary air, which is admitted through holes in the main tube. This dilution results in an overall air/fuel ratio of 60 to 70 : 1, thus giving a temperature acceptable to the turbine and at the same time an increased mass flow and therefore improved propulsive efficiency. It is very important that the gases issuing from the combustion chambers should be thoroughly mixed so that their temperature at the turbine is substantially uniform. The temperature distribution of the gases is particularly important when the mean outlet temperature is high, because any erratic distribution causes excessively high local turbine temperatures and damage to the turbine.

Combustion Efficiency

36. While effecting the chemical combination of the air and fuel, the combustion chamber releases the chemical energy of the fuel in the form of heat, causing a temperature rise of 1,300° to 1,400° C. The combustion efficiency may be determined broadly by the temperature rise across the system. Assuming an average air/fuel ratio and good mixing, it may be defined as :—

$$\frac{\text{Actual Temp. Rise}}{\text{Theoretical Temp. Rise}}$$

The actual temperature rise is the measured figure, and the theoretical temperature rise is derived from the best balance between the calorific value of the fuel, the heat content of the air and fuel at combustion chamber entry, and the exhaust gas.

37. In practice, however, there are certain losses which can be put down to the following causes :—

(*a*) Incomplete combustion.

(*b*) Turbulence necessarily created for flame stability.

(*c*) Radiation.

(*d*) Skin friction.

Combustion efficiency is generally assumed to be in the region of 95% over the useful operating range.

Vapour Combustion System

38. Before considering vapour combustion systems, some of the more important aspects of the atomizing systems already described must be examined. With the vortex system, having obtained the best conditions of turbulence and metering of the airflow, the rate of burning is an inverse function of the size of the fuel particles, *i.e.* the larger the particles (poor atomization) the lower is the rate of the burning. An analysis of the combustion process under these conditions shows that fuel particles drift forward into a region of turbulent air. In order to complete the combustion the fuel particles must first be vaporized, and then the individual molecules must be given more heat energy (activation energy) before complete combustion can occur. On receiving this energy a period (known as the ignition lag) elapses before the individual molecules give up their stored heat.

39. It will therefore be appreciated that the most important factors controlling the primary stages of combustion are :—

(*a*) The vaporization of the fuel.

(*b*) Heating the vaporized fuel to ignition point.

(*c*) Ignition lag.

With the atomizing system the amount of fuel vaporization depends on the size of the fuel particles and the spray characteristics. Both these factors vary with the pressure drop across the burner orifice, which is a function of fuel flow, and therefore of throttle opening and altitude. Heating of the vaporized fuel to ignition point depends on the amount of recirculation of the burning gases in the combustion zone and on radiation heating (a function of the brightness) from the flame. The brightness of the flame depends on the pressure of the gas and therefore on altitude. The ignition lag depends mainly on the charge temperature.

40. It is essential that (*a*) and (*b*) of para. 39 should be controlled as closely as possible, and that (*c*) of para. 39 should be made as short as possible. Therefore the rate of combustion increases with decreasing size of the fuel molecules, consequent on proper vaporization. The heat for vaporization comes from the combustion of the fuel, consequently a practical solution to obtain complete vaporization is to place the vaporizer in the flame tube (Fig. 14). If, however, the fuel is vaporized in a pipe without the presence of air, cracking of the fuel occurs, resulting in carbon deposits. To overcome this trouble, air is passed through the vaporizer with the fuel, the air sweeping away the vapour as soon as it is formed, thus preventing overheating and cracking. The presence of the air allows the fuel to evaporate at a lower temperature, and the charge enters the combustion zone as a very hot mixture of air and fuel vapour, *i.e.* in a suitable state for immediate combustion. The admission of secondary and tertiary air is arranged in a manner fundamentally similar to that adopted for the vortex system.

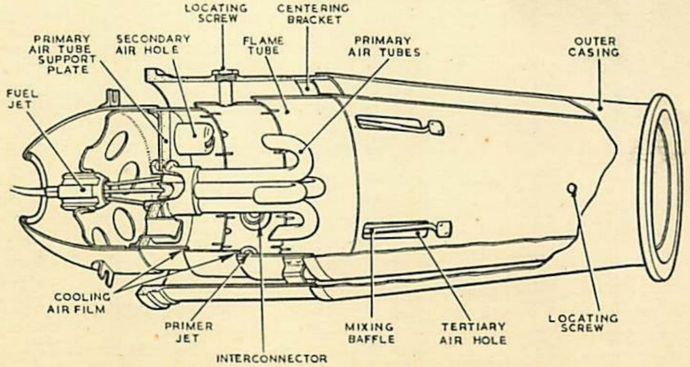

Fig. 14. Vapour System Combustion Chamber.

41. The main points of interest in the vapour system are :—

(*a*) Combustion efficiency is not seriously affected by variations in fuel pressure, mixture ratio and air temperature and pressure.

(*b*) A low-pressure fuel system may be used.

(*c*) The system can be applied to the annular or multiple combustion-chamber arrangements.

(*d*) The system operates satisfactorily with a wide range of fuels.

(*e*) There are no involved production problems.

Further information and constructional details of the vapour combustion system are given in A.P. 4293A, Vol. 1, and A.P. 4282, Vol. 1, Sect. 1.

Combustion Chamber and Burner Deposits

42. Experience has shown that operating conditions giving low combustion efficiency, *i.e. idling* at high altitude, are the most likely conditions to cause burner and flame tube fouling with carbon deposits. Any formation of carbon around atomizing burners upsets the spray pattern and results in low combustion efficiencies, which in turn lead to further carbon formation. This gradual build-up causes overheating and distortion of the flame tubes.

Flame Tube Materials

43. The flame tube is subject to a number of stresses arising from thermal expansion, and consequently the material must have sufficient high-temperature strength to resist distortion and cracking under these stresses. Pressure pulsations from the airstream and the flame, lead to the development of alternating stresses in the flame tube, so that resistance of the material to fatigue is essential. Flame tubes are usually manufactured from a heat-treated nickel-chrome steel containing silicon, manganese, aluminium, and titanium. The air-casing is usually made from stainless steel, as the stress and temperature requirements are comparatively low.

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