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28. DESIGNS AND CHARACTERISTICS OF COMBUSTION CHAMBERS

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We shall investigate several combustion chamber designs for modern gas-turbine engines to determine how they satisfy the requirements imposed upon them.

At present, there are still no established opinions on combustion chamber design and therefore chambers of modern gas-turbine engines may be quite different in form, methods of mixing fuel with air, organization of the combustion chamber, cooling of the chamber walls, and creation of a uniform temperature field at the chamber outlet.

Combustion chambers can be divided into three groups with respect to construction.

The first group includes annular chambers in which the engine has one common annular chamber between the compressor and turbine.

The second group includes tubular block chambers, which are several individual chambers in a common housing.

The third group includes tubular individual chambers, in which the engine has several separate chambers in the annular space between compressor and turbine.

Low weight and small size are the advantages of the annular chambers in comparison with individual chambers. The advantage of individual tubular chambers is that production and finishing of these small chambers is a comparatively easy task. Combersome experimental high-power units requiring large amounts of air are not needed to test individual chambers.

Tubular chambers are most advanced, combustion being relatively complete and operation relatively stable under various exploitation conditions.

At present, most gas-turbine engines have 6 to 10 combustion chambers of the tubular types.

Annular Combustion Chambers, and Zone (Figures 282-283)

The combustion products are mixed with air which has not participated in combustion in the second part of the chamber (B). This is the zone of mixing and after burning.

The air entering the chamber is divided into two streams, primary and secondary. Primary air enters the combustion zone through annular holes (V in Figure 283) of the burners, which are placed in the forward part of the chamber and equipped with injectors. Secondary air passes through the annular space G which surrounds the combustion zone. At the end of this space are forty V-shaped mixing nozzles arranged in a chockerboard pattern on both the inner and outer jackets. This creates a very fine grid of eighty nozzles to promote good mixing of the burning gases coming from the chamber A along the central ring with secondary air leaving the annular cavity surrounding the combustion chamber through the mixing nozzles.

There is a row of holes in the forward part of the outer jacket 7 through which a small amount of air serving for cooling enters the space behind the jet device of the turbine from the narrow canal between the housing 6 and the outer jacket 7.

The inner jacket 8 also has two rows of holes in the forward part, through which air enters the canal formed by the inner jacket 8 and the central bases of the chamber 10, and then into the hollow blades of the jet device of the turbine in order to cool them.

The front unit in the forward part of the chamber has 16 burners with injectors. Each burner has an outer cone 2 and an inner cone 3, at the end of which is a deflector (baffle) 4.

The main fuel injector (Figure 284) consists of housing 1, screen ~~netted~~ filter 3, and head 4. The injector head has ball valve 11 and a swirl 15.

Fuel enters into the inlet hole A of the injector and passes through the filter to the fuel ball valve 11, which drops by centrifugal force into the valve housing. Here the fuel passes through the canal V and then through the five holes G, which are drilled tangentially to the inner cylindrical surface of the swirl 15. Thus the fuel flowing into the combustion chamber through the central orifice (d=0.6 mm) is whirled intensively, which atomizes the jet flowing from the injector.

The combustion chamber is equipped with six supplementary starting injectors places between the main burners, and two spark plugs (Figure 285) are placed near the two upper injectors (Figure 285). The starting injectors are located in the forward part of the chamber where air velocity is very low. The injectors swirl the jet and provide fine fuel atomization.

In the burner of the chamber (Figure 286), air leaves the compressor with a velocity of approximately 150 meters per second, dropping to 100 meters per second in front of the combustion chamber. About 60-70% of the total air discharge enters the combustion zone of the chamber, while the remaining air is directed to the mixing canals through the holes G. Most of the primary air entering the combustion zone passes through canal 1 with a velocity of 60-70 meters per second. Swirls 2 form along the outlet from these canals. These swirls pick up the drops of the fuel spray 3 which leaves the injector in the form of a cone with an angle of approximately 30°. A small amount of air passes around the injector through the inner annular slot, as a result of which air is preliminarily mixed with part of the fuel in the inner cone of the burner.

Thus, the necessary conditions for good mixing of fuel with air and combustion of the mixture are created by partial mixing in the inner cone and the air swirls in the outlet from canal 1.

Important data on the test characteristics of one annular combustion chamber is shown below:

Air discharge	$G_A = 19$ kg/sec
Fuel ~~expenditure~~ consumption	$G_F = 1120$ kg/hour
Air Excess Coefficient	$\alpha \equiv 4$
Atmospheric Pressure at Chamber Inlet	$p_2 = 3.2$ kg/cm^2
Air Temperature at Chamber Inlet	$t_2 = 1.60°C$
Air Velocity at Chamber Inlet	$W_2^1 = 100$ m/sec
Pressure Loss in Chamber	$\Delta p = 0.15$ kg/cm^2
Average Gas Temperature at Chamber ~~Outlet~~	$t_3 \approx 750°C$
Gas Velocity at Chamber Outlet After Mixing	$W_3 = 95$ m/sec
Coefficient of Heat Liberation	ξ[illegible]$_{co} = 0.93$–0.95
Combustion Intensity With Respect to Total Chamber Volume	$Q_c = 104 \cdot 10^6$ kal/m^3/hour
Combustion Intensity With Respect to Volume of Combustion Zone	$Q_c' = 240 \cdot 10^6$ kal/m^3/hour
Total Chamber Volume	$V_c = 0.11$ m^3
Volume of Combustion Zone	$V_c' = 0.48$ m^3

[Coefficient of heat liberation is probably the same as "temperature efficiency" defined as the ratio: $\frac{\text{Actual Temperature Rise}}{\text{Theoretical Temperature Rise}}$. Combustion intensity is close to our heat-release rate, being expressed in heat units per volume units per hour instead of heat units per volume units per hour per atmosphere].

The combustion chamber discussed here was designed after long experiment, but still gives comparatively satisfactory results only for definite velocities, temperatures, and pressures of the air flow.

If the air velocity or pressure changes while the overall air excess coefficient remains constant, the composition of the mixture in the combustion region will change and will not correspond to the maximum combustion speed because of the change of conditions of formation of the annular swirls. Thus, with an increase in the air flow velocity in the swirl space, a relatively greater quantity of air will be admitted, the air excess coefficient will increase and for a certain maximum air velocity, the flame will collapse, i. e., be extinguished.

A change of fresh air temperature or fuel consumption, i.e., of the gas temperature, also influences the combustion process.

In the combustion chamber under consideration, for example, combustion is poor at great heights, i.e., stability of the process is broken and combustion is relatively incomplete, due to the air temperature decrease and poorer atomization.

The flame collapse boundary was studied experimentally in a cylindrical combustion chamber. (See Figure 287 for a diagram of the test unit and the chamber studied.)

In the experiments, by changing the amount of fuel injected, i.e., by changing the composition of the mixture, a regime was selected at which combustion became unstable and rapidly stopped for a further increase of fuel consumption. Proximity to this critical regime was recognized by intensification of noise in the chamber. In addition, approach to flame collapse conditions was revealed by vibration of the manometer needle registering fuel pressure, this vibration being caused by gas pressure variations at the unstable flame front. In each te~~x~~st, gas velocity was minimum at starting and was gradually increased to the desired value.

Experiments (Figure 288, 289, 290 summarize the results) have been conducted to determine the flame collapse boundary for two different atmospheric pressures at the combustion chamber inlet ($P_A = 0.9$ and 1.2 atmospheres) as a function of the air excess coefficient. The air temperature in both cases was 15°C.

The results obtained for both pressures are also compared (Figure 290). The comparison was made for the lower broken curves, since these obviously determine the beginning of possible flame collapse and are of practical importance. The results obtained show that the influence of atmospheric pressure upon the flame collapse boundaries is negligible in the region investigated.

A comparison of the flame collapse boundaries is next made for atmospheric pressure p_v of 1.2 atmospheres and two air temperatures, 15 and 90°C (Figure 291). As diagrams show, the air temperature increase considerably expands the region of stable combustion.

Flame collapse and the difficulty of starting an engine at high flight altitudes are due in considerable measure to the influence of air temperature.

All experiments showed a marked influence of air velocity upon the flame collapse boundary, especially for low air excess coefficients alpha α. A definite air velocity, the increase of which led to flame collapse, corresponds to each value of alpha for definite pressures and air temperatures.

The investigations also showed that the quility of atomisation, the fuel composition, and the way in which the combustion products are drawn from the chamber all influenced the flame collapse boundary.

The Tubular Block Combustion Chamber

The tubular block chamber consists of several individual chambers connected in a common housing in one block between the compressor and turbine (schematic diagram of this chamber is shown in Figure 292).

Each individual combustion chamber (Figure 293) has an individual jacket 1, in which are installed the injector 9 and the spark-plug 10. Only three chambers are supplied with spark plugs, fuel being ignited in the remaining chambers when starting the engine through the corrugated connecting sleeves.

The main fuel combustion takes place in the precombustion chamber, situated in the forward part of the chamber. The combustion products are mixed with diluting air in the mixer, located behind the precombustion chamber.

In the forward part of the precombustion chamber, there is an air swirl 4 with 6 bent blades, which are welded to the walls of the precombustion chamber and to the central tube 5.

The rear part of the precombustion chamber is equipped with a jet stabilizer 3, consisting of a solid bottom, the reflector (baffle) 6, and ten tubular inclined braces 7 (forming a truncated cone) welded to the reflector. The braces are hollow canals through which air passes into the precombustion chamber from the annular slot A. There are slots B between the braces, through which the gases flow out of the precombustion chamber.

The injector in the center of the precombustion chamber sprays fuel toward the air flow (Figure 294). The injector is equipped with a swirl 4 with tangential canals which twist the outgoing fuel.

Each chamber has an outer casing 1 forming an annular canal A through which air which has not participated in combustion passes into the mixer.

In the high-temperature zone, the chamber casing is protected by the screen 8 made of 1-millimeter sheet steel covered with aluminum. All six chambers are covered by a common housing made of sheet steel. The air fed by the compressor into the combustion chamber is divided into two flows. Primary air enters the precombustion chamber and participates in fuel combustion. Air enters the precombustion chamber through the swirl and the flow is made highly turbulent. The central air jet, which passes through the central tube of the swirl, impinges on the fuel jet which is fed into the flow and increases the angle of the fuel spray cone. The resistance of the precombustion chamber to the passage of gases is great due to the solid bottom and narrow slots at the end of the precombustion chamber, and only 20-30% of the air fed from the compressor passes through it.

These factors create favorable conditions for afterburning of the mixture in the precombustion chamber, and the red-hot bottom of the stabilizer promotes stability of the combustion process.

The remaining air (secondary air) passes into the annular canal A and then is distributed in the following manner:

The main part of secondary air passes along the annular slot into the space over the stabilizer 3 and enters the back part of the precombustion chamber through the tubular inclined braces 7, where it is mixed at the bottom of the stabilizer with the combustion products and participates in burning the incompletely-burned mixture. Part of the air passes alongside the screen 8, cools it, and passes into the mixer where it is mixed with the combustion products.

The main mixing of the combustion products with secondary air takes place in the space over the stabilizer 3 of the precombustion chamber, where air enters from canal A and the combustion products through the slots B of the stabilizer. Comparatively good mixing is attained rapidly in the mixer due to the intensive eddies emerging behind the bottom of the stabilizer. Partial burning of unburnt fuel takes place here.

Below we give the more important data on one of the block combustion chambers for normal operation.

Air Discharge Through One Chamber	$G_A = 3.4$ kg/sec
Fuel ~~Expenditure~~ Consumption in One Chamber	$G_F = 218 \cdot 220$ kg/hour
Air Excess Coefficient	$\alpha = 3.8$
Atmospheric Pressure At Chamber Inlet	$p_2 = 3.1$ kg/cm^2
Air Temperature at Chamber Inlet	$t_2 = 160°C$
Air Velocity at Combustion-Chamber Entry	$W_2^1 = 80$ m/sec
Pressure Loss in the Chamber	$\Delta p = 0.185$ kg/cm^2
Average Gas Temperature of Chamber Outlet	$t_3 \approx 760°C$
Coefficient of Heat Libration	$\xi_{cc.} = 0.92-0.95$
Combustion Intensity With Respect to Total Chamber Volume	$Q_c = 1.34 \cdot 10^6$ kal/m^3 hour
Total Volume of One Chamber	$V_c = 0.0167$ m^3

The Tubular Combustion Chamber (Figures 295-296)

The chamber consists of an inner flame tube and an outer casing.

The flame tube, made of heat-resistant sheet steel, has two parts, namely, the head, consisting of the swirl 4, the plate (tarelka) 3, and the cone 5, and the housing, having cylindrical 6 and conical 8 sections. The swirl 4 is in the center of the flame tube head and consists of an inner ring A, and outer ring V, and the blades B between them, connected with the rings by a spot weld. The plate 3 and the cone 5 have many holes for passing and "turbulizing" air entering the flame tube.

The flame tube housing consists of two conical parts connected by a housing ring having many holes and a cylindrical part. The cylindrical part of the flame tube has two rows of holes to admit air into the combustion zone from the annular cavity formed by the flame tube housing and the casing. The second conical section of the flame tube has four rows of holes, through which air from the same annular cavity enters the mixing zone.

Each chamber has one injector of the open type, installed in the inner ring of the swirl, which admits fuel in the direction of flow (Figure 297). Entering the injector, the fuel passes through the filter and enters the annular space, from which point it is directed into the swirl, which has three tangentially placed holes. After being swirled intensively, the fuel jet passes out through the nozzle of the injector into the air flow.

The air fed by the compressor into the combustion chamber is divided into two flows.

Primary air enters the flame tube head through the central canal and passes into the cylindrical part of the flame tube, partly through the swirl vanes and partly through the holes of the plate and cone. Additional air enters the combustion zone through the two rows of holes in the cylindrical part of the flame tube.

The swirl and breakdown of the air flow by the perforated plate and cone surfaces promotes strong "turbulization" and good mixing of the flow entering the flame tube. The amount of twisting of air by the swirl and the dimensions of the swirl and head are selected to create reversed eddied flows of hot gases which ignite the fresh mixture and yet do not disturb uniform mixture distribution along the chamber when the chamber is operating normally. Tests ~~[illegible]~~ show that the twisting of air by the swirl and reversed eddied flows of hot gases provide the combustion speed necessary for flame stabilization under the most diverse operating conditions of the chamber, while the coefficient of heat liberation ~~[illegible]~~. $\xi_{c.c.}$ is high for all conditions.

Secondary air enters the mixing zone by passing through the annular cavity between the flame tube housing and the combustion chamber casing and through the four rows of holes on the second conical part of the flame tube, and also through the holes in the ring connecting the two conical parts of the tube. Intake of air mixing with the hot gases is increased towards the end of the tube because the diameters of the holes of the last rows are larger than those of the first two rows.

Thus, after combustion of the main mass of fuel in the first cylindrical part of the flame tube, where the air excess coefficient does not exceed $\alpha = 1.5$ and where, consequently, high temperatures are developed, the combustion products passing along the tube are mixed gradually with the secondary air coming in through the radial holes. This results in combustion of unburnt fuel and decreases the temperature of the gases (t_3) to an average of 850-875°C for an overall air excess coefficient $\alpha = 3.8$.

The important data for one of the tubular combustion chambers is given below.

Air Discharge Through One Chamber	G_A = 3.17 kg/sec
Fuel Consumption ~~Expenditure~~ in One Chamber	G_F = 200-210 kg/hour
Air Excess Coefficient	α = 3.8

Atmospheric Pressure at Chamber Inlet	$P_2 = 4.2$ kg/cm^2
Air Temperature at Chamber Inlet	$t_2 = 200$°C
Pressure Loss in Chamber	$\Delta p = 0.18$ kg/cm^2
Average Temperature of Gases at Chamber Outlet	$t_3 \approx 830$°C
Coefficient of Heat Liberation	$\xi_{c.c.} = 0.97$

Tests of the characteristics (Figure 298) of a chamber demonstrate that the temperature of gases in front of the turbine varies over the broad interval from 750 to 1100° K; at the same time, the coefficient of heat liberation remains almost unchanged.

The peculiarity of another tubular combustion chamber (Figure 299) is the use of two-canal injectors and special ignition units.

The fuel enters the injectors (Figure 300) through two pipes, the starting pipe and the main pipe. From the main pipe, the fuel enters the annular space around the conical swirl 3 and then passes through ring 7 into the lamellar swirl 4, which has six tangential slots G. Fuel enters the vortex chamber V from the lamellar swirl and goes out through the injector nozzle 5.

From the starting canal, the fuel passes through the spiral canals of the conical starting swirl 3, enters the vortex chamber V, and is sprayed into the combustion chamber through the injector nozzle 5.

For high ~~expenditures~~ consumption, the fuel enters both pipes. In this case, part of the fuel passes through the lamellar swirl and part through the conical swirl, after which all fuel enters the vortex chamber V of the injector and from there is sprayed into the combustion chamber through the nozzle.

For low consumption, the fuel enters the injector only through the starting canal, which is also the low-gas canal. In this case, the fuel passes only through the conical swirl, and then through the vortex chamber and nozzle.

Use of the two-canal injector guarantees good atomization of the fuel under all operating conditions.

The ignition unit (Figure 301) consists of a starting injector, a sparkplug, and a control mechanism, the solenoid valve. When starting the combustion chamber, the valve is opened, and the starting fuel enters the starting injector, through which it is sprayed into the spark-forming space around the plug. The walls of the spark-forming cavity, which are projected inside the combustion chamber have a row of holes though which secondary air, by passing between the flame tube housing and the chamber jacket, enters the atomized jet of starting fuel and forms the mixture ignited from the plug. The tongue of ignited starting fuel is spread into the main combustion zone of the chamber, where ignition of the main mixture takes place.

Ignition units are installed in two chambers. The fresh mixture in the other chambers is ignited with the help of flame-transmitting tubes which connect the combustion spaces of all chambers.

The important parameters of this combustion chamber as obtained from tests are shown below:

Discharge of Air Through One Chamber	$G_A = 4.5$ kg/sec
Fuel Expenditure in One Chamber	$G_F = 290$ kg/hour
Air Excess Coefficient	$\alpha = 3.8$
Atmospheric Pressure at Chamber Inlet	$p_2 = 4.1$ kg/cm^2
Average Temperature of Gases at Chamber Outlet	$t_3 = 850^\circ$C
Coefficient of Heat Liberation	$\xi_{c.c.} = 0.96-0.98$
Combustion Intensity With Respect to Total Chamber Volume	$Q_c = 102 \cdot 10^6$ kal/m^{2}hour
Total Chamber Volume	$V_c = 0.0285$ m^3

Limiting ourselves to the most typical combustion chambers of gas-turbine engines which we have considered, we conclude the following:

Good mixture-formation should be especially strived for in the design of chambers, since this process limits to a considerable degree the combustion process. In a number of cases, the combustion speed is determined by the speed of mixing of fuel with air. Therefore, mixture-formation problems play an important part in designing combustion chambers, especially those of gas turbine engines, where large amounts of fuel must be burned with high heat release in a gas flow moving with high speed. All modern combustion chambers of gas-turbine engines are equipped with well-designed units and special injectors which provide rapid and complete mixing of fuel and air.

The second characteristic of all modern combustion of gas-turbine aircraft is that all chambers are divided into two zones, i.e., the combustion zone and the mixing zone.

At the present development of metal studies as applied to the use of turbine blades which do not have special cooling, the temperature of gases in front of the turbine must not exceed 850-870°C. This temperature is reached when a fuel-air mixture is burned with an air excess coefficient in the mixture of 3.5-4.0.

Great difficulties were encountered in organizing the combustion process for such poor mixtures in the gas flow because the speed of the gas flow in modern combustion chambers for gas-turbine engines is approximately equal to the flame propagation speed of a normal mixture ($\alpha \approx 1$). A poorer mixture, as is well-known, decreases the speed of flame propagation. Therefore, the flame will collapse and be extinguished in the combustion of poor mixtures.

In order to provide the necessary combustion speeds of the mixture at the end of the chamber, we must divide the combustion process into two parts, namely, into combustion of the main fuel mass, and mixing of the combustion products with additional air. Thus, the combustion chamber is divided into two zones, the combustion zone, where the main mass of fuel is burned with an air excess coefficient providing high flame propagation speeds, and the mixing zone, where the temperature required in front of the turbine is attained by mixing of the combustion products with diluting air. For this reason, the air entering the chamber from the compressor is divided into two parts in all modern chambers. The first part (primary air) enters the main combustion zone, while the second part (secondary air) does not participate in the main combustion but is mixed with the combustion products in the mixing zone to reduce the gas temperature to the required value.

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