COMBUSTOR CHAMBERS

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Summary

The requirements to stable firing range, complete fuel burnup, turbine inlet temperature field non-uniformity, pressure drop, emissions of harmful substances are given which are necessary to ensure reliable and economic combustor operation.

The prospects of upgrading the combustor working process are considered and the low-NOx combustors firing lean homogeneous mixtures along with the long-term operational problems are reviewed.

Further improvement in combustors should be directed to increase the pre-mixing efficiency and to provide for stable combustion when gaseous and liquid fuels are fired. Catalytic combustors are among the most promising trends in this field. Main results of experiments and industrial tests of catalytic combustors are given.

1. Introduction

The purpose and role of the combustor in the gas turbine cycle is described providing the brief prehistory of the combustor evolution and the working process. Depending on the purpose of a gas turbine, fuel used, and heat cycle, the classification of combustors is given by the types and the design thereof. The advantages and drawbacks of the external, annular, tubular and sectionalized combustors are reviewed.

Various methods of firing are reviewed vs. ecological and economical characteristics. The purpose and the design of main components of the combustor such as igniter, stabilizer, swirlers, burner, atomizers, combustion liner, mixers and gas plenum are described.

2. Gas Turbine Combustor and its Application.

In a modern gas turbine unit (GTU), the combustor is the most responsible and heat loaded component defining reliability, efficiency and ecological friendliness of the unit as a whole.

The purpose of the combustor is to increase the temperature of the air compressed in the compressor to that of the working gases fed to the GT blades. The temperature is increased due to fuel firing in the flow of the air supplied by the compressor. In the process of fuel oxidation, the fuel chemical energy is converted to the thermal energy imparted to the working fluid (air) delivered to the turbine from the combustor. The air to the combustor is fed either directly from the compressor or after being preheated in the regenerator. In the case of a multi-stage GT, the combustor receives the gas-air mixture from the dedicated turbine.

The combustor in the GTU cycle is a semi-constrained space continuously fed with fuel and oxidizer (air with a certain percent of oxygen) and discharging the combustion products. The flow of air fed to the combustor is split into the primary air to form the fuel-air composition providing for complete combustion, and the secondary air to cool down the metal and to be mixed with the combustion products to reduce the their temperature to the required level. The combustor firing space is divided into the combustion and mixing zones.

The amount of the air fed to the combustor is generally rather large (almost as high as three times and above) required for fuel complete combustion. This ensures the preset turbine inlet temperature level of the combustion products.

Despite of a simple design of the combustor, the working process in it is very complicated including mixture formation, burnup, heat and mass transfer both inside the combustor volume and during gas flow-components interaction.

The rationale of the combustor lies in successful stable and pulse-free firing of both liquid and gaseous fuels at high temperature, low total head loss, turbine inlet temperature field nonuniformity with limited dimensions and weight of the combustor components, and provision of the required reliable and long-term operation.

3. Brief Prehistory

Because combustor is an integral part of a gas turbine its history is inseparable from the evolution of gas turbine engine.

The history of the last two centuries abounds with evidences of the attempts of many investigators to find the perpetual mobile capable of transforming the fuel energy into the mechanical work in a most simple way. The idea of a heat engine close in principle to a modern gas turbine came back to 1791 when the first patent was granted to J. Barber (Great Britain).

The attempts of numerous scientists and inventors from various countries to create a rational, viable design of a gas turbine were doomed until the birth of the fundamentals of a theory of the processes governing turbine operation.

A well-known Russian scientist -- academician L. Euler, constructed the turbomachinery fluidics (theory of jets) two centuries ago. The hydrodynamics of blade form and turbine cascades is based on the fundamental works by Russian scientists N.E. Zhoukovsky and S.A. Chaplygin [B. 3: Y. P. Storozhuk. Combustors of GTU and Combined Cycle Plants. Machine-building Publishers, Moscow, 1978], founder of a theory of the fundamentals of modern gas dynamics. In 1897, P. D. Kouzminsky [B. 3], mechanical engineer of the Navy of Russia, worked out the original design of a gas turbine, which was constructed and prepared to testing by the author in 1899-1900. The gas turbine of P. D. Kouzminsky design was the world's first practical embodiment of a gas turbine.

Figure 1 illustrates the world's first application of a radial turbine to drive a small steam-launch. The turbine operated on a steam-gas mixture of "pure" combustion products, resulting from firing kerosene, mixed with superheated steam to reduce the mixture temperature. The trial test turbine speed was 8000 rpm. The maximum combustor pressure was found to be 1.5 kPa with the design pressure of 10 kPa. The operation of the combustor was not a success because of too high temperature despite the addition of a superheated steam. The turbine efficiency was three percent maximum, but for the first time turbine provided a useful work.

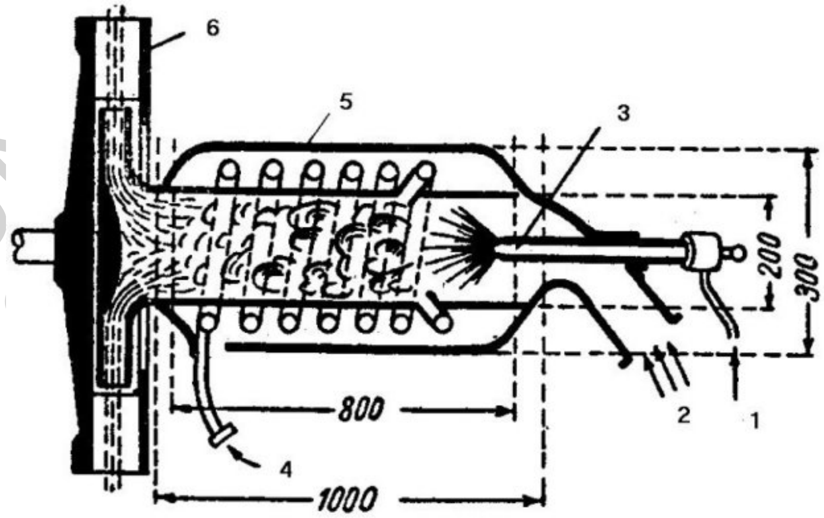

Figure 1. Gas Turbine and Combustor of P.D. Kouzminsky Design (1897)

In the period of 1905-1906, a commercial installation was constructed in Paris by the design of engineers Armango and Lemal [B. 1: Lefebvre A. H. Gas Turbine Engine Combustor Processes. Hemisphere Publishing Corporation, 1986] of 400 h.p. (~ 300 kW) capacity.. The combustor, multistage centrifugal compressor and Curtis turbine made up the facility. The turbine and associated compressor speed was 4250 rpm.

The longitudinal cross-sectional view of the combustor is shown in Fig. 2. The liquid fuel was injected via jet 1 and the air was fed by tube 2. Starting ignition was by igniter 3 and subsequent fuel evaporation and ignition were due to utilization of the heat from the lining.

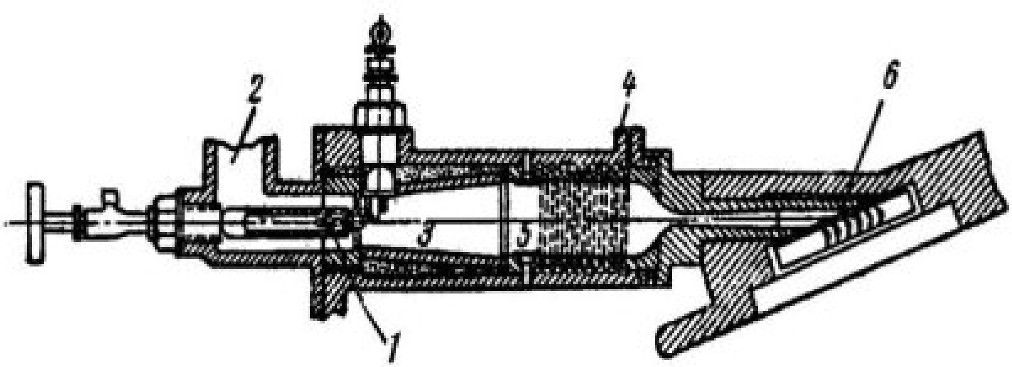

Figure 2. Combustor of Armango and Lemale Design

The temperature of the combustion products was decreased by evaporation of the water supplied from the coil. The water was fed to the coil via connection 4 and to the combustor - via opening 3. The combustion products were directed to turbine 6, the developed power of which was absorbed by the compressor capable of compressing the air to a pressure of 0.5 MPa. The major part of the air was utilized by the facility and the remaining part was used for the technological purposes. Thus, the turbine, like the GT of P. D. Kouzminsky provided a useful work.

The above-mentioned gas turbines and GTU, as well as other similar installations of that period suffered from a common disadvantage of low efficiency. In this connection, all attempts of scientists and inventors, manufacturers and companies to create a gas turbine valid for practical applications had not been for a long time a success. Just in 1939, Brown Boveri constructed stationary GTU of 4000 kW and 18 percent efficiency.

The low efficiency of first GTU was due to imperfect design of compressors, turbines and combustors and lack of the technology of manufacturing heat-resistant materials. The evolution of GTU and, in particular, of combustors was greatly accelerated by the construction of aircraft GT engines during the World War II and in the post-war period. The large-scale works and field tests of various concepts enabled the optimal design principles to be elaborated and technological issues to be solved ensuring wide application of GTU first for aviation and later in other branches of the industry, in power industry, in particular.

In the process of the GTU development, the approaches and ideas, the designers were guided by in the selection of the combustor configuration and main parameters, had been perfected. Figure 3a illustrates the simple combustor -- cylindrical tube interconnecting the turbine and compressor. Unfortunately, such design is not practicable because of high-pressure losses in the compressor-combustor-turbine train.

The pressure losses due to the heat input (firing) are in general proportional to the square of the air flow velocity. Since the compressor outlet velocity is close to 150 m/s, the pressure losses may reach in this case of one-fourth of the total compressor pressure rise.

To decrease the pressure losses to the acceptable level, use is made of the diffuser (refer to Fig.3b) which is capable of decreasing the air velocity as low as by about five times. However, it is insufficient because the prevention of flameout and keeping stable firing can be obtained by providing a low-velocity zone using the back currents (streams). Figure 3c shows how it is reached by using a plate.

This device suffers, however, from a drawback where the air/fuel ratio of 3.0-10.0 is required to obtain the preset temperature rise. This figure considerably exceeds the ignitability limit of fuel-air mixtures. In an ideal case, the air/fuel ratio shall be 1.1-1.2, though, for example, to reduce NOx emissions, the figure may be increased up to about 2.0-2.5.

This drawback can be eliminated, as shown in Fig.3d, by using a perforated combustion liner. A low-velocity zone is established in the combustion liner wherein firing is maintained by the circulating flow of combustion products, which continuously ignites the fresh fuel-air mixture fed to the combustor. The excess (not needed for firing) air portion is introduced into the combustion liner upstream of the firing zone to be mixed there with the hot combustion products thereby lowering their temperature to the level acceptable for the turbine. Thus, one can see that Fig.3 illustrates the logical evolution of the working process in the combustor of a most spread scheme.

Now, a number of new ecological requirements are claimed to combustor designs. To meet the standards, the combustors of novel designs with new fuel firing technologies are under way to be described hereinafter.

4. Combustor Arrangement in the Gas Turbine System

Depending on the GTU application, fuel, and heat cycle various types and arrangements of combustors are used. Therefore, it is next to impossible to create a unified combustor to meet a wide spectrum of requirements and parameters of the working process. By now, several types of combustors are available to provide for a selection of a design that satisfies the most of the combustor requirements claimed by a specific GTU. As regards the integration into GTU circuit, the combustors are classified as main and those used for intermediate gas preheating. Against the arrangement, the combustors are known as external and in-built.

The external combustors (Fig.4a) are arranged in a separate casing together with the combustion liner in parallel or perpendicular to the unit longitudinal axis. Such combustors are readily integrated with GTU, especially of the regenerative type, are convenient to be serviced and repaired. The long tubes between the combustor and turbine provide for good conditions for reliable mixing of the combustion products. However, along with such advantages, the external combustors feature the following substantial drawbacks: larger dimensions and availability of cross-over pipelines which increase GTU overall dimensions and weight (complicating the compensation for gas/air duct thermal expansions), as well as difficulties in testing and operational development of the full-size combustors.

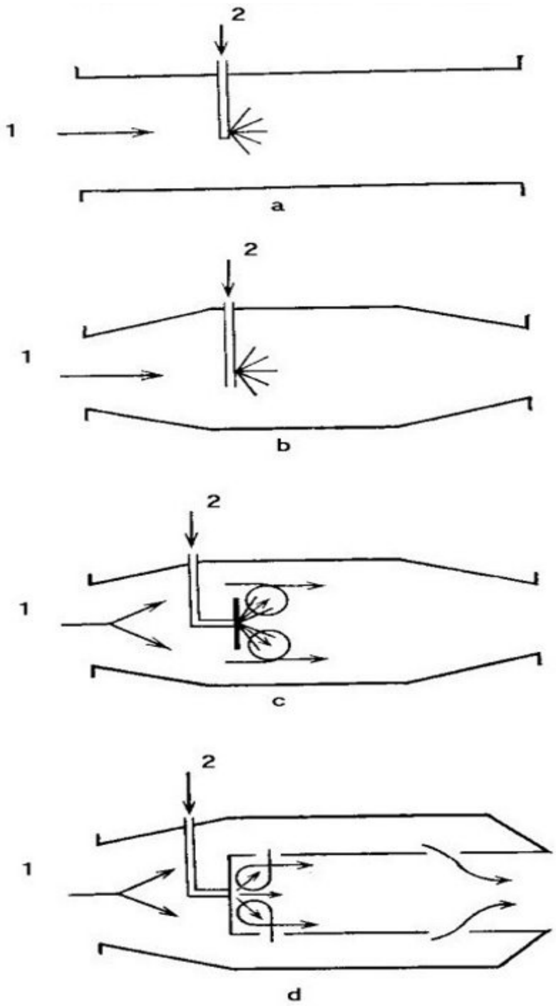

Figure 3. History of Design Evolution of Traditional Gas Turbine Combustor

The in-built combustors have a common casing with GTU. Depending on the design, the combustors are subdivided into annular (Fig.4b), tube-annular (Fig.4c), and sectionalized (Fig.4d).

The annular-type combustors, having a common annular firing zone (Fig.4b), are widely used in the aircraft gas-turbine manufacture. They possess a number of advantages as compared to the sectionalized and tube-annular designs. As regards annular-type combustors, the overall dimensions, including those of the firing zone space, are utilized to a better extent. Provisions are available for adequate stabilization and startup due to the absence of the flame crossover nozzles. Under otherwise equal conditions, such a combustor is of a lower weight and overall dimensions, and is convenient for the integration into the GTU.

In the stationary gas-turbine manufacture, the annular-type combustors are mostly used for intermediate and low capacity GTU as having some design imperfections of insufficient robustness with large diameters and inadequate stiffness because of intrinsic fabrication. The above factors are aggravated by easy buckling of the combustion liner with local overheat resulting in air redistribution and, hence, in the change of the temperature field. The mal-distribution of the temperature field can be improved by increasing the number of the jets used arranged in the swirlers of the burner unit. In this case, the fuel was found to be distributed in the airflow more uniformly. Also, among the disadvantages are impossibility of providing test conditions for large combustors similar to the full-size combustor. Certain problems relate to assembly, disassembly and inspection of the combustors.

The tube-annular combustors are made up by individual combustion liners inside the common annular casing wherein they are uniformly located round the shaft between the compressor and turbine (Fig.4c). This layout is an attempt to combine the compact design of the tube-annular combustor and the advantages of the sectionalized combustor. GTU with tube-annular combustors are of the compact design, have no long outer hot pipelines, ensure fast startup and picking up the working load. The rig and commercial operational development for such combustors is easier.

The sectionalized combustors, having combustion liners arranged in individual casings and a common air inlet (Fig.4d), feature much easier fuel-air mixing and intensive cooling of the combustion liner walls because of the uniform air distribution round the combustion liner. The operational development for such combustors is simpler and the individual combustors and their components can be rapidly replaced without disassembly of the GTU. However, the sectionalized combustors need large overall dimensions and weight for the same heat release rate of the tube-annular and annular combustors. The sectionalized combustors require more complex flame crossover nozzles complete with special compensators.

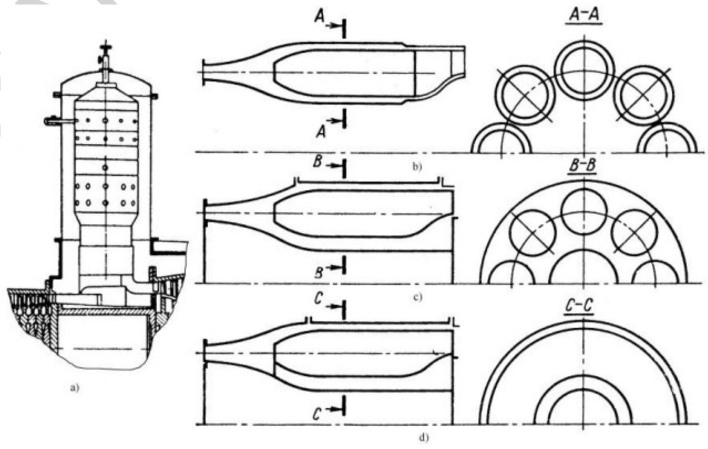

Figure 4. Classification of Combustors by Components Layout (Assembly in GTU)

Also, the combustors are classified according to the flow of air and combustion products as straight-through flow, reverse-flow and angular (Fig.5). In the straight-through flow combustors the air and combustion products streams are in the same direction, while in the reverse-flow and angular flow combustors the above streams are is in the opposite direction.

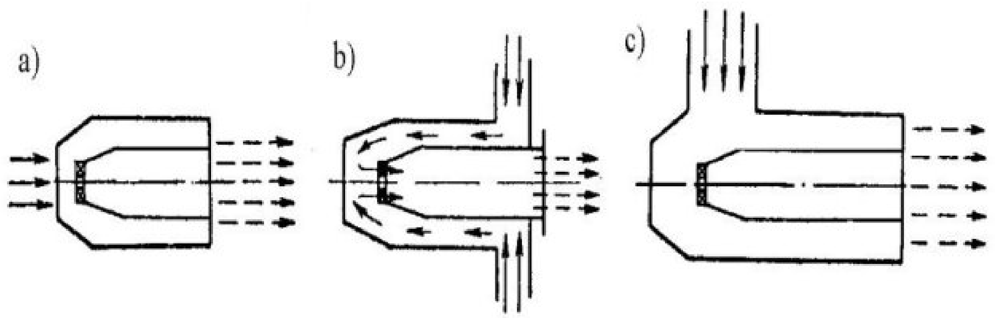

Figure 5. Classification of Combustors by Air and Gas Flow Patterns

For the criterion of the combustor firing rate, thermal loads of the working space and the sectional areas of the combustor are applied. The combustor heat release rate characterizes the utilization efficiency of the space occupied by the combustor. It is in fact the amount of heat released per unit of fire zone space per unit of time,

$$Q_V = (m_F.\Delta H_C) / V_L \cdot P_c \qquad (1)$$

where m_F is the combustor fuel consumption, Q_V is the fuel LHV, V_L is the combustion liner volume up to the combustor mixer, P_c is the combustor pressure. The heat release rate reflects the combustor fuel residence time.

The higher the heat release rate of the fire zone, the less is the combustor fuel residence time. In other words, the increased volumetric heat release rate demands the enhancement of all working processes in the combustor associated with firing which, as a rule, needs additional energy input. The heat release rate of the combustor cross-sectional area is defined by the following relationship:

$$Q_A = (m_F.\Delta H_C) / A_L \cdot P_c \qquad (2)$$

where A_L is combustion liner median cross-sectional area.

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Biographical Sketch

Anatoly G. Tumanovsky was born in 1939. In 1962 he graduated from Moscow Institute of Energetic (MEI). His work experience: Since 1962 until now – All-Russia Thermal Engineering Institute (Moscow). Expert in gas turbine combustor process, participant in research and development of several types of low NO_x combustors (NO_x < 25ppm). Manager of works on clean coal TPS, water chemistry optimization, reduction of harmful gaseous emission and waste water effluents, investigation of organic fuel and oils, thermal-physical processes in power generating equipments. Author of more than 200 published papers and 15 patents. Currently Dr. Anatoly G. Tumanovsky is the First Deputy Executive Director – Director of Science of JSC “All-Russia Thermal Engineering Institute” (JSC “VTI”).