COMBUSTION PROCESS IN THE GAS TURBINE ENGINE COMBUSTORS

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This study aimed to explain the whole burning process in the combustion chambers of gas turbine engines. Combustor is a crucial component of the gas turbine engine through which the chemical energy of the fuel is converted into thermal energy with minimal pressure loss and maximal efficiency meanwhile the emitted harmful pollutants and the deposit must be minimised. This heat addition process has many aspects which are must be examined. The fuel atomization, the best fuel-air mixture preparation, flame propagation, dilution are key elements of the whole combustion.

INTRODUCTION

The main purpose of the gas turbine combustors is to heat the compressed air up to a maximum temperature that which the turbine can tolerate. This heating process is achieved by burning the fuel thereby the chemical energy of fuel convert into thermal energy.
A combustion chamber must be capable of allowing fuel to burn efficiently over a wide range of operating conditions without incurring a large pressure loss. So the combustion chamber performance is very important.

The basic requirements of all combustors may be listed as follows:

1. High-combustion efficiency (i.e., the fuel should be completely burned so that all its chemical energy is liberated as heat)
2. Low pressure loss
3. Wide stability limits (i.e., the flame should stay alight over wide ranges of pressure and air/fuel ratio)
4. Reliable and smooth ignition, both on the ground (especially at very low ambient temperatures) and, in the case of aircraft engines, after a flameout at high altitude
5. An outlet temperature distribution (pattern factor) that is tailored to maximize the lives of the turbine blades and nozzle guide vanes
6. Low emissions of smoke and gaseous pollutant species
7. Freedom from pressure pulsations and other manifestations of combustion-induced instability
8. Size and shape compatible with engine envelope
9. Design for minimum cost and ease of manufacturing
10. Maintainability
11. Durability
12. Petroleum, synthetic, and biomass-based multifuel capability.

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PROCESSES IN COMBUSTORS

The whole combustor performance depends on many fundamental sub-processes which are take place in the combustion chambers.

I examine all process individually in this paper, which are the follows:

- decreasing of axial air speed using diffuser
- atomization and mixing
- flame stabilization
- combustion comletition
- dilution

The air enters the combustor, at which point it divides and flows into three separate passages. Two of these passages convey air to the inner and outer liner annuli in roughly equal proportions. The central passage discharges the remaining air into the liner, which provides air for atomization and dome cooling.
Three zones can be distinguished in the liner of the combustor. About 15-20 per cent of the air is introduced around the jet of fuel in the primary zone to provide the necessary high temperature for rapid combustion. Some 30 percent of the total air is then introduced through holes in the flame-tube in the secondary zone to complete the combustion. Finally, in the dilution zone the remaining air is mixed with the products of combustion to cool them down to the temperature required at inlet to the turbine [1][2].
The locations of the combustion zones described above, in relation to the various combustor components and the air admission holes, are shown in Figure 1.

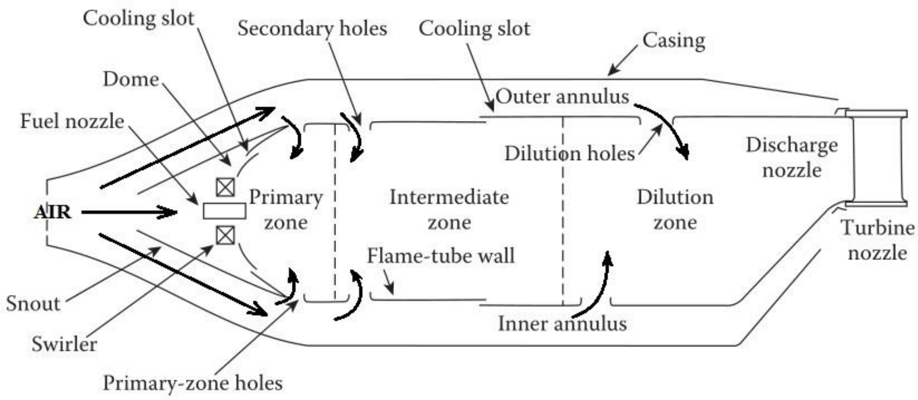

Figure 1. Main components and combustion zones of a conventional combustor [1]

DIFFUZER

Air leaves the compressor at a speed on the order of 180 m/s, but this is too high for the combustion therefore it is reduced to around 30-50 m/s before entering the combustor in order to prevent the flame from being blown away. The other reason of the speed decreasing is minimizing the pressure loss of the combustion chamber. For example, for an air velocity of 170 m/s and a combustor temperature ratio of 2.5, the pressure loss incurred in combustion would be approximately 25% of the pressure rise achieved in the compressor. Thus, before combustion can proceed, the air velocity must be greatly reduced, usually to about one-fifth of the compressor outlet velocity. This reduction in velocity is accomplished by fitting a diffuser between the compressor outlet and the upstream end of the liner.

The function of the diffuser is not only to reduce the velocity of the combustor inlet air, but also to recover as much of the dynamic pressure as possible, and to present the liner with a smooth and stable flow [1][2][3].

In its simplest form, a diffuser is merely a diverging passage in which the flow is decelerated and the reduction in velocity head is converted to a rise in static pressure. In long diffusers of low divergence angle, the pressure loss is high due to skin friction along the walls as shown in figure 2. With an increase in divergence angle, both diffuser length and friction losses are reduced, but stall losses arising from boundary-layer separation become more significant. Clearly, for any given area ratio, there is an optimum angle of divergence at which the pressure loss is a minimum. Usually this angle lies between 6° and 12° [1].

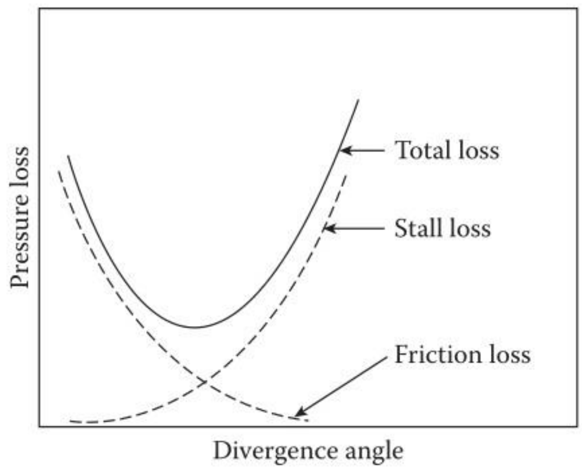

Figure 2. Influence of divergence angle on pressure loss. [1]

The types of frequently used diffusers:

- Two-dimensional diffusers (Figure 3.a)
- Conical diffusers (Figure 3.b)
- Annular diffusers (Figure 3.c)
- Vaned diffusers (Figure 3.d)

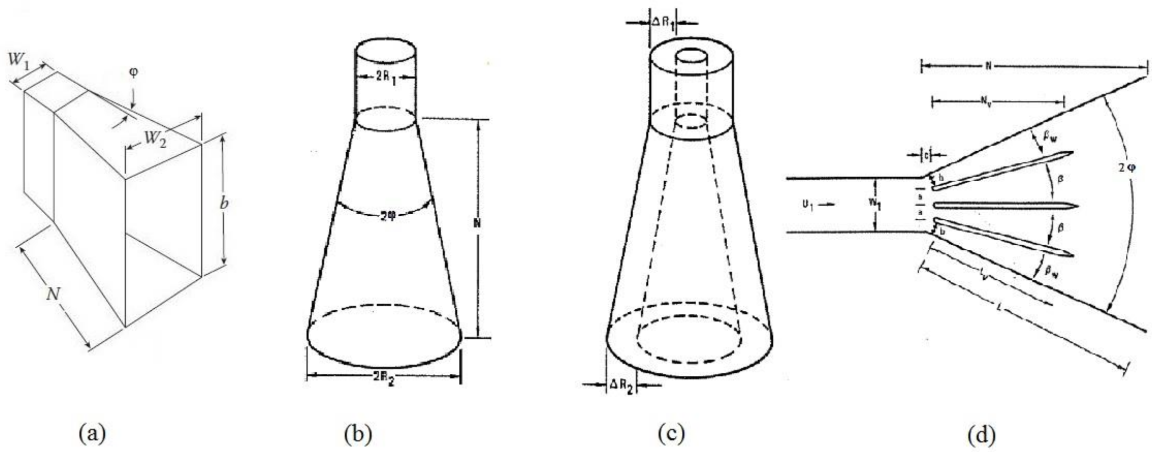

Figure 3. (a) Two-dimensional diffuser; (b) Conical diffuser; (c) Annular diffuser; (d) Vaned diffuser [4]

PRIMARY ZONE

The main function of the primary zone is to anchor the flame and provide sufficient time, temperature, and turbulence to achieve essentially complete combustion of the incoming fuel–air mixture.
The zonal method of introducing the air cannot by itself give a self-sustaining flame in an air stream which is moving an order of magnitude faster than the flame speed in a burning mixture. To stabilize the combustion it is therefore necessary to set up local regions with much smaller velocity. The solution is a recirculating flow pattern which directs some of the burning mixture in the primary zone back on to the incoming mixture. Many different types of flow patterns are employed, but one feature that is common to all is the creation of a toroidal flow reversal that entrains and recirculates a portion of the hot combustion gases to provide continuous ignition to the incoming air and fuel. Primary air is introduced through swirler, so that the resulting vortex motion will induce a region of low pressure along the axis of the chamber. This vortex motion is sometimes enhanced by injecting the secondary air through primary and secondary holes.as shown in Figure 4 [1][2].

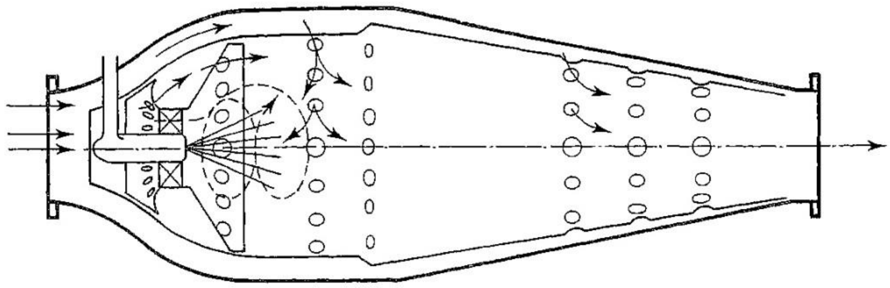

Figure 4. Recirculation zone in combustor equipped with swirler [2]

Swirlers

One of the most effective ways of inducing flow recirculation in the primary zone is to fit a swirler in the dome around the fuel injector. Vortex breakdown is a well-known phenomenon in swirling flows; it causes recirculation in the core region when the amount of rotation imparted to the flow is high, as illustrated in Figure 5.

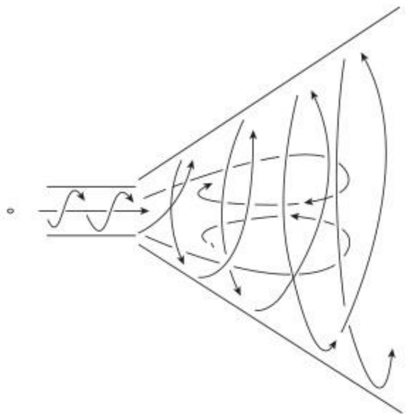

Figure 5. Flow recirculation induced by strong swirl [1]

The two main types of swirlers are axial and radial, as illustrated in Figure 6. They are often fitted as single swirlers, but sometimes as double swirlers that are mounted concentrically and arranged to supply either co-rotating or counter-rotating airflows [1].

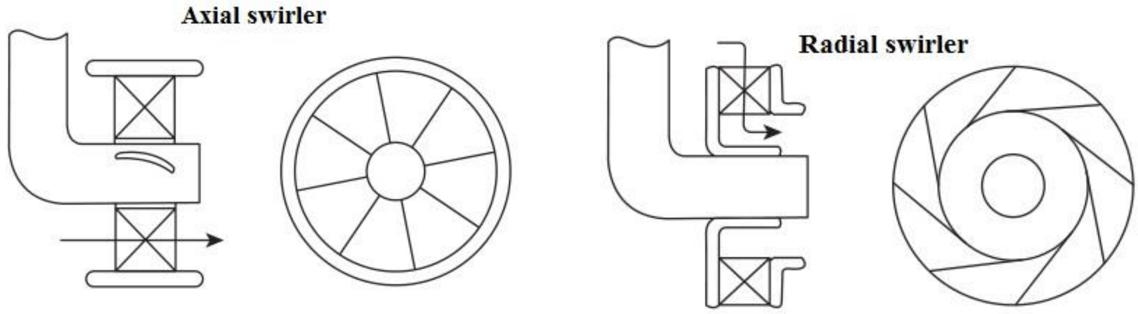

Figure 6. Two main swirler types [1]

The recirculation region in a free swirling flow is shown in Figure 7. Since the flow is assumed to be axisymmetric, only half the flow pattern is considered. The recirculation region is contained within the curve AB. The point B is called the stagnation point. Conditions of zero axial velocity are represented by the dashed curve AB. Typical axial swirl velocity profiles are shown in Figure 7. All the velocity components decay in the downstream direction. After the stagnation point (point B), the reverse axial velocities disappear, and further downstream the peak of the axial velocity profile shifts toward the centerline as the effect of swirl diminishes [1].
Experimental data show that the size of the recirculation zone is increased by [1]:
1. An increase in vane angle
2. An increase in the number of vanes
3. A decrease in vane aspect ratio
4. Changing from flat to curved vanes

SECONDARY ZONE

If the primary-zone temperature is higher than around 2000 K, dissociation reactions will result in the appearance of significant concentrations of carbon monoxide (CO) and hydrogen (H_2) in the efflux gases. Should these gases pass directly to the dilution zone and be rapidly cooled by the addition of massive amounts of air, the gas composition would be “frozen,” and CO, which is both a pollutant and a source of combustion inefficiency, would be discharged from the combustor unburned. Dropping the temperature to an intermediate level by the addition of small amounts of air encourages the burnout of soot and allows the combustion of CO and any other unburned hydrocarbons (UHC) to proceed to completion [1].
Incomplete combustion may be caused by local chilling of the flame at points of secondary air entry. This can easily reduce the reaction rate to the point where some of the products into which the fuel has decomposed are left in their partially burnt state. Since the lighter hydrocarbons into which the fuel has decomposed have a higher ignition temperature than the original fuel, it is clearly difficult to prevent some chilling from taking place, particularly if space is limited and the secondary air cannot be introduced gradually enough. If devices are used to increase large-scale turbulence and so distribute the secondary air more uniformly throughout the burning gases, the combustion efficiency will be improved but at the expense of increased pressure loss. A satisfactory compromise must somehow be reached [2].

DILUTION ZONE

The role of the dilution zone is to admit the air remaining after the combustion and to provide an outlet stream with a temperature distribution that is acceptable to the turbine. This temperature distribution is usually described in terms of "pattern factor"
The amount of air available for dilution is usually between 20 and 40% of the total combustor airflow. It is introduced into the hot gas stream through one or more rows of holes in the liner walls. The size and shape of these holes are selected to optimize the penetration of the air jets and their subsequent mixing with the main stream [1].
The crucial temperature is that to which the first turbine rotor is exposed (the stator outlet temperature, SOT) is the temperature of the flow into the rotor after hypothetical mixing of the cooling air with the hot gases. For a modern large civil engine SOT is not more than 1850 K, but for combat engines this temperature can be as high as about 2300 K. The highest flame temperature is about 2600 K, so in order to prevent the turbine the hot products must be cooled down in the last section of the combustion chamber [3].
An ideal pattern factor (Figure 7.) would be one that gives minimum temperature at the turbine blade root, where stresses are highest, and also at the turbine blade tip, to protect seal materials. Attainment of the desired temperature profile is paramount, owing to its major impact on the maximum allowable mean turbine entry temperature and hot-section durability [1].

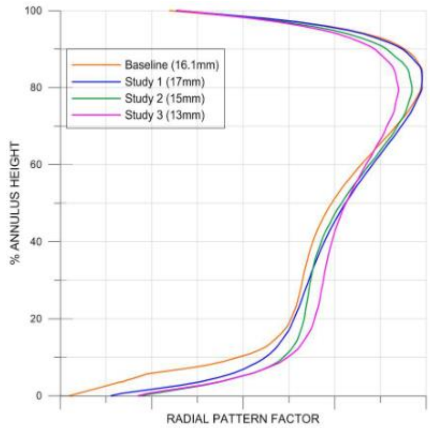

Figure 7. Radial temperature profile [6]

PRESSURE LOSS

The stagnation pressure of the products at the combustor outlet is less than the stagnation pressure of air at combustor inlet. This phenomenon is called pressure drop or pressure loss.

$$\Delta p_{3-4} = p_2 - p_3 \tag{1}$$

The pressure loss factor:

$$\sigma_{combustor} = \frac{p_3}{p_2} \tag{2}$$

where Δp_{3-4} pressure drop int he combustor
p_2 stagnation pressure at combustor inlet
p_3 stagnation pressure at combustor outlet
$\sigma_{combustor}$ combustor pressure loss factor

The pressure loss factor is about 95-97 % in a modern engine.
Combustion chamber pressure loss is due to two distinct causes:

- Skin friction and turbulence (cold loss)
- The rise in temperature due to combustion (hot loss).

$$\Delta p_{3-4} = \Delta p_{cold} + \Delta p_{hot} \tag{3}$$

The cold loss arises from sudden expansion, wall friction, turbulent dissipation, and mixing. Cold losses can be measured by flowing air without fuel through all the slots, holes, orifices, and so on. The cold loss can be predicted with the aid of the Fanno-line functions (Figure 8).
The hot loss, often called the fundamental loss, arises because an increase in temperature implies a decrease in density and consequently an increase in velocity and momentum of the stream. A pressure force must be present to impart the increase in momentum. One of the standard idealized cases considered in gas dynamics is that of a heated gas stream flowing without friction in a duct of constant cross-sectional area. The stagnation pressure drop in this situation, for any given temperature rise, can be predicted with the aid of the Rayleigh-line functions (Figure 8) [1][3].

$$\Delta p_{hot} = \frac{\dot{m}^2 R}{A^2 p}(T_3 - T_2) \tag{4}$$

$$\sigma_{hot} = \frac{p_3}{p_2} = \frac{p_2 - \Delta p_{hot}}{p_2} = 1 - \frac{\dot{m}^2 R}{A^2 p^2}(T_3 - T_2) \tag{5}$$

where
Δp_{hot} pressure drop of hot loss
σ_{hot} pressure (hot) loss factor
$\dot{m}$ mass flow
A combustor cross section area
p pressure
R univerzal gas constant
T_3 temperature at combustor outlet
T_2 temperature at combustor inlet

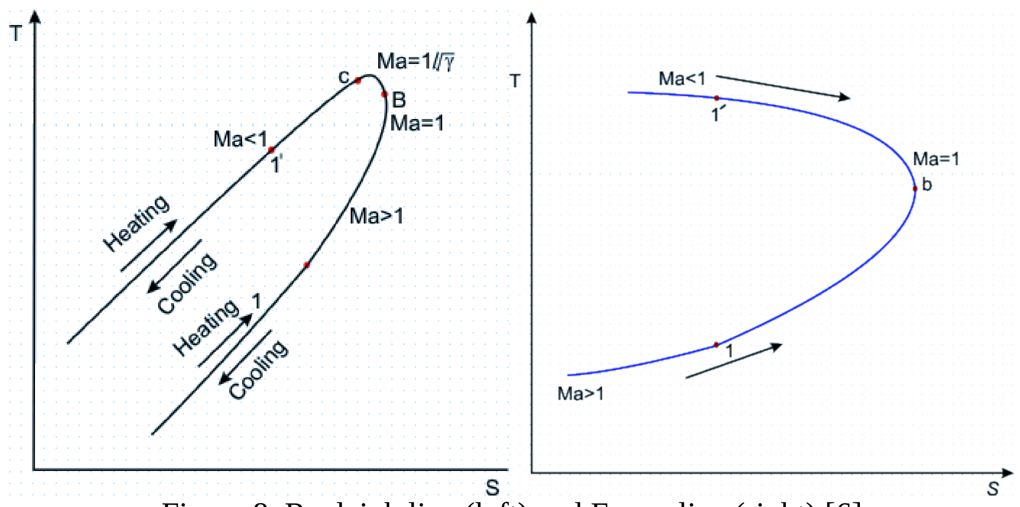

Figure 8. Rayleigh line (left) and Fanno line (right) [6]

COMBUSTION EFFICIENCY

The main objective of the combustor is to transfer all the chemical energy of the fuel to the gas stream. In practice this will not occur for many reasons; for example, some of the fuel may not find oxygen for combustion in the very short time available [1][3].
To obtain high efficiency from the combustor, the following conditions must be achieved:

- Fuel and air have adequate time and adequate space to mix and react
- Completely vaporized fuel and mixed with air before burning

Combustion inefficiency represents a waste of fuel, but mainly because it is manifested in the form of pollutant emissions, such as unburned hydrocarbons and carbon monoxide.
The combustion efficiency can be expressed as follows:

$$\eta_c = \frac{Q_{actual}}{Q_{theoretical}} = \frac{c_p \dot{m}_g (T_3 - T_2)}{\dot{m}_f F} \tag{6}$$

where

η_c	combustion efficiency
Q_{actual}	actual heat liberation
$Q_{theoretical}$	theoretical heat liberation
c_p	specific heat
$\dot{m}_g$	gas mass flow
$\dot{m}_f$	fuel mass flow
F	fuel heating value

SUMMARY

In this paper I presented the theoretical background of the combustors. The combustion chamber is almost the simplest part of the engine, but the processes which are accommodated in the combustor are the most sophisticated, because the subject of combustion embraces both physics and chemistry. The designers must carry out lots of experimental investigation which must be used to determine the dimensions and designs of a high performance combustor. The rapidly increasing use of Computational Fluid Dynamics (CFD) in recent years has had a major impact on the design process, greatly increasing the understanding of the complex flow. The engineers have been continuously improving the combustion systems since Sir Whittle started his first engine.

References

[1] Arthur H. Lefebvre, Dilip R. Ballal: Gas Turbine Combustion, Alternative Fuels and Emissions, Taylor and Francis Group, 2010

[2] H. Cohen, G.F.C. Rogers, H.I.H.Saravanamuttoo: Gas Turbine Theory, 4th Edition, Cornwall, 1996

[3] Nicholas Cumpsty: Jet Propulsion, Cambridge University Press, Cambridge, 2003.

[4] R.D.Blevins: Applied Fluid Dynamics Handbook, New York, 1984

[5] Ranjith P. V., M. Shivashankar, G. Sivaramakrishna, Vimala Narayanan: Reduction of Gas Turbine Combustor Pattern Factors using CFD, International Journal of Engineering Research & Technology (IJERT), 2014

[6] Varga Béla, Kavas László: Gázturbinás hajtóművek égőterei és nyomásveszteségük becslése, REPÜLÉSTUDOMÁNYI KÖZLEMÉNYEK XXVIII. ÉVFOLYAM, 2017