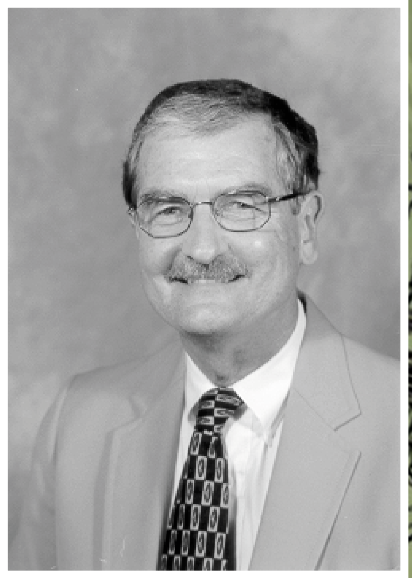
3.2.1.1

Conventional Type Combustion



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3.2.1.1-1 Introduction

Brayton Cycle

The role of the combustor in a gas turbine engine is two-fold. First, the combustor transforms the chemical energy resident in the fuel into thermal energy for expansion in the turbine. Second, the combustor tailors the temperature profile of the hot gases at the exit plane in order to not compromise the material constraints of the turbine. To fulfill this two-fold role, the combustor is designed to mix fuel with air at elevated pressure and temperature, to both establish and sustain a stable continuous combustion reaction, and to mix the products of combustion to establish the desired exhaust temperature profile. The combustor processes are, as a result, a complex combination of fluid mixing, chemical kinetics, and heat transfer. To contain and control these processes, the design of the "conventional" combustor has evolved over seven decades for the production of propulsive thrust and electrical power.

The thermodynamic path over which the gas turbine engine operates is the Brayton Cycle (Figure 1). The compressor [**C**] ingests and compresses ambient air to elevated pressures that vary in the range of a few to many tens of atmospheres depending on the engine design and application. The "Pressure Ratio" (ratio of outlet to inlet pressure of the compressor, P_2/P_1) is a major factor in establishing the overall thermodynamic efficiency of the engine. The higher the pressure ratio, the higher the overall thermodynamic efficiency.

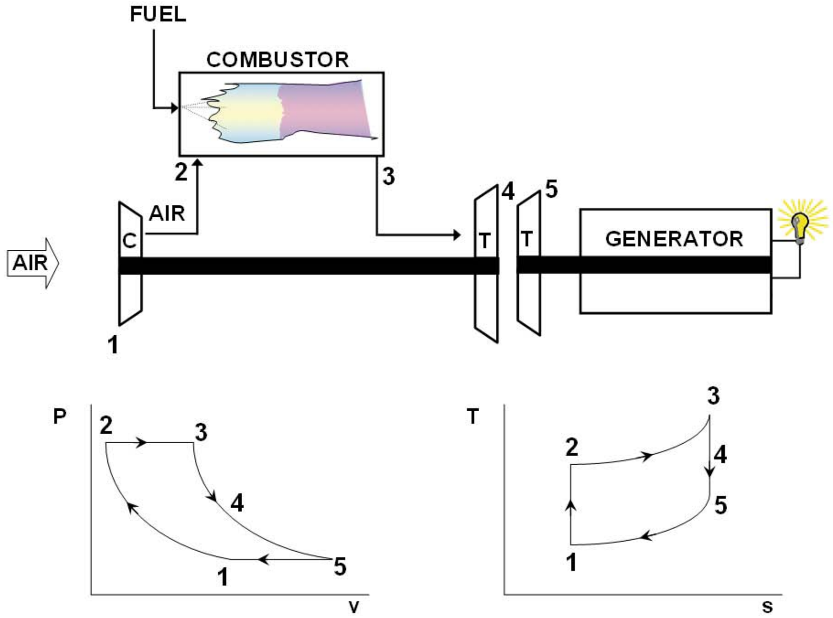

Fig. 1. Gas Turbine Brayton Cycle for Electric Power Generation

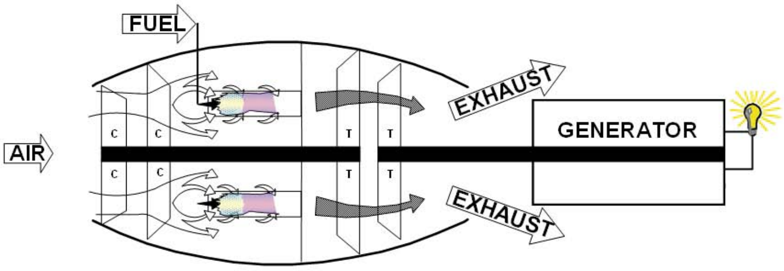

Fig. 2. Stationary Gas Turbine Electric Power Generator

Combustor Inlet Conditions

The compression of the ambient air from State Point 1 to State Point 2 is accompanied by an increase in the temperature of the air. As a result, the air exits the compressor and enters the combustor at both an elevated pressure and an elevated temperature.

In addition to air, fuel is also injected into the combustor at the inlet. The fuel (such as natural gas, coal syn gas, or petroleum liquids) is the source of energy required to "drive" the cycle.

Goal of the Combustor

The goal of the combustor is to convert the chemical energy bound in the fuel into thermal energy. The thermal energy can then be expanded through a turbine [**T**] to produce (1) the power required to operate the compressor, and (2) the power required to turn a generator and produce electricity.

To accomplish this goal, the combustor serves as the vehicle to:

- Combine and mix the air and fuel entering the combustor,
- Ignite the mixture of fuel and air,
- Contain the mixture during the combustion reaction, and
- Tailor the temperature distribution of the hot gases at the exit plane.

Continuous Combustion

The processes that occur within a gas turbine combustor (e.g., injection of the air and fuel, mixing of the air and fuel, combustion reaction) are "continuous" rather than intermittent, and occur at constant pressure. This is in contrast to the automobile spark ignited "Otto Cycle" engine where the combustion is intermittent and accompanied by a significant increase in pressure. The gases exit the gas turbine combustor as a steady flow and are then continuously expanded through turbine stages. After the final expansion stage, the spent gases are then exhausted into the atmosphere.

3.2.1.1-2 Combustor Features

The design of gas turbine combustors has evolved over many decades with the final configuration based on the best of engineering judgment and intuitive reasoning. As demands have developed for efficiency and lower environmental impacts, engineering tools such as computational fluid dynamics[1] and laser diagnostics[2] have evolved to facilitate the design process. This notwithstanding, engineering judgment coupled with intuitively based empirical correlations, continues to serve as the anchor to modern design.

Throughout the evolution of combustor technology, the basic requirements for combustor design have remained. In particular, the following five basic features are integral to the combustor design: a primary zone, a secondary zone, a dilution zone, various wall jets, and the management of heat transfer at the combustor boundary (Figure 3).

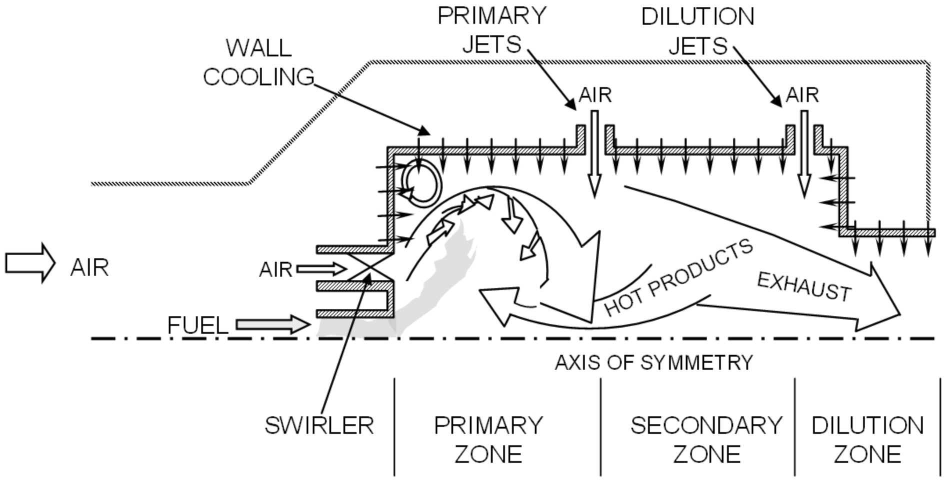

Fig. 3. Combustor Features

3.2.1.1-3 Primary Zone

The air exiting the compressor enters the combustor through four major injection points, each of which has a particular role. Each injection point convects approximately one-quarter of the total air flow into the combustor. Two of these injection points (swirler, primary air wall jets) control both the structure of, and the mixing within, the primary zone.

Swirler. The first entry point for the compressor air is through swirler vanes that are positioned at the front face of the combustor and typically surround the fuel injection port. The swirl vanes impact a circumferential velocity component to the air and thereby thrust the air radially outward as the air enters the combustor. This creates a pressure void at the center line and induces a backflow to fill the centerline pressure deficit. This effectively creates, as a result, a recirculation flow that extends approximately one duct diameter downstream and defines the "Primary Zone" of the combustor. The strength of the swirl is defined by the swirl number, $S_{N:}$

$$S_N = \frac{2G_m}{D_{sw}G_t} \tag{1}$$

where:

G_m = Axial Flux of Angular Momentum
G_t = Axial Thrust
D_{sw} = Diameter of Swirler

The swirl number must exceed 0.6 in order to induce a recirculation zone.

"Aerodynamic Spark Plug." The fuel is injected at an angle to mix with the swirler air that is exiting the swirler. Mixing of the fuel and air is facilitated by the turbulence that is created by the passage of the air through the swirler. The resultant fuel/air mixture is then recirculated and mixed with energetic "hot products" of combustion that are pulled and entrained into the recirculation zone from downstream. These energetic species provide the ignition source for the fresh mixture of fuel and air. In effect, the recirculation zone combines as a combined aerodynamic "blender" and "spark plug."

Primary Air Jets. Wall jets affect the mixing, stoichiometry, and structure of the flows in gas turbine combustors. Due to this dominating role, a substantial literature has evolved to guide the design and estimate the behavior of jets injected into a crossflow.[3] In a typical combustor design, two sets of air wall jets (primary and dilution) are prescribed (Figure 3). The primary air jets are located approximately one duct diameter downstream from the combustor inlet and serve two major functions. First, the jets bring closure to the recirculation zone by providing a strong force against which the primary zone cannot easily penetrate. Without the set of primary air jets, the dynamics of the recirculation zone would create aerodynamic fluctuations and result in pressure oscillations, undesirable noise, and elevated pollutant emission.

Secondly, the primary jets bifurcate with a substantial percentage of the flow directed upstream to mix with the recirculating fuel/air mixture, and the remainder mixing downstream into the secondary zone (Figure 4). The primary jet flowing upstream augments the swirler air to establish the overall stochiometry of the primary zone.

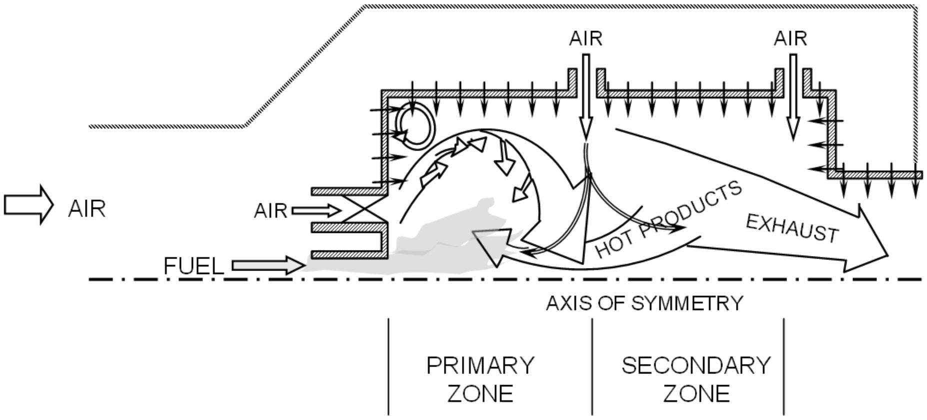

Fig. 4. Bifurcation of Primary Jets

The stochiometry describes the actual fuel-to-air ratio compared to the chemically correct or "stoichiometric" ratio. A number of indices (e.g., theoretical air, excess air) can be used. For gas turbine combustion, the equivalence ratio (ϕ) is the index that is typically adopted:

$$\phi = \frac{(\text{Fuel/Air})_{\text{actual}}}{(\text{Fuel/Air})_{\text{stoichiometric}}} \tag{2}$$

The primary zone is typically fuel rich (ϕ>1.0) in order to promote reaction stability (e.g., preclude blow-out).

Mixing. Combustion is a complex coupling of fluid mechanics and chemical kinetics (Figure 1). A large scale, macro fluid mechanical structure ("recirculation zone") mix the fuel and air within the primary zone and entrain hot, energetic species to ignite the fresh reactant mix. Chemical kinetics determine the paths and rate at which the reaction proceeds. The fluid mixing and chemical kinetics occur in parallel throughout the primary zone and over a range of scales. In particular, the zone of recirculation is at the macro scale and, within this zone, a range of turbulent eddy scales exists and persists.

The size of the macroscale mixing associated with recirculation is on the order of the combustor diameter (Figure 3). Within the macroscale recirculation zone, mixing of the fuel, air, and recirculated energetic products occurs on the "microscale." Whereas the macroscale recirculation zone is a "blender" on the scale of the duct diameter, the microscale mixing occurs within "mini-blender" packets that vary in (1) the concentrations of fuel and air (Figure 5), and (2) size.

The microscale mini-blenders are turbulent eddies generated (1) at the physical boundaries of the inlet plane, and (2) within the shear that exists between the various flows in the primary zone. The most important shear layer (layer separating two streams of differing velocities) exists between the entering fuel and air streams, and within the steep velocity gradient associated with the macroscale recirculation zone.

Each turbulent eddy will experience a finite lifetime (~tens of milliseconds) within the reaction zone before breaking up, mixing with adjacent eddies, and forming a new eddy. Some eddies containing unreacted fuel and air will ignite. Others will not, waiting to mix with other eddies to acquire sufficient energetic species of the necessary mixture ratio that is required for ignition.

In traditional combustors, the fuel and air are injected separately (i.e., "non-premixed"). The reaction is often referred to as a "diffusion flame" and the combustor as a "diffusion combustor." This is a misnomer. In a diffusion flame, the fuel is not premixed with the air prior to reaction, and the reaction occurs at the interface between the fuel and the air. Within the primary zone of a gas turbine combustor, the injection of reactants, the mixing of the reactants, the entrainment and mixing of energetic species, and reaction are occurring simultaneously throughout the volume of the recirculation zone. A variety of fuel/air packets are formed with a myriad of mixture ratios. As a result, mixing of the fuel and air indeed occurs before reaction of the individual packets. The extent to which, in the aggregate, the fuel and air mix prior to reaction depends upon the fuel properties, the fuel and air injection hardware, and the time for mixing prior to reaction. While not premixed (the fuel and air are injected separately), the reaction is not a diffusion flame. Instead, the reaction is a "partially-mixed" "distributed reaction." To approached a premixed reaction, the fuel and air must be either (1) intensely mixed after injection in a zone that precedes reaction but precludes auto-ignition ("rapidly mixed, non-premixed"), (2) introduced over a spatially large area through a large number of discrete injection points ("spatially injected, non-premixed"), or (3) premixed prior to injection ("premixed"). Due to safety, non-premixed operation has been the preferred option. The need to reduce the emission of pollutant species, however, has sought a reaction in the primary zone that behaves closer to a premixed reaction. For stationary gas turbines, all three options listed above are being developed and deployed. For aero-propulsion applications, only the first two options are being developed and deployed.

Gaseous fuels (e.g., natural gas, syn-gas) will mix more rapidly with the air than liquid fuels. Liquid fuels are injected as small droplets and must first evaporate into a vapor before mixing with the air can occur. (Some droplets may not completely evaporate and will react as a small diffusion flame.)

Heat Release. The transformation of the chemical energy bound in the fuel to thermal energy is a two-step process. The first step is associated with the primary zone. Here, the hydrogen and carbon bonds in the fuel are converted relatively fast through a series of reactions to carbon monoxide (CO) and water (H_2O) (Figure 6). Approximately two-thirds of the chemical energy bound in the fuel is released to thermal energy in this first phase. The radiative flux emanating from CO is light blue (Figure 7). In actual engines, this cannot be observed. In a laboratory model combustor with appropriate optical assess, the light blue emission is discernable at the edges surrounding the "white-light" associated with the long-duration exposure of the film (Figure 8).

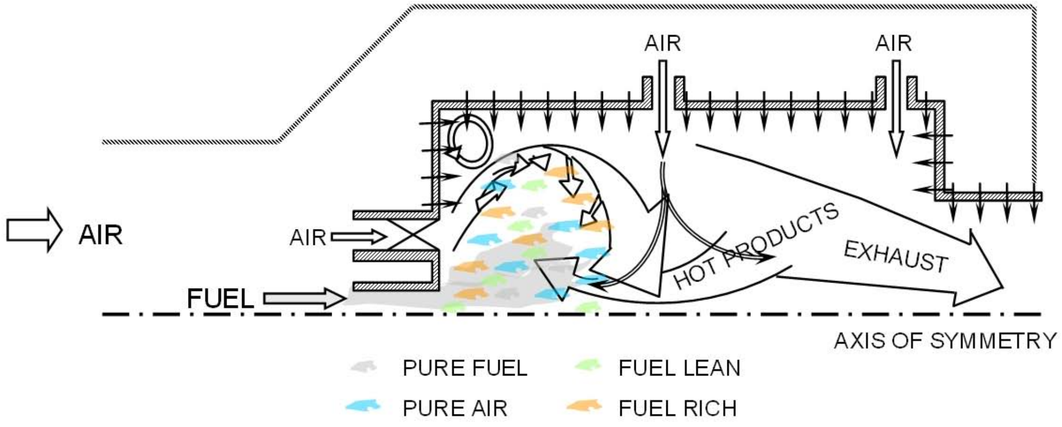

Fig. 5. Microscale Eddies

The CO produced retains one-third of the chemical energy. The release of the residual energy bound in the CO does not occur readily in the primary zone due to (1) the relatively slow kinetic rate for the oxidation of CO to carbon dioxide (CO_2), (2) the relatively short residence time in the recirculation zone, and (3) the rich stochiometry of the primary zone. Herein is the role of the secondary zone.

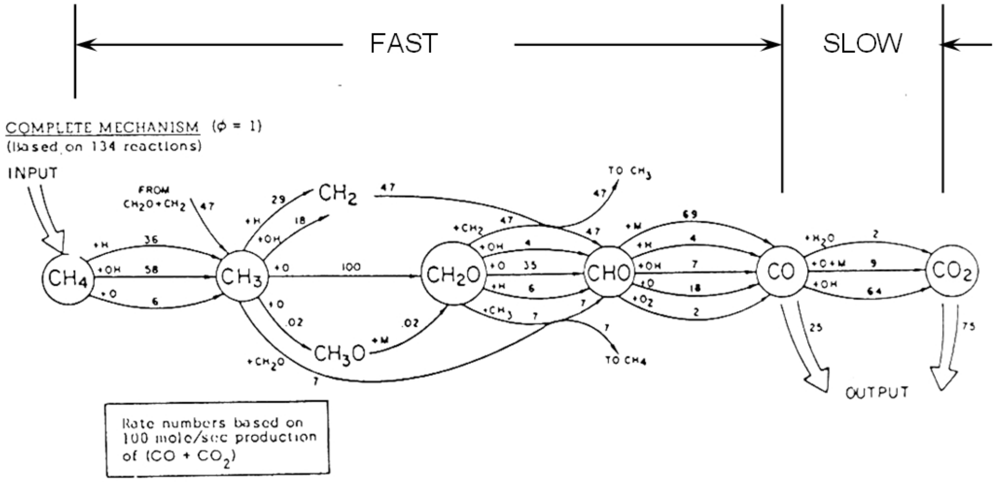

Fig. 6. Heat Release Chemistry (Example for Methane, CH_4, as the Fuel)

Source: 4. Samuelsen, G. S., The Combustion Aspects of Air Pollution, Advances in Environmental Science and Technology, Vol. 5, pp. 219-322, John Wiley & Sons ,1975.

3.2.1.1-4 Secondary Zone

The role of the secondary zone is to oxidize the CO to CO_2. The principal elementary kinetic reaction that governs the oxidation is:

$$CO + OH \Rightarrow CO_2 + H \tag{3}$$

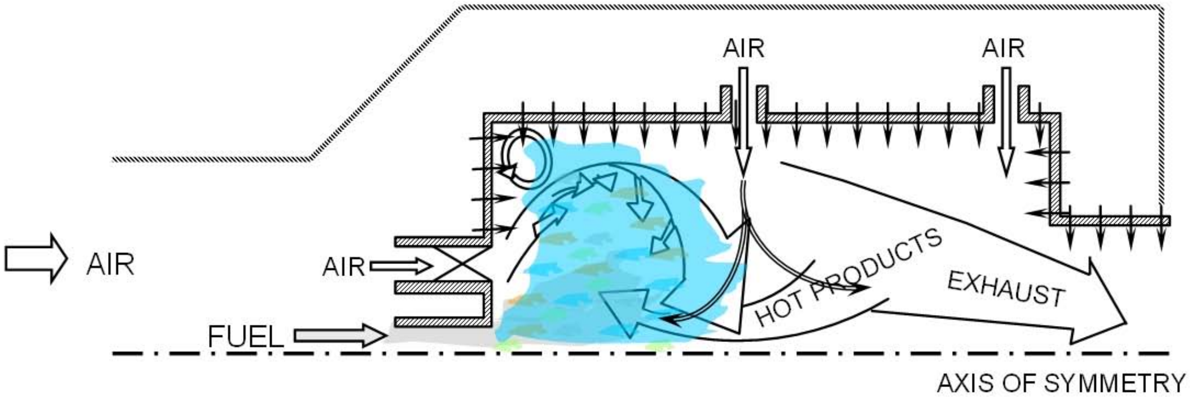

Fig. 7. Radiative Properties of the Primary Zone

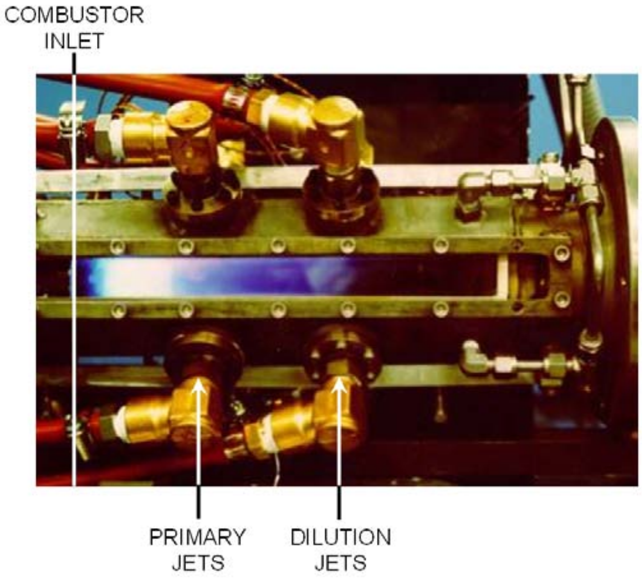

Fig. 8. Model Combustor Operating on JP-4

Source: Cameron, C.D., Brouwer, J., and Samuelsen, G.S., A Model Gas Turbine Combustor with Wall Jets and Optical Access for Turbulent Mixing, Fuel Effects, and Spray Studies, Twenty-Second Symposium (International) on Combustion, The Combustion Institute, pp. 465-474, 1988.

The strategy is to increase the sluggish forward reaction rate by (1) establishing an overall lean mixture ratio (e.g., ϕ~0.8) through the primary jet bifurcation, (2) retaining the temperature at an elevated level, and (3) providing the residence time needed to promote the oxidation. The emission from CO_2 is purple (Figure 9). The effectiveness of the secondary zone is evident in Figure 8 where a purplish light emission, characteristic of the CO_2 molecule, is observed between the primary and dilution jets.

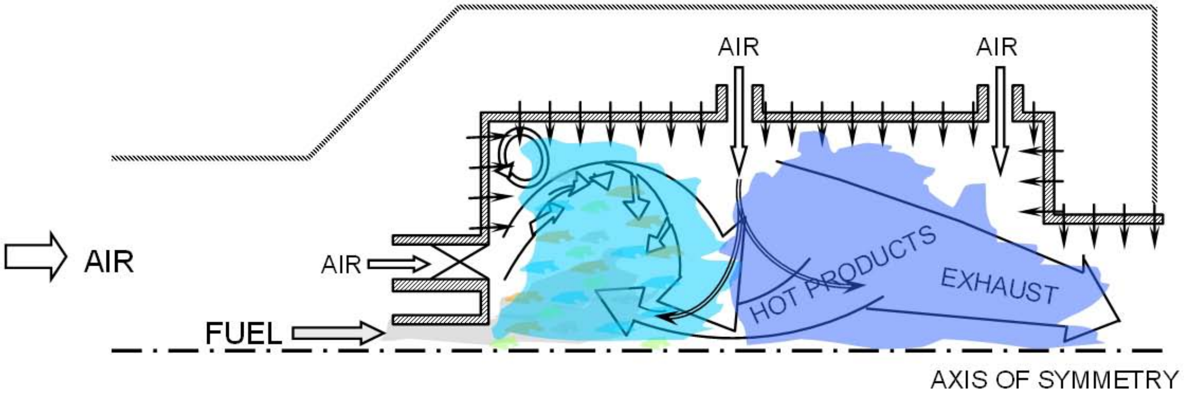

Fig. 9. Radiative Properties of the Primary and Secondary Zones

3.2.1.1-5 Dilution Zone

The role of the dilution zone is to reduce the temperature of the combustion products and mix the resultant gases in order to establish a temperature that will uphold the integrity of the turbine blades. This is accomplished by second major set of air jets. The dilution jet flow, approximately one-quarter of the total air flow exiting the compressor, is sufficient to reduce the overall equivalence ratio of the gases exiting the combustor to a very lean condition (e.g., ϕ~0.3) with a corresponding concentration of oxygen of 15% by volume.

To protect the integrity of the turbine section, it is not sufficient to reduce the mean temperature. The radial and circumferential variation in local temperature from the mean can create hot spots and degrade, damage, and possibly destroy a turbine component (e.g., blade, stator, seal). As a result, the temperature profile at the exit plane must meet design criteria. The temperature profile is characterized by various indices including the “Pattern Factor,” the “Profile Factor,” and the “Turbine Profile Factor.”

A combustor designer will work with the turbine design team to establish the exit plane temperature "design profile" (Figure 10). The temperature is reduced at the root (0% Blade Span) to protect the blade attachment to the shaft, and reduced at the 100 percent span point to manage the clearance at the wall. The peak temperature occurs closer to the 100 percent span point due to the larger circumferential area of the turbine that can manage the elevated heat flux.

The actual temperature profile may deviate from the design profile. The Pattern Factor reflects the extent to which the maximum temperature deviates from the average temperature rise across the combustor $\{T_3 - T_2\}$:

Pattern Factor

$$= \frac{\{T_{max} - T_3\}}{\{T_3 - T_2\}} \tag{4}$$

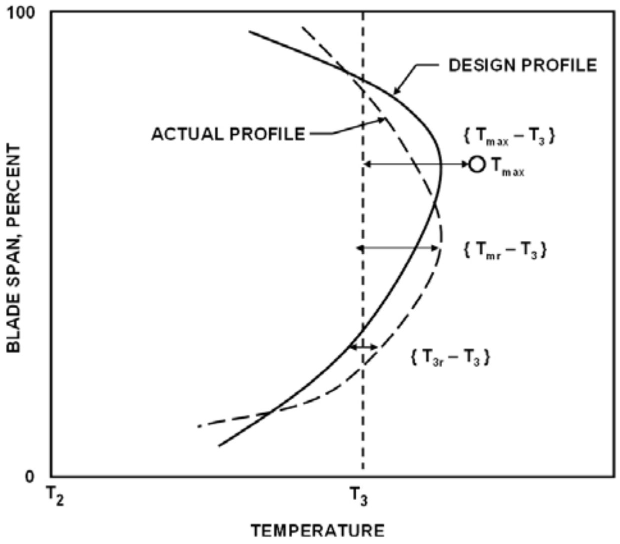

Fig. 10. Exit Plane Temperature Profiles

Source: Lefebvre, Arthur H., Gas Turbine Combustion, Second Edition, Taylor and Francis, p. 120, 1998.

The Profile Factor characterizes the extent to which the maximum circumferential mean temperature, T_{mr}, deviates from the average temperature rise across the combustor:

Profile Factor

$$= \frac{\{T_{mr} - T_3\}}{\{T_3 - T_2\}} \tag{5}$$

The Turbine Profile Factor addresses the maximum temperature difference by comparing the average temperature at any given radius around the circumference (T_{3r}) and the design temperature for that same radius (T_{3des}):

Turbine Profile Factor

$$= \frac{\{T_{3r} - T_{3des}\}_{max}}{\{T_3 - T_2\}} \tag{6}$$

The goal is for the actual profile to match the design profile. The dilution jet penetration is the major force that directly determines the extent to which this match is achieved. In general, the combination of the number of dilution jets and the orifice size for each jet is selected such that the centerline of the dilution jets penetrates from the wall a distance that corresponds to 1/3 of the duct diameter.

3.2.1.1-6 Heat Transfer

A substantial design consideration in the management of the air flow exiting the compressor is to address the heat transfer demands of the combustor liner. The reaction within the combustor produces a substantial radiative flux of heat to the liner wall. Unless this heat is dissipated from the wall, the wall will be compromised and fail. To preclude this, approximately one-quarter of the compressor air flow is allocated to liner cooling. Designs for accommodating this cooling flow are small holes in the liner with louvers on the inside wall to direct the flow along the internal boundary (Figure 3). New designs incorporate liner materials with hundreds of closely spaced holes that promote a diffusive flux of air at all points along the liner.

3.2.1.1-7 Combustor Configurations

Gas turbine combustors first evolved in a "can" configuration. Over time, a length-to-diameter ratio of ~3.0 has emerged as necessary to (1) physically accommodate the three zones (primary, secondary, and dilution), and (2) achieve the combustion efficiency, combustion stability, and pollutant emission required of viable, commercial systems. Due to the simplicity of this configuration, many modern stationary gas turbine engines today retain a can geometry.

To accommodate the evolution of larger engines and the annular flow of air exiting compressors, a can-annular configuration evolved as the second-generation strategy for propulsion engines. The Pratt & Whitney JT8D was the epitome of this design, constituted for many years the major population of aero-propulsion engines, and powered the Boeing 727 and early series of Boeing 737s.

The third-generation configuration is the "full-annular" geometry which provides an exact match in the open annular area to both the compressor exit and the turbine entrance. Modern aero-propulsion engines adopt this geometry universally in order to embrace many advantages including a reduced combustor length (and hence a higher thrust to weight ratio), and the ability to accommodate a wider range turndown (e.g, from idle to taxi, to cruse, to full power) with a low environmental signature. With the exception of some aero-derivative engines, stationary gas turbine designs have retained the can geometry for (1) ease of maintenance, and (2) ability to incorporate advanced low-emission combustor strategies (e.g., premixed injection, catalytic surfaces).

Configuration options also include whether or not the combustor system will be "in-line" with the compressor and turbine. Due to the requirement of aero-propulsion engines to be efficiently packaged with a minimum length and overall weight, the in-line configuration is standard. Stationary gas turbine engines are free from these constraints. As a result, engines designed from scratch for stationary applications are outfitted with can combustors that are often not in-line in order to support (1) ease of access, and (2) ease of maintenance. Aero-propulsion engines that are applied as well for stationary power generation will be often retrofitted with out-of-line can combustors as a substitute to the relatively elegant in-line annular configuration for the aero application.

3.2.1.1-8 Notes

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1. Mongia, H. C., Reynolds, R. S., and Srinivasan, R., "Multidimensional Gas Turbine Combustion Modeling: Applications and Limitations," *AIAA Journal*, Vol. 24, No. 6, pp. 890-904, 1986.
2. McDonell, V.G. and Samuelsen, G.S., "Measurement of Fuel Mixing and Transport Processes in Gas Turbine Combustion," *Measurement, Science, and Technology,* Topical Issue on Measuring Techniques for Turbomachinery, Vol. 11, pp. 870-886, 2000.
3. Holdeman, J.D., "Mixing of Multiple Jets with a Confined Subsonic Crossflow," *Progress in Energy and Combustion Science*, Vol. 19, No. 1, pp. 31-70, 1993.

BIOGRAPHY

3.2.1.1 Conventional Type Combustion
3.2.1.3 Rich Burn, Quick-Mix, Lean Burn (RQL) Combustor

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