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PART 1

OVERVIEW AND KEY ISSUES

1 Aero Gas Turbine Combustion: Metrics, Constraints, and System Interactions

Randal G. McKinney and James B. Hoke

1.1 Introduction

The aircraft gas turbine engine is a complex machine using advanced technology from many engineering disciplines such as aerodynamics, materials science, combustion, mechanical design, and manufacturing engineering. In the very early days of gas turbines, the combustor section was frequently the most challenging (Golley, Whittle, and Gunston, 1987). Although the industry's capability to design combustors has greatly improved, they remain an important design challenge.

This chapter will describe how the combustor interacts with the rest of the engine and flight vehicle by describing the relationship between attributes of the engine and the resulting requirements for the combustor. Emissions, a major engine performance characteristic that relies heavily on combustor design, will be introduced here with more detail found in following chapters. The wide range of operating conditions a combustor must meet as engine thrust varies, which is a major challenge for combustor design, will also be described. Last, the relationship between combustor exit temperature distribution and turbine section durability will be discussed.

1.2 Overview of Selected Aircraft and Engine Requirements and their Relation to Combustor Requirements

Aircraft gas turbine engines have been used in many different sizes of aircraft since their introduction in the 1940s. Small aircraft such as single-engine turboprops use engines of low shaft horsepower, which are of small physical size. Business jets and smaller passenger aircraft may use turbojets or turbofans with thrust in the range of several thousand pounds, usually with two engines per aircraft. The other extreme includes four-engine aircraft with turbofan engine thrusts as high as seventy thousand pounds and very large twin-engine aircraft with thrust per engine in the one hundred thousand pound class. These thrust designs are also physically very large, with fan diameters over 100 inches. In all of these applications, the engine system imposes a common set of requirements upon the combustor, as summarized in Table 1.1.

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Table 1.1. *Engine system-level requirements and supporting combustor characteristics*

Engine requirement	Combustor characteristic
Optimize fuel consumption	High combustion efficiency and low combustor pressure loss
Meet emissions requirements	Minimize emissions and smoke
Wide range of thrust	Good combustion stability over entire operating range
Ground and altitude starting	Easy to ignite and propagate flame
Turbine durability	Good combustor exit temperature distribution
Overhaul and repair cost	Meet required combustor life by managing metal temperatures and stresses

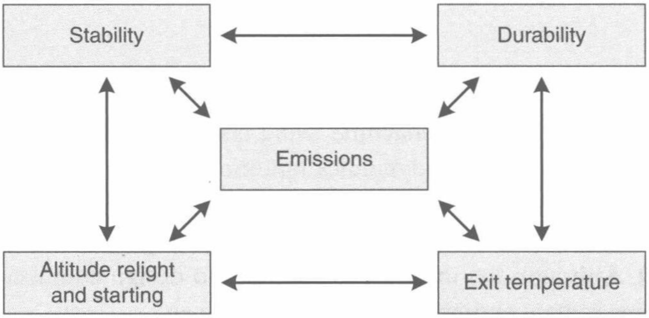

Figure 1.1. Combustor performance requirements are interrelated.

As shown in Figure 1.1, these requirements are interdependent. Years of design and development within the industry have produced successive designs that improve upon all of the requirements concurrently. Although emissions are the focus of this text, each of these other requirements interacts with the emissions constraints and will be introduced briefly.

1.3 Combustor Effects on Engine Fuel Consumption

Gas turbine engines are Brayton cycle devices. An ideal version of such a cycle comprises isentropic compression, addition of heat at constant pressure, and isentropic expansion through the turbine. Figure 1.2 is a simplified schematic of the effect of such a cycle on the pressures and temperatures in the engine. In real engines, all of the processes incur some loss of performance versus the ideal, manifested as a stagnation pressure loss in the combustor. Combustion systems incur pressure losses because of flow diffusion and turning, jet mixing, and Rayleigh losses during heat addition (Lefebvre and Ballal, 2010). However, at most power conditions, the efficiency with which the fuel chemical energy is converted into thermal energy is very high, typically greater than 99.9 percent. "Low" levels of 98 to 99.5 percent can be seen at low-power levels. In general, though, the combustion system is a small parasitic effect on overall fuel consumption.

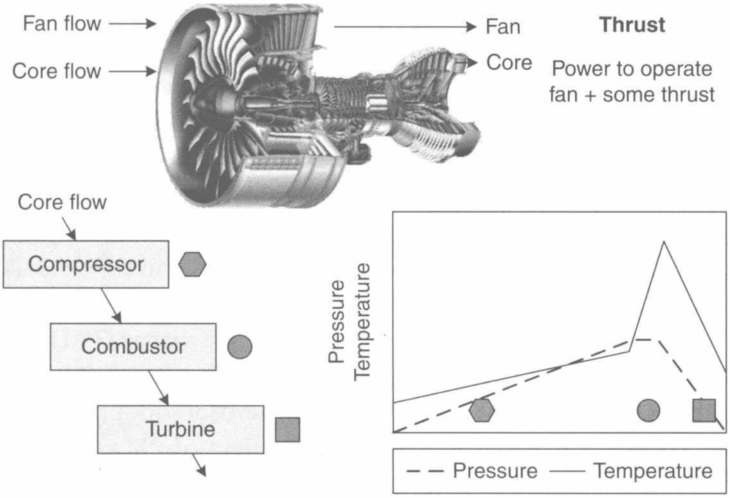

Figure 1.2. Summary of component characteristics.

1.4 Fundamentals of Emissions Formation

The pollutants emitted by engines that are of most interest are carbon monoxide (CO), unburned hydrocarbons (UHC), nitric oxides (NO_x), and particulate matter (PM or smoke). At low-power conditions, the inlet combustor pressure and temperature are relatively low, and reaction rates for kerosene-type fuels are low. Liquid fuel must be atomized, evaporated, and combusted, with sufficient residence time at high enough temperatures to convert the fuel into CO_2. If the flow field permits fuel vapor to exit the combustor without any reaction, or, if partially reacted to species of lower molecular weights, UHC will be present. If a portion of the flow field subjects a reacting mixture to a premature decrease in temperature via mixing with cold airstreams, these incomplete or quenched reactions lead to the production of CO, as detailed in Chapter 7.

At high power conditions, high air pressures and temperatures lead to fast reactions, with the result that CO and UHC are nearly zero. At these elevated temperatures, emissions of NO_x and PM become more prevalent. NO_x can be formed through several processes, but the dominant pathway is thermal NO_x, as described by the extended Zeldovich mechanism, also detailed in Chapter 7.

$$\begin{gathered} O_2 = 2O \\ N_2 + O = NO + N \\ N + O_2 = NO + O \\ N + OH = NO + H \end{gathered}$$

The formation rate is exponentially related to the temperature in the flame, peaking near stoichiometric conditions. Thermal NO_x emissions can be reduced by limiting the time the flow spends at the high temperature and/or by reducing the maximum temperatures seen in the flame via stoichiometry control. Other NO_x formation mechanisms, such as NO_x formed in the flame zone itself, are also described in Chapter 7, but are negligible for aircraft engines.

When fuel-rich regions of the combustor flow exist at high pressures and temperatures, the formation of small particles of carbon can occur. These carbon particles result from complex chemical processes and undergo multiple processes within the combustor such as surface growth, agglomeration, and oxidation prior to leaving the combustor, as detailed in Chapter 5. These particles pass through the turbine and exit the engine in the exhaust. When the concentration of the particles in the exhaust is high enough to be visible, as was often the case in early gas turbines, it is referred to as smoke or soot. Recently, the more general term *particulate matter* (PM) has been used to describe this emission. Modern engine smoke levels are invisible but still possess large quantities of very small soot particles and aerosol soot precursors (see Chapter 5) at the exhaust. Emerging research on the effect of PM on health and climate focuses more attention on measuring, modeling, and understanding the processes governing PM production.

These relationships between engine power conditions and emissions production lead to the behavior shown in Figure 1.3. As shown in the figure, levels of UHC and CO are highest at low power and drop quickly with increasing thrust. Conversely, NO_x and PM increase with engine power and are typically maximized at maximum power. Chapters 5 and 7 discuss these emissions formation processes in more detail.

1.5 Effect of Range of Thrust and Starting Conditions on the Combustor

Flight gas turbine engines must provide a range of thrust and thrust response to power the aircraft mission. Missions vary depending on the aircraft application. Commercial aircraft and military transports have similar missions. Military fighters and other specialized aircraft can have very different missions because their use is not exclusively for the transport of payload between two points. Design requirements are also very different for commercial and military applications. Military fighter engines are often designed for maximized thrust developed per unit weight so that the maneuverability of the aircraft is maximized. Military fighter engines also fly at a wide range of thrust throughout the flight envelope and must undergo frequent rapid thrust transients. Typically, commercial engines are designed for maximum fuel efficiency per unit thrust. They fly at high altitude to achieve the best fuel efficiency and often do not have to endure the aggressive and numerous thrust transients of military fighter engines. Engine combustors must operate stably and efficiently over the full range of operating conditions, and must reliably relight if an engine shutdown or flameout should occur in flight.

1.5.1 Engine Mission Characteristics

A typical commercial engine mission consists of ground starting, taxi, takeoff, climb to altitude, cruise, deceleration to flight idle and descent, approach, touchdown,

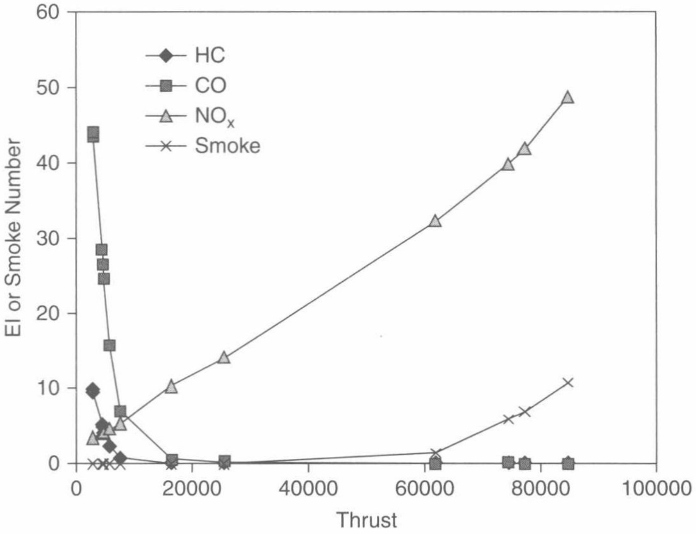

Figure 1.3. Emissions versus power level for the PW4084.

thrust reverse, and taxi in. The extremes in combustor operating conditions drive the overall design approach. The combustor must meet performance, operability, and emissions metrics over the full range of operation. In order to do so, it must operate at the following extremes:

1. Minimum fuel-air ratio – This occurs during decelerations from high power to low power. Flight decelerations normally occur when descending from high altitude cruise and during approach throttle movements. They can also occur in emergencies. Minimum fuel-air ratio typically depends on the thrust decay rate, as the time response of the engine turbomachinery that governs the airflow is much longer than that of the fuel flow. Risk of weak extinction (flameout) is highest during decelerations.
2. Minimum operating temperatures and pressures – These occur at flight and ground idle conditions. Low pressure and temperature challenges combustion efficiency due to slower fuel vaporization and chemical kinetics.
3. High operating temperatures and pressures – These occur at takeoff, climb, thrust reverse, and cruise conditions. These conditions result in the bulk of NO$_x$ formation and the most severe liner metal temperatures.
4. Ignition conditions – Ignition normally occurs on the ground but also occasionally in flight. Ignition is required at near surrounding ambient pressure and temperature. High altitude and extremely cold conditions are typically the most challenging to achieve ignition, flame propagation, and flame stabilization. These conditions lead to low temperature (–40ºF) and pressure (4 psia at 35,000 ft.) combustor inlet conditions.

Thus, the combustor design must meet the performance, emissions, and durability requirements at low- and high-power operations without compromising stability

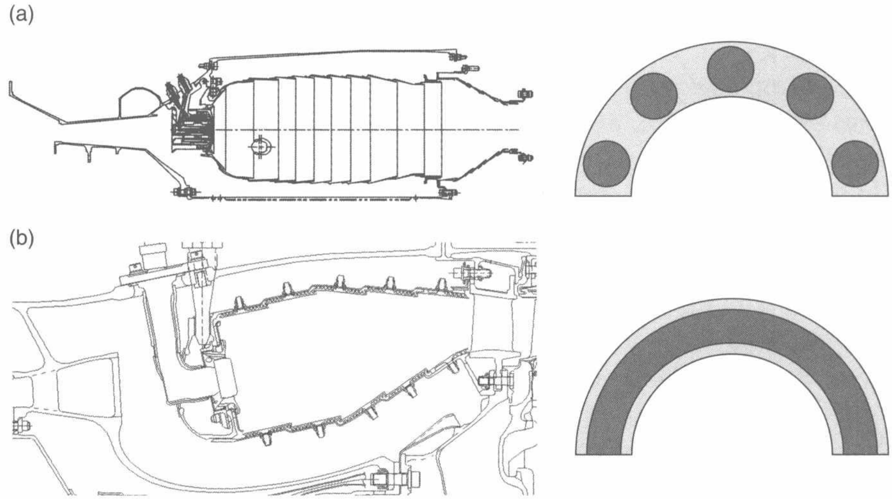

Figure 1.4. (a) Can-annular combustor (Pratt & Whitney JT8D-200); (b) RQL annular combustor (IAE V2500).

and ignition. This requires favorable combustion fuel-air stoichiometry to meet requirements at all operating conditions. Two principal approaches have been used to achieve stoichiometry control in the industry. The first, fixed geometry without fuel staging, is the most common approach and is in the large majority of engines in service. These systems have all fuel injectors operating at all conditions. The second approach controls local fuel-air ratio through fuel staging. In these systems, not all fuel injectors operate at low power. This enables more active control of the local combustion fuel-air ratio.

1.5.2 Fixed-Geometry Rich-Quench-Lean (RQL) Combustors

Fixed-geometry combustors have been used in the gas turbine industry since its inception. Early designs used multiple cans in a circumferential array. The cans transitioned through an annular duct to the turbine (Figure 1.4a). Later designs used an annular duct geometry that allowed for reduced overall length and weight (Figure 1.4b). Annular combustors also have reduced liner surface area relative to can-annular combustors and therefore use less cooling. All designs use multiple fuel injectors to provide spray atomization and fuel-air mixing. Achieving good atomization and fuel-air mixing is critical for efficient combustion, low emissions, and good temperature uniformity into the turbine. Normally, the fuel is injected in the front end of the combustor and flow recirculation is created to provide a stabilization region for the combustion process. This is typically accomplished with air swirlers, which leads to vortex breakdown and flow recirculation. The stabilization zone promotes recirculation of hot product gases forward to the incoming fuel spray, thereby providing a continuous ignition source and faster fuel droplet evaporation. Accelerated droplet evaporation is critical to high-efficiency combustion at low-power conditions, when low air inlet temperatures are insufficient to provide fast enough evaporation.

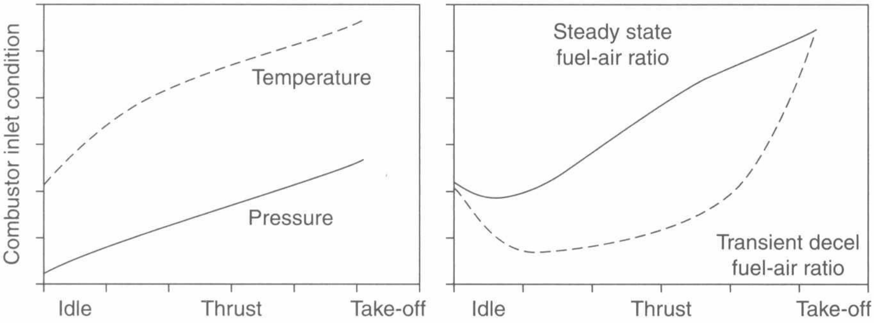

Figure 1.5. Combustor operating conditions.

If continuous ignition is not provided at low power, the vaporization and reaction times can exceed the combustor residence time and flameout occurs.

The airflow distribution in a fixed-geometry combustor must be selected to achieve both low- and high-power performance requirements. Conditions at the combustor inlet vary significantly between low-power idle and high-power takeoff conditions. At idle, inlet temperature, pressure, and global fuel-air ratio are relatively low. At takeoff, the opposite is true (Figure 1.5). The operating temperatures and pressures are largely a function of the engine thermodynamic cycle; therefore the most significant parameter for the combustor designer to consider is the fuel-air ratio. Because air is introduced in stages along the length, the designer can tailor the airflow distribution to achieve key performance metrics. This creates a distribution in fuel-air ratio along the length of the combustor, leading to variations in local temperature as power level is adjusted. The difference in fuel-air ratio between high-power takeoff and low-power deceleration and idle conditions is critical because it determines the range of local fuel-air ratio in the front end of the combustor. For most modern gas turbines, the difference is large enough that the front end operates fuel rich (f/a > 0.068 for jet fuel) at takeoff conditions. Consequently, fixed-geometry combustors are referred to as rich-burning or rich-quench-lean (RQL) designs. This refers to the rich front-end fuel-air ratio that is diluted (quenched) by additional airflow in the downstream section of the combustor to reach the fuel-lean conditions at the combustor exit. The RQL-type design has several advantages and challenges, which are discussed later in this chapter.

As previously described, the challenges at low power are combustion efficiency and stability. The local fuel-air ratio in the RQL combustor front end at idle is designed to generate high recirculating gas temperatures (Figure 1.6). Therefore, the local fuel-air ratio should be near the stoichiometric (f/a ~.068 for jet fuel) fuel-air ratio to achieve high combustion efficiency. High combustion efficiency minimizes unburned hydrocarbon and carbon monoxide emissions that predominate at idle. Some increase in NO_x emissions is generated by the hot front end, but emissions at idle are not significant when compared to high power. By designing for near stoichiometric conditions at idle, stability can be ensured at deceleration conditions, where minimum fuel-air ratio occurs. If the minimum fuel-air ratio during deceleration is

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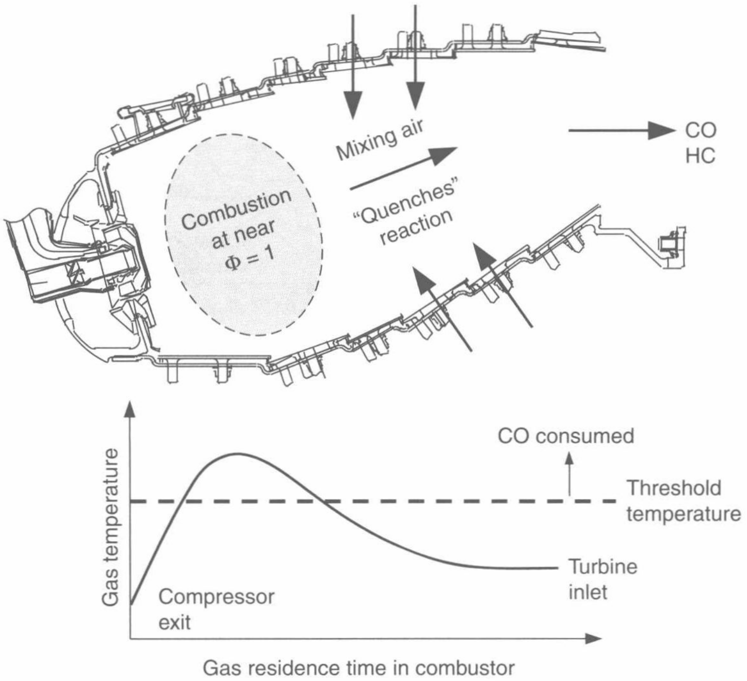

Figure 1.6. Combustor at low power.

not more than one-third below idle fuel-air ratio, the local fuel-air ratio in the front end is maintained above the weak extinction limit and flameout is avoided. Limiting of minimum deceleration fuel-air ratio is accomplished by the engine control and controls the maximum thrust decay rate for the engine transient.

At high-power conditions, the principal emissions challenges are NO_x and smoke. The RQL combustor axial temperature distribution at high power is depicted in Figure 1.7. The front end is fuel rich and consequently has lower flame temperatures. The dilution or quench region is characterized by peak gas temperatures as the fuel-rich mixture transitions through stoichiometric fuel-air ratio to the fuel-lean conditions at the combustor exit. In the front end, smoke is formed due to the combustion at fuel-rich conditions. Some of the smoke formed in the front end is oxidized in the high-temperature, oxygen-rich quench region. Thus, the front-end airflow level must be set with understanding of the formation and oxidation processes. The NO_x emissions are formed in both the front end and quench regions at high power. NO_x formation is exponentially a function of gas temperature, but also depends on the residence time at the local temperature. The highest rate of formation occurs in the quench region because it is the region where peak temperatures occur. However, time at peak temperature in the quench region is relatively short due to high mixing rates. In contrast, the formation of NO_x in the front end is not negligible because it has relatively longer residence time due to the flow recirculation. The presence of cooling flow in the front end also leads to NO_x formation when it interacts with the fuel-rich gas mixture.

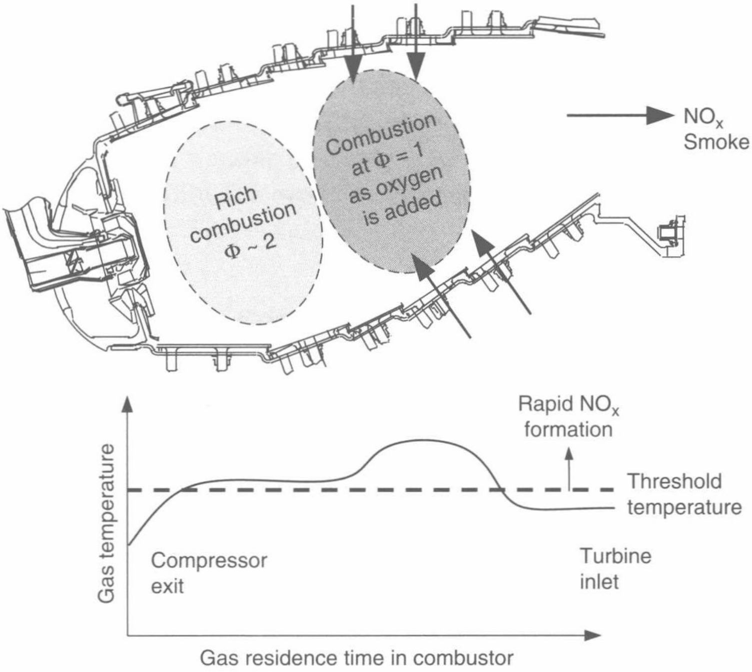

Figure 1.7. Combustor at high power.

Recent advances have shown that substantial reductions in residence time and NO_x can be achieved without compromising combustor stability and low-power performance. Use of fuel injectors that produce small droplets uniformly dispersed within the airflow and rapid air jet mixing has enabled the residence time reduction. These advanced RQL combustor designs (Figure 1.8) have demonstrated NO_x reduction of over 50 percent when compared to early annular combustors. They are also shorter and have lower volumes to reduce residence times. Reduced-length combustors are lighter and also have reduced surface area requiring film cooling. Advanced cooling schemes have been deployed to minimize NO_x emissions and temperature streaks into the turbines.

Overall, the RQL combustor has demonstrated excellent service history. Because it does not require complex controls to modulate fuel between injectors, it has demonstrated very good reliability. It also has inherently favorable stoichiometry for stability because the front-end airflow is minimized for NO_x control purposes. The front-end airflow is established as the minimum amount required for smoke control. If the fuel-air ratio range between high power and low power is large, the airflow required to control smoke can be larger than desirable for flame stability during decelerations. In these instances, the selected minimum transient fuel-air ratio must be raised to protect flight safety and reliability. In turn, raising the minimum fuel-air ratio limit increases the time required to decelerate the engine and can result in a safety risk during emergencies. If the deceleration time cannot be met with the revised minimum fuel-air ratio, then stability must be addressed by other means, such as by clustering fuel injectors provided with either more fuel or reduced airflow. This

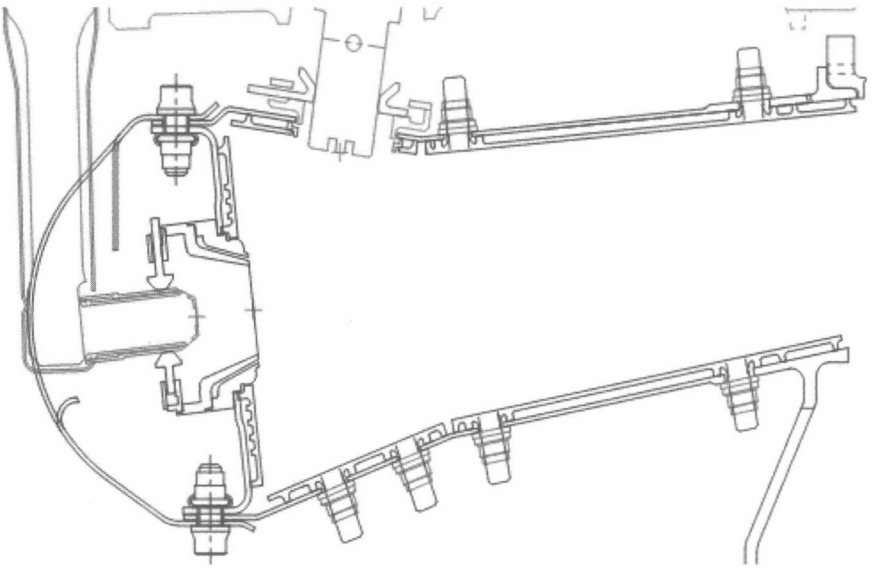

Figure 1.8. Advanced RQL combustor (Pratt & Whitney PW1500 TALON X).

zone remains above the weak extinction level locally and protects against flameout at worst-case deceleration conditions.

The critical challenges for the RQL design approach are smoke and liner durability. As previously discussed, uniform mixing of fuel and airflow in the injectors can result in reduced smoke levels. When the fuel injector stoichiometry is fuel rich overall, the uniformity of the fuel-air distribution within the injector becomes critical. A poorly mixed injector with a wide distribution will have regions that range from fuel lean to very fuel rich. The latter can produce the bulk of the smoke in the combustor. This occurs because the highest smoke generation often takes place in the most fuel-rich regions where there is sufficient residence time. Because the front end is designed with gas recirculation to achieve stability, these zones can produce smoke. Thus, the mixing and recirculation patterns are critical to smoke control.

The presence of fuel-rich and stoichiometric gases also introduces a liner durability challenge. Because modern gas turbines operate at high temperatures and pressures, peak gas temperatures can exceed 4200°F. Metallic liners have a practical temperature limit of <2000°F for designs that meet typical durability life requirements. Therefore, the liner must be cooled to prevent failure. Virtually all aero engine combustors feature hot side film cooling. Film cooling provides a protective layer of airflow on the liner surface that prevents convective heat transfer from high temperature gas. However, when fuel-rich gases in the front end interact with cooling, the film air provides oxidant for high-temperature combustion. Therefore, the presence of cooling air increases NO_x formation in the forward portion of the combustor. In the aft section of the combustor, cooling does not readily mix radially and therefore decreases gas temperatures near the walls. The result is higher temperatures in the midstream. The midstream peaked temperature profile also increases the hottest streak temperature exiting the combustor. Therefore, aft cooling airflow affects the temperature profile and uniformity entering the turbines. Consequently, it is desirable to reduce cooling throughout the combustor. Improved liner designs have enhanced heat transfer efficiency, enabled emissions reductions, and strengthened turbine durability. The evolution of liner cooling designs will be discussed in a later section.

1.5.3 Fuel-Staged Combustors

Having discussed RQL approaches, we next consider fuel-staged combustors, which have seen limited use in commercial aircraft service. First-generation designs were introduced in the 1990s, and updated designs are scheduled for release in future engines. The overall approach in a fuel-staged combustor is to control the combustion stoichiometry through use of fuel injection in multiple locations. Where the fixed-geometry RQL combustor injected fuel and air as uniformly as possible in the front end of the combustor, the staged combustor deliberately provides for multiple airflow and fuel flow zones. The objective is to achieve fuel-lean combustion conditions for NO_x reduction at high power. The fuel-lean conditions keep gas temperatures low and virtually eliminate the highest temperatures associated with stoichiometric conditions that exist in the RQL design.

The lack of fuel-rich and stoichiometric combustion creates two immediate benefits when compared to an RQL design. The first is that the fuel-lean flame produces very low levels of soot emissions. This means that carbon particulate emissions have the potential to be lower from fuel-staged combustors. Significant future efforts are required to characterize the full range of particulates emitted from both types of combustors (see Chapter 5). The second benefit is that the staged lean combustor requires less film cooling air for the liner. Because the lean reaction produces less soot, it is less luminous, resulting in reduced radiation heat load on the liner. Additionally, because the peak gas temperatures are lower, the convective heat loading is reduced. These factors allow for reduced liner cooling flux. This air can in turn be used for emissions control or to improve combustor exit temperature uniformity.

In a fuel-staged combustor, a large amount of airflow is mixed with the fuel at the injection point, so that fuel-lean conditions are achieved at high power with all fuel injectors flowing. The large amount of airflow and fuel-lean conditions pose a stability challenge at low power due to the fuel-air ratio lapse that occurs between high power and low power. To mitigate the stability risk, some of the fuel injectors are turned off at low power. This allows for the control of the combustion stoichiometry at idle to ensure high combustion efficiency. The zone that operates at low power is referred to as the pilot *zone*, and the high-power fuel injectors are referred to as the *main zone*. A difficult challenge for staged combustor designs is the transition between operating with only the pilot at low power and all fuel injectors at high-power conditions. The transition often occurs at mid-power conditions such as approach thrust where fuel-air ratio, pressure, and temperature are not as high as cruise, climb, and takeoff. Therefore, the local fuel-air ratio in the main stage may be unfavorable for efficient combustion at the lower temperatures and pressures. Consequently, more complex staging systems may be required where the main stage fuel injectors are turned on at different overall fuel-air ratios so that high efficiency is maintained. These fuel-air ratios are referred to as *staging points*. Initial designs were applied to engines with relatively low fuel-air lapse levels. These designs were operated with two fuel stages and a single staging point. More recent designs applied to engines with higher fuel-air ratio lapse may require more than a single fuel staging point to maintain staging efficiency.

Staging can also affect engine acceleration time from idle to higher power conditions. This is because of two factors. The first is the aforementioned combustion efficiency near the staging point. Lower efficiency results in reduced heat release and slower acceleration. The second is potential delay time to deliver fuel to the main fuel injectors. If some of the fuel flow is needed to fill fuel manifolds and fuel injectors, a delay occurs in the time to achieve combustion heat release and engine acceleration. Therefore, it is desirable to keep the main stage fuel system as filled as possible to achieve prompt acceleration when the throttle is moved. However, a full main stage fuel system is vulnerable to fuel coking. *Fuel coking* refers to the hard carbonaceous compounds formed in the internal passages of the fuel system when the fuel undergoes pyrolysis reactions when it is heated in the absence of air. Such compounds can block or reduce the flow of fuel through the main stage hardware. Coking is most common inside the fuel injectors because they are exposed to the high temperatures inside the diffuser casing. In the extreme, coking can limit thrust by limiting fuel flow. Most modern engines have idle air temperatures near or above the level at which significant coking occurs (400°F). This air is in contact with the main stage fuel injectors containing the stagnant fuel. To prevent fuel coking, cooling and insulation features must be incorporated to prevent fuel from contacting passage walls over the critical temperature for coking. Some designs use the pilot fuel flow to cool the stagnant main fuel injectors. Other possibilities include using air pressure to purge the fuel from the most vulnerable areas.

A final challenge to the fuel-staged combustor designer is combustion instability. *Combustion instability* refers to temporal fluctuations in the heat release. Such fluctuations can be attributed to several mechanisms, typically involving excitation of natural fluid mechanic instabilities in the flow or fuel-air ratio oscillations. In the extreme, instabilities can damage hardware and result in engine damage and failure. All combustors have risk of instability, but staged lean combustors have been more prone to them. It is unclear if this tendency is related to differences in acoustic driving resulting from heat release distribution differences or to changes in acoustic damping as the combustor is modified for lean-staged operation (Lieuwen and Yang, 2005).

1.5.4 Ignition and Engine Starting

Gas turbine combustors are required to ignite on the ground and in flight. Ignition in flight is rare because it occurs after unplanned engine shutdown. The combustor should ignite promptly after the fuel is turned on and provide efficient combustion to accelerate the engine to idle power. Delayed ignition can cause excess fuel accumulation in the combustor and increased pressure pulses at light off. Increased pressure pulses can result in compressor stall that prevents engine acceleration to idle. On the ground and at low-speed flight conditions, the engine rotors are turned with a starter to provide airflow to the combustor for ignition and combustion. At higher-speed flight conditions, the ram airflow turns the rotor in a process referred to as *windmilling*. Ignition energy is typically delivered with a spark igniter. At least two igniters are placed in the typical annular combustion chamber to provide redundancy in the event of a failure. The spark produces plasma sufficient to initiate the combustion reaction. The ignited reactants must then be transported to an area where the reaction can stabilize and propagate to the other fuel injectors in the combustor. The same features that provide flame stability at idle and deceleration conditions are relied upon at sub-idle starting operations. The pressure at light off is usually near the outside ambient pressure because the rotors are not producing significant work. However, at higher flight speeds, the total pressure is typically slightly higher than ambient due to the stagnation effect. Temperatures at ignition are highly dependent on the thermal state of the engine. For the first start of the day on the ground, temperatures are usually only slightly higher than ambient. Altitude relight temperatures are highly dependent on the amount of time the engine has been shut down. For quick relight attempts less than a minute after shutdown, temperature at the combustor inlet can be greater than 200ºF. If the engine is shut down and windmilling for thirty minutes or longer, the air temperature is closer to the outside ambient.

Most commercial aircraft must meet requirements for both ground and altitude starting. The ground starting requirements include a range of ambient temperatures and airport altitudes. Typical ground starting ambient temperature requirements vary between –40 and 120ºF. Airport altitude requirements typically range between sea level and eight thousand feet. Altitude relight requirements are typically expressed on a flight envelope (Figure 1.9). There is a high-speed windmilling envelope and a lower-speed starter assisted envelope. The maximum altitude required for air starting depends on the aircraft. Commercial airliners normally require altitude relight capability of at least twenty-five thousand to thirty thousand feet. Business jets often require capability at thirty-five thousand feet because of their higher cruising altitude.

At the highest altitudes and in extreme cold, combustor ignition conditions can be very challenging. Pressures of less than five psia and temperatures below 0ºF are typical for an engine that windmills until cold. These conditions inhibit the atomization of fuel and vaporization of droplets. Low temperature and pressure also slow the reaction kinetics that promotes stabilization and propagation of flame. Therefore, design of the combustor should provide for three key features that enable ignition: a good fuel spray, a favorable airflow velocity, and the proper spark igniter location.

Small fuel droplets are critical to the formation of vapor necessary for ignition. Two types of fuel injectors are typically used: pressure atomizing and airblast

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