SAC Flow Structure Evolution

An Experimental Analysis of Combustor Flow Structure Evolution

1. Introduction: The Aerodynamics of Combustion

In the design of Gas Turbine Combustors (GTC), aerodynamics—specifically the structure of the internal flow field—plays a critical role in ensuring flame stability and managing pollutant emissions. The primary mechanism for flame anchoring is the establishment of a Central Recirculation Zone (CRZ), a region of reverse flow that continuously ignites the incoming fuel-air mixture.

This study presents an experimental investigation into how modifications to the combustion chamber geometry can be used to control the flow field structure. The analysis of the resulting aerodynamic changes was conducted using two-component Laser Doppler Velocimetry (LDV).

2. Experimental Methodology and Boundary Conditions

The experimental approach involved systematically altering the combustor geometry and measuring the resulting isothermal flow field under controlled conditions.

2.1. Diagnostic System and Test Facility

Measurements were conducted using a two-component Laser Doppler Velocimetry (LDV) system from Artium Technologies Inc. This system utilizes diode-pumped solid-state (DPSS) lasers as its light source. To trace the flow, the air was seeded with olive oil particles with a diameter range of 1 to 5 micrometers (μm).

2.2. Test Conditions

The following boundary conditions were maintained for all experiments:

- **Flow:** Isothermal
- **Pressure:** Ambient
- **Temperature:** 70±1ºF
- **Total Pressure Drop:** 4.9%

2.3. Combustor Configurations

Four distinct geometric configurations were investigated to isolate the effects of specific design features.

Configuration	Description
CONFIG 1	A baseline swirl cup feeding a dump combustor with a rectangular cross-section. The chamber has a width-to-breadth ratio of 85%.
CONFIG 2	Identical to CONFIG 1 but with an asymmetric combustion dome installed. The dome features a 9° difference in the expansion angle between its two sides.
CONFIG 3	The swirl cup and dome are installed in a Single Annular Combustor (SAC) sector with a tilted inner liner. Both primary and secondary dilution jets are blocked.
CONFIG 4	The same SAC sector setup as CONFIG 3, but with both the **primary and secondary** dilution jets fully open.

3. Baseline Flow Analysis: The Dump Combustor (CONFIG 1)

The flow structure of CONFIG 1, a swirl cup discharging into a rectangular dump combustor, serves as the baseline for this analysis. The chamber's confinement, defined by its width-to-breadth ratio of 0.85, directly influences the three-dimensional shape of the CRZ, resulting in a CRZ with an approximate diameter ratio of 0.85.

Key characteristics of the CRZ in this baseline case include:

- It extends downstream to a length of 6.5R, where R is the radius of the swirler flare.
- The magnitude of the axial (reverse) velocity within the CRZ is typically 10 m/s.

The tangential velocity profile initially exhibits the characteristics of a Rankin vortex (a combination of a solid-body rotation core and a free vortex outer region) near the swirler exit at an axial position of $Z/R=0.2$. Further downstream, this transitions to a more uniform forced vortex behavior.

4. Parametric Study: The Impact of Geometric Alterations

This section systematically analyzes the aerodynamic changes resulting from each successive geometric modification.

4.1. Effect of the Combustion Dome (CONFIG 2 vs. CONFIG 1)

The installation of the combustion dome has significant aerodynamic consequences. The dome effectively eliminates the corner recirculation zone and removes the low-velocity regions that form near the combustor walls in a simple dump configuration.

A critical finding is that the dome's 9° asymmetry in its expansion angle produces a significant asymmetry in the velocity field, with higher velocities observed along the surface with the greater expansion angle. This, in turn, results in a noticeable tilting of the Central Recirculation Zone. Furthermore, the dome damps fluctuations in the expanding jet region, reducing the root mean square of the axial velocity (RMSA)—a measure of turbulence—by 42% compared to the baseline CONFIG 1.

4.2. Effect of Combustor Confinement (CONFIG 3 vs. CONFIG 2)

When the swirl cup and dome assembly is installed in the Single Annular Combustor (SAC) sector, the tilted inner liner significantly alters the flow field. This change in confinement geometry causes a 40% reduction in the CRZ Length, shortening it from 8R to 4.8R. The tilting of the combustor wall also increases the strength of the CRZ, with the reverse velocity in its core increasing by approximately 20% relative to CONFIG 2.

4.3. Effect of Primary Dilution Jets (CONFIG 4 vs. CONFIG 3)

Comparing the blocked-jet case (CONFIG 3) to the open-jet case (CONFIG 4) reveals the dominant role of the primary and secondary jets. When active, these jets dictate the termination point of the CRZ, overriding the influence of the downstream liner geometry.

The jets also have a profound impact on turbulence. Opening the jets increases the RMSA in the expanding jet region by 25% and leads to a 60% increase in turbulence activities in the upper portion of the CRZ.

5. Comparative Summary of Key Flow Features

The following table synthesizes the key aerodynamic results, providing a direct comparison of how each geometric feature influences the combustor flow field.

Configuration	Key Geometric Feature	CRZ Length	Relative CRZ Strength (Core Velocity)	Relative Turbulence (RMSA in Jet Region)
CONFIG 1	Dump Combustor (Baseline)	6.5R	Baseline	Baseline
CONFIG 2	Asymmetric Dome	8R (baseline length within the rectangular chamber before liner modification)	Similar to Baseline	42% reduction vs. CONFIG 1

CONFIG 3	Tilted SAC Liner (Jets Blocked)	4.8R (40% reduction vs. CONFIG 2)	~20% increase vs. CONFIG 2	Similar to CONFIG 2
CONFIG 4	SAC Liner with Open Primary & Secondary Jets	Terminated by jets	~4% increase vs. CONFIG 3	25% increase vs. CONFIG 3

6. Conclusions and Design Implications

This experimental analysis demonstrates that targeted geometric modifications are a powerful method for controlling the flow field structure in a gas turbine combustor. The key findings and their design implications are summarized below.

- **Dome Design Trade-Offs:** The combustion dome is effective at eliminating unwanted corner recirculation and damping turbulence (reducing RMSA by 42%), which can improve dynamic stability. However, this stability comes at the cost of reduced turbulence-driven mixing and creates high surface velocities that may accelerate liner wear, particularly in asymmetric designs which can induce flow distortion.
- **Confinement vs. Swirler:** The overall confinement geometry (e.g., chamber aspect ratio, liner tilt) is the primary factor dictating the CRZ's size and shape. In contrast, the swirl cup configuration mainly influences the strength of the CRZ, specifically the magnitude of the reverse flow velocity in its **lower portion near the combustor front end**.
- **Primary Jets:** Primary jets are a dominant aerodynamic feature. They control the termination point of the CRZ and significantly increase turbulence levels in the regions of jet interaction.
- **Design Principle:** Any geometric modifications intended to shape the flow field must be evaluated in the presence of primary jets. The strong influence of the jets can fundamentally alter or override the flow characteristics established by the upstream geometry (swirler and dome).