SAC Aerodynamics

A Technical Deep Dive: Analyzing the Aerodynamics of a Gas Turbine Combustor Sector

Introduction: The Critical Role of Aerodynamics in Combustor Design

This analysis details the experimental investigation of aerodynamics within a realistic Single Annular Combustor (SAC) sector, also known as a Fuel Rich Dome Combustor. In the design and development of Gas Turbine Combustors (GTC), aerodynamics are of the first priority, playing a vital role in combustion stability, emissions, and overall dynamics. This article will focus specifically on the experimental methodology used and the key numerical findings from the study, which are based on Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) measurements.

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1. The Experimental Apparatus: Anatomy of the SAC Sector

1.1 The Combustor Test Rig

The SAC sector used in this experiment is a realistic model comprising multiple key components designed to simulate actual GTC conditions. These components include:

- A swirl cup with counter-rotating coaxial radial inlet swirlers
- An inlet diffuser and inlet cowl
- Film cooling strips (eight on each side)
- A combustion dome with cooling slots
- Inner and outer passages for cooling and dilution air
- A liner with a variable cross-section, cooling strips, and holes for primary and secondary dilution jets

1.2 The Test Facility and Seeding

Air was supplied to the combustor via a test facility built around an 8-inch PVC pipe manifold. An internal honeycomb structure provided uniform flow to the SAC diffuser inlet. The manifold was fed by a 2-inch pressurized air pipe, and pressure sensors and thermocouples were mounted inside to monitor inlet conditions.

For the flow measurements, an atomizer was used to generate olive oil seeding particles with a diameter of 1-5 μm, which were introduced into the manifold through a seeding port.

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2. Advanced Diagnostics: The PIV and LDV Measurement Systems

Two primary diagnostic techniques, Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV), were used to conduct the detailed flow field measurements.

2.1 Particle Image Velocimetry (PIV) System

The PIV system, manufactured by LaVision Inc., consisted of the following key components:

- **Cameras:** Two 1376 x 1040 pixels, 12-bit LaVision imager intense CCD cameras.
- **Lasers:** Two 120 mJ, 15 Hz pulse Nd-Yag lasers synchronized with the cameras.

To extend the measurement volume, the two cameras were placed one on top of the other. This setup was a real challenge due to the reduced width of the SAC sector exit port, which is designed to fit a turbine nozzle ring.

2.2 Laser Doppler Velocimetry (LDV) System

The two-component LDV measurements were conducted using a system from Artium Technologies Inc. Its primary components were:

- **Lasers:** Two diode-pumped solid-state (DPSS) lasers.
- **Optics:** A 500 mm focal length transmitter and a 300 mm focal length receiver.
- **Processors:** Two ASA signal processors.

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3. Experimental Parameters and Test Conditions

The experiments were performed under precisely controlled isothermal conditions. The key parameters and specifications for the PIV and LDV tests are detailed below.

Parameter	Specification
Flow Condition	Isothermal
Ambient Conditions	70±1ºF temperature and ambient pressure
Coordinate System Origin	Center of the swirler exit (flare center)
LDV Pressure Drop	4.9%

LDV Data Count	> 7000 (radial velocity) and > 3000 (axial velocity)
PIV Pressure Drops	4.3% and 7.6%
PIV Averaging	200 instantaneous images averaged for mean flow field
PIV Processing	32x32 pixel interrogation area with 50% overlap
PIV 3D CRZ Planes	X-Z planes at Y distances of 0.66R, 1.12R, and 1.32R

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4. Key Aerodynamic Findings and Results

The combination of LDV and PIV diagnostics yielded several critical insights into the combustor's internal aerodynamics.

4.1 Effect of Pressure Drop on Flow Structure

The primary conclusion regarding pressure drop is that the overall flow structure is independent of the pressure drop—a typical behavior for flows at high Reynolds numbers. PIV measurements conducted at 4.3% and 7.6% pressure drops demonstrated that the Central Recirculation Zone (CRZ) and all associated wake regions maintained their absolute size. However, the velocity magnitudes were found to change proportionally to the square root of the pressure drop.

4.2 Turbulence, Ignition, and Reaction Zones

High turbulence activity, a key factor in mixing and combustion, was observed in several distinct areas within the combustor sector:

- Around the jet boundaries (shear layers).
- In the central region where dilution jets mix with the main flow, which is the area of **maximum turbulence activity**.
- As the main jet issues from the swirler cup flare.

These high-turbulence regions are significant because reacting flow video analysis shows that reaction primarily takes place in these areas, making them candidates for the development of periodic oscillations. Further analysis with a high-speed camera revealed that during ignition, these same regions may ignite before others.

As the fuel equivalence ratio was increased from 0.2 to 0.9, the reaction zone was observed to start at the CRZ edge and progress downstream, first to the primary jet boundaries and then to the secondary jet boundaries.

4.3 3D Structure of the Central Recirculation Zone (CRZ)

Off-center PIV measurements were utilized to reconstruct a 3D image of the Central Recirculation Zone. The specific dimensions of the reconstructed CRZ were found to be:

- **Height:** Roughly constant at 2.7R
- **X-direction extent:** Up to 1.6R
- **Y-direction extent:** Up to 1.3R

The key conclusion drawn from these dimensions is that the confinement of the SAC sector has a strong influence on the 3D shape of the CRZ. This is supported by comparing the CRZ breadth/width ratio (~0.85) to the SAC primary zone's breadth/width ratio (~0.81), which are closely matched.

4.4 Instantaneous Behavior of Dilution Jets

Instantaneous PIV results revealed a strong, dynamic interaction between the dilution jets and the surrounding flow field. The jets were observed to be in "continuous up and down fluctuations." This dynamic behavior can be classified into three distinct scenarios:

1. **Symmetric Impingement:** Both jets impinge toward the centerline, resulting in a fairly symmetric flow where a portion of the flow moves up and another portion moves down toward the flare.
2. **Asymmetric Scenario 1:** The right dilution jet shoots up while the left shoots down. In this case, the primary zone structure is controlled by the left jet feeding the CRZ, and the post-recirculation zone is controlled by the upward-shooting right jet.
3. **Asymmetric Scenario 2:** The left dilution jet shoots up while the right shoots down, producing a similar but opposite effect on the flow field compared to the second scenario.

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5. Summary of Conclusions

This experimental investigation successfully mapped the complex aerodynamic field within a realistic GTC sector. The main conclusions from the study are summarized below:

1. The use of PIV successfully delineated the complex flow features, showing good agreement with LDV measurements and validating its use in this challenging geometry.
2. At high Reynolds numbers, the pressure drop does not influence the overall flow field structure; the size of the CRZ and jet wake regions remains constant.
3. Off-center PIV measurements proved effective for reconstructing the 3D structure of the Central Recirculation Zone, enabling a better understanding of its role in flame stabilization.

4. The confinement geometry of the combustor sector has a strong and direct influence on the 3D shape of the CRZ.
5. The primary dilution jets play a critical role in dictating the flow field. Their continuous, dynamic fluctuations, including symmetric and asymmetric impingement, directly control the structure of the Central Recirculation Zone and the mixing characteristics in the secondary region.