SAC design

Deconstructing Combustor Design: A Technical Analysis of a Single Annular Combustor (SAC) Methodology

1. Introduction: Automating Preliminary Combustor Design

The design of Gas Turbine Combustors (GTC) is an inherently complex and time-intensive process, involving coupled non-linear equations and extensive calculations. The source paper addresses this challenge by presenting a detailed, automated methodology for the preliminary design phase. The primary objective is to create a systematic, step-by-step procedure for a Fuel Rich Dome Combustor (also referred to as a Single Annular Combustor or SAC).

This technical analysis performs a deep dive into the paper's methodology. It extracts the key governing equations, critical design assumptions, and performance evaluation criteria that form the foundation of this automated approach.

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2. Foundational Inputs and Air Distribution Logic

The design process originates from a set of required parameters derived from the engine's thermodynamic cycle. These inputs define the operational requirements:

- m_a: Compressor exit mass flow rate
- T_{03}: Compressor exit total temperature
- P_{03}: Compressor exit total pressure
- **FAR**: Fuel-to-Air Ratio
- **TIT**: Turbine Inlet Total Temperature
- π_b: Combustor pressure ratio
- $\Delta P_b / P_{03}$: Total pressure loss through the combustor
- **NFN**: Number of fuel nozzles

The first critical step is **air distribution**. The goal is to apportion total airflow (m_a) between the dome (m_{dome}) and the liner passage ($m_{passage}$). This is essential for managing fuel atomization, flame stabilization, and liner cooling.

Key Calculations

The process begins with an energy balance to determine the required fuel flow rate (m_f) and subsequent ratios.

Total Fuel Flow Rate (m_f):

$$m_f = \frac{m_a \cdot C_{pa} \cdot (TIT - T_{03})}{HV \cdot \eta_b}$$

*(Where $C{pa}$ is the specific heat of air, HV is the fuel heating value, and η_b is combustion efficiency).*_

Air-to-Fuel Ratio (AFR) & Equivalence Ratio (Φ_{PZ}):

These are derived directly from the calculated m_f and the input air mass flow.

Distribution Assumptions

The logic relies on typical values derived from conventional designs:

Parameter / Ratio	Assumed Value / Range	Purpose / Rationale
$m_{a,atom}/m_f$	2 to 3	Ensure sufficient atomization of fuel.
m_{dome}/m_a	10–15%	Typical for conventional combustors.
Φ_{PZ}	1.4 to 1.5	Avoid low efficiency at idle and smoke at high power.
ω_3	0.75 kg s^{-1} m^{-2} atm^{-1}	Typical combustor loading parameter.

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3. Combustor Sizing and Reference Velocity

Once the air distribution is defined, the combustor's main physical dimensions are estimated using the **velocity method**. This anchors the initial layout in established practice by constraining flow characteristics.

Reference Velocity (V_{ref}):

$$V_{ref} = \frac{m_a}{\rho_3 A_{ref}}$$

*(Where ρ_3 is the air density at the compressor exit and $A*{ref}$ is the combustor reference area).*_

Combustor Length (L):

The length is determined by scaling laws involving the length-to-diameter ratio and pressure drop factors:

$$L \quad f\left(\frac{L}{\quad}, \frac{\Delta P_L}{ref}\right)$$

*(Where $\Delta P_L/q*{ref}$ is the liner pressure drop normalized by the reference dynamic head).*_

> **Note:** The methodology assumes a combustor velocity (V_c) between **35–60 m/s** and a dome velocity (V_d) between **7–12 m/s**.

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4. Aerodynamic Performance: Pre-Diffuser Design

The pre-diffuser recovers inlet dynamic head, converting kinetic energy into static pressure before the air enters the combustion zone.

Ideal Pressure Recovery Coefficient (C_{pi}):

This represents the theoretical maximum recovery assuming no frictional losses.

$$C_{pi} = 1 - \frac{1}{A^2}$$

(Where A is the diffuser Area Ratio, $A*{exit} / A*{inlet}$).

The design process iterates the Area Ratio (A) from **1.4 to 3.0** to minimize total pressure loss. The diffusion angle (2) is constrained to **4°–8°** to prevent flow separation.

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5. Fuel Atomization and Flame Stabilization

Effective fuel preparation and flame anchoring are contingent on the fuel injection and air swirl subsystems.

5.1. Dual Orifice Fuel Nozzle

A dual-orifice design is mandated to handle the wide turndown ratio of gas turbines.

- **Primary (Pilot):** For low-flow/idle conditions ($C_{d,p} \approx 0.36$).
- **Secondary (Main):** For high-power conditions ($C_{d,s} \approx 0.27$).

Nozzle Flow Number (F_I):

$$F_I = \frac{m_f}{\Delta P_f \rho_f}$$

(Where ΔP_f is pressure drop across the nozzle and ρ_f is fuel density).

5.2. Axial Swirler Design

The swirler generates a Central Recirculation Zone (CRZ) to recirculate hot combustion products and anchor the flame.

Swirl Number ():

To establish a stable CRZ, the Swirl Number must typically be 0.6.

$$= \frac{2}{3}\left[\frac{1-(d_h/d_o)^3}{1-(d_h/d_o)^2}\right]\tan$$

(Where d_h is hub diameter, d_o is outer diameter, and is the vane angle).

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6. Thermal Management and Liner Cooling

With gas temperatures exceeding **2000°C**, active cooling is mandatory. The methodology employs a heat transfer balance model accounting for convection, radiation, and conduction.

Film Cooling Effectiveness (η_f):

This defines the performance of the cooling air film in insulating the wall.

$$\eta_f = \frac{T_g - T_{aw}}{T_g - T_c}$$

*(Where T_g is hot gas temp, $T*{aw}$ is adiabatic wall temp, and T_c is cooling air temp)._

Thermal Barrier Coating (TBC) Conduction:

If a ceramic coating is used, the temperature drop across the coating is calculated as:

$$Q_{cond} = \frac{TC}{t_{TC}}(T_{w1} - T_{if})$$

*(Where $k*{TBC}$ is thermal conductivity, t_{TC} is thickness, and T_{if} is the interface temperature)._

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7. Performance Evaluation: Emissions and Droplet Lifetime

The final step evaluates the combustor's efficiency and environmental impact.

7.1. Fuel Spray and Evaporation

For complete combustion, the droplet lifetime ($_d$) must be less than the residence time ($_{res}$).

Droplet Lifetime (D-squared Law):

$$_d = \frac{^2_0}{K}$$

(Where $_0$ is the initial droplet diameter and K is the evaporation constant).

7.2. NOx and CO Emissions

Empirical NOx Estimation:

Useful for rapid system-level trade-offs.

$$I = 0.15 \times 10^{16} (_{res})^1 \exp\left(\frac{-71100}{T_{st}}\right) P_{03}^{0.25} (V_c)^{-1}$$

Physics-Based Zeldovich Mechanism:

For fundamental analysis, the thermal NOx formation is modeled using three core reactions:

1. $+_2 \quad +$
2. $+_2 \quad +$
3. $+H \quad +H$

These are combined into a final rate generation equation:

$$\frac{d[]}{dt} = \frac{2[][_2]_{f1}\left(1 - \frac{_{b1}{_{b2}}[]^2[]}{_{f1}{_{f2}}[_2][_2]}\right)}{1 + \frac{_{b1}[]}{_{f2}[_2] + _{f3}[H]}}$$

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8. Conclusion

The technical methodologies extracted from the source paper form a cohesive framework for the preliminary design of a Fuel Rich Dome Combustor. By balancing empirical correlations for rapid sizing with first-principles calculations for kinetics and heat transfer, this automated tool allows designers to efficiently explore the design space and assess performance trade-offs.