AAE 538: Air-Breathing Propulsion

Lecture 18: Combustion in Gas Turbines

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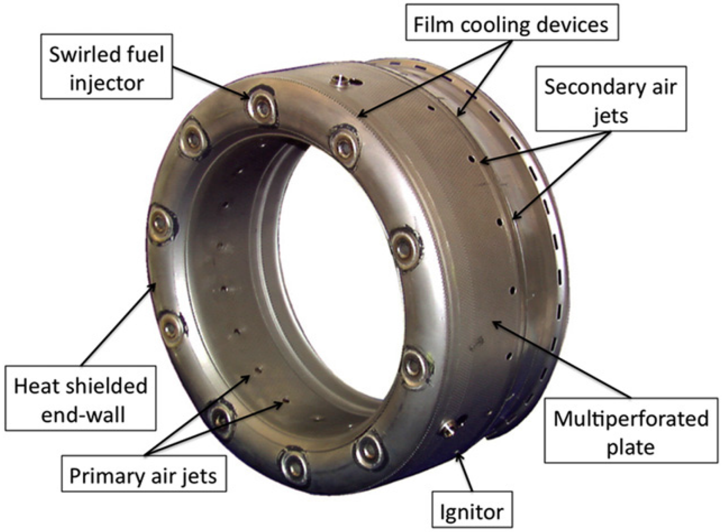
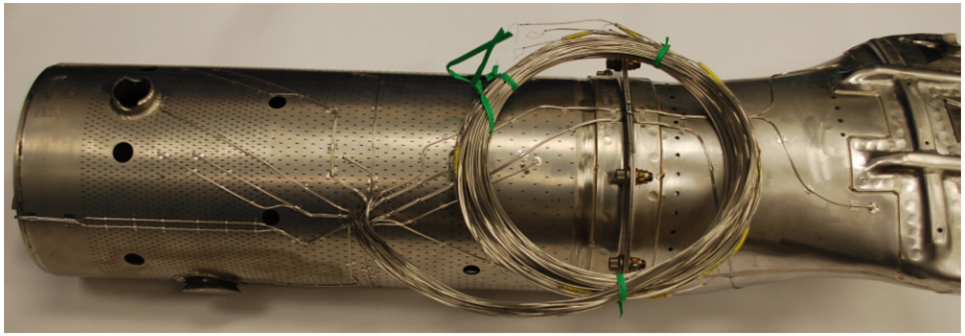
Introduction

- Up to this point we have modelled the combustor as a region in the engine where the fluid stagnation temperature is increased uniformly due to ____.
  - We now seek a deeper understanding of the processes inside the combustor.
  - In the end, we want to manipulate these processes to achieve our desired performance.

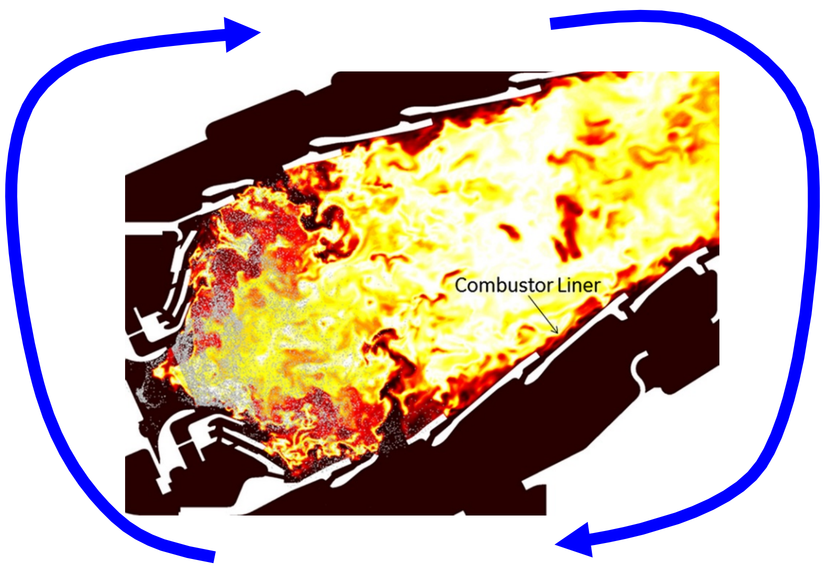




Combustion linear examples for can-type (above, left) and annular (above, right) combustion chambers.

Introduction

- Combustion processes in propulsion applications can be globally-characterized as having a ______________________________.
  - The volumetric heat release rate in a typical steam power plant is on the order of $8\ BTU/ft^3 s$
  - In a jet engines, the this rate can be greater than ________________________.
- Multi-scale, multi-physics design



Introduction

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Premixed Combustion in Industrial Systems

- Land-based, industrial turbines typically operate with a ____________________ system design.
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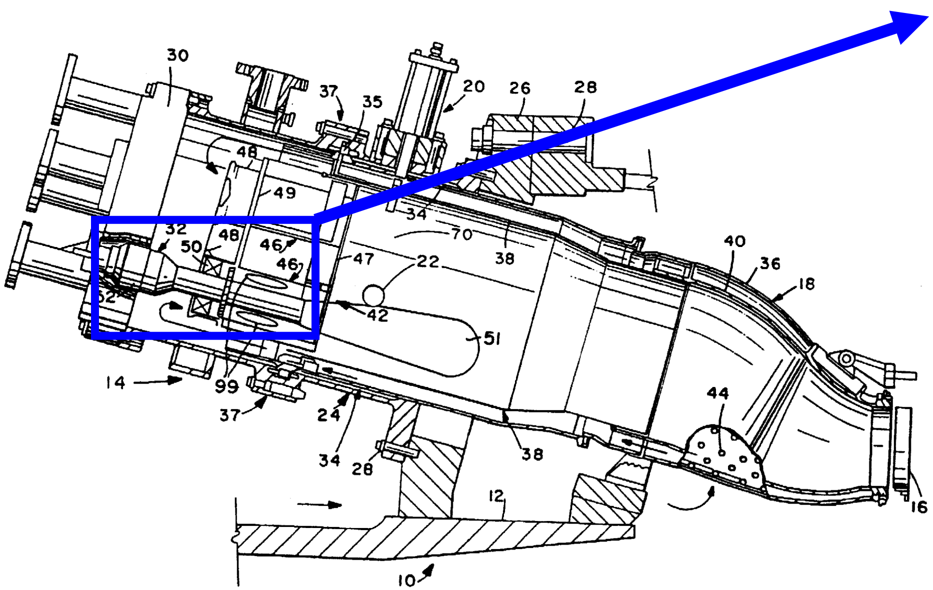
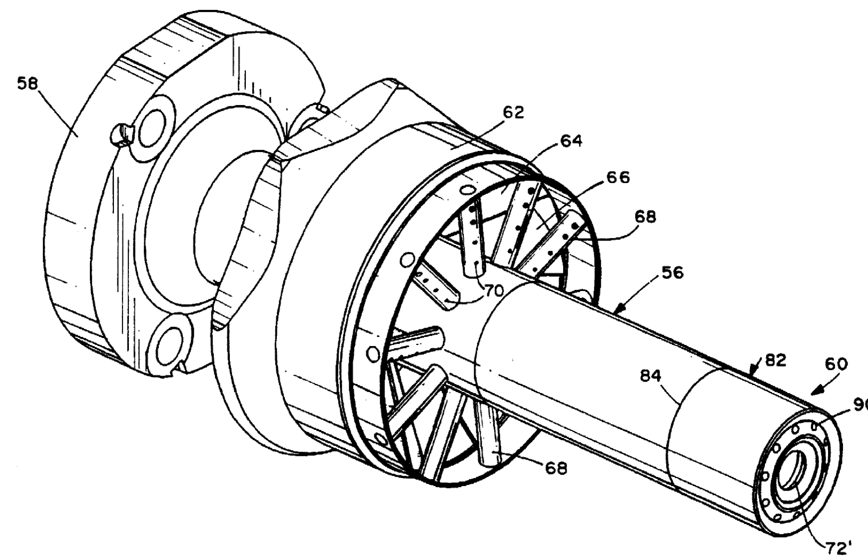
  -
  -

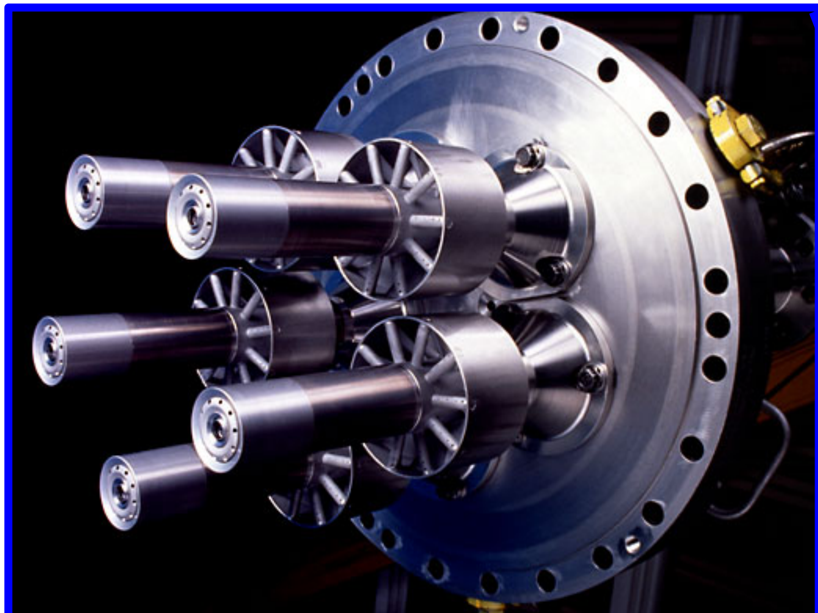


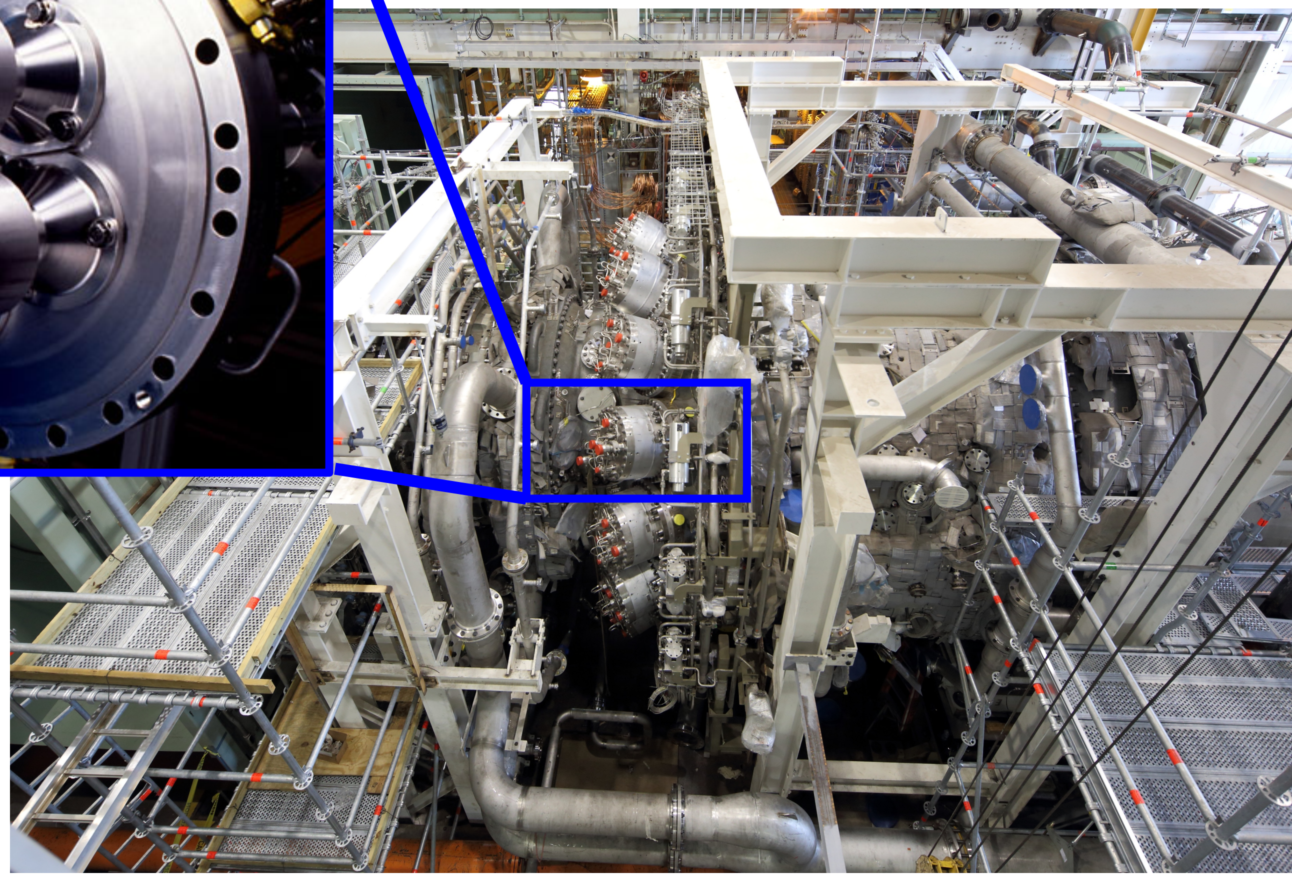


Extracted from patent number 5,685,130
(General Electric Company)
Dry, Low-NOx Combustion System

Introduction

Premixed Combustion in Industrial Systems

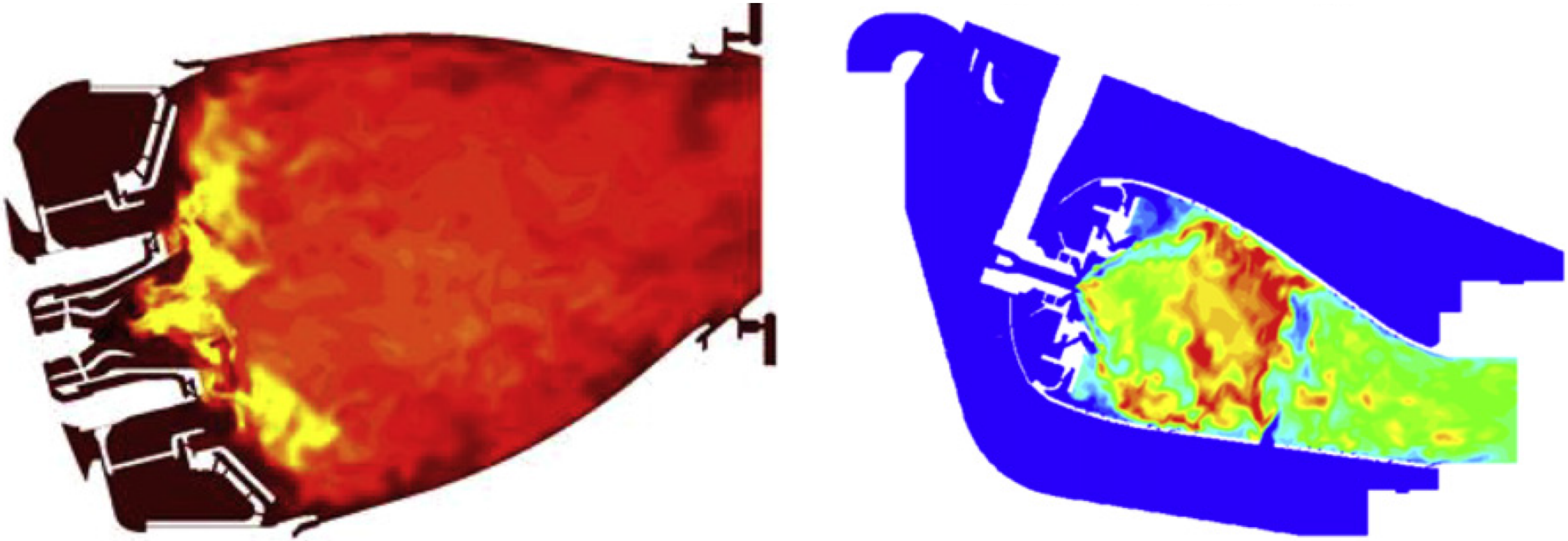




Power-plant installation of a GE Power gas turbine with DLN combustor technology

Introduction

Two Principal Architectures for Propulsion

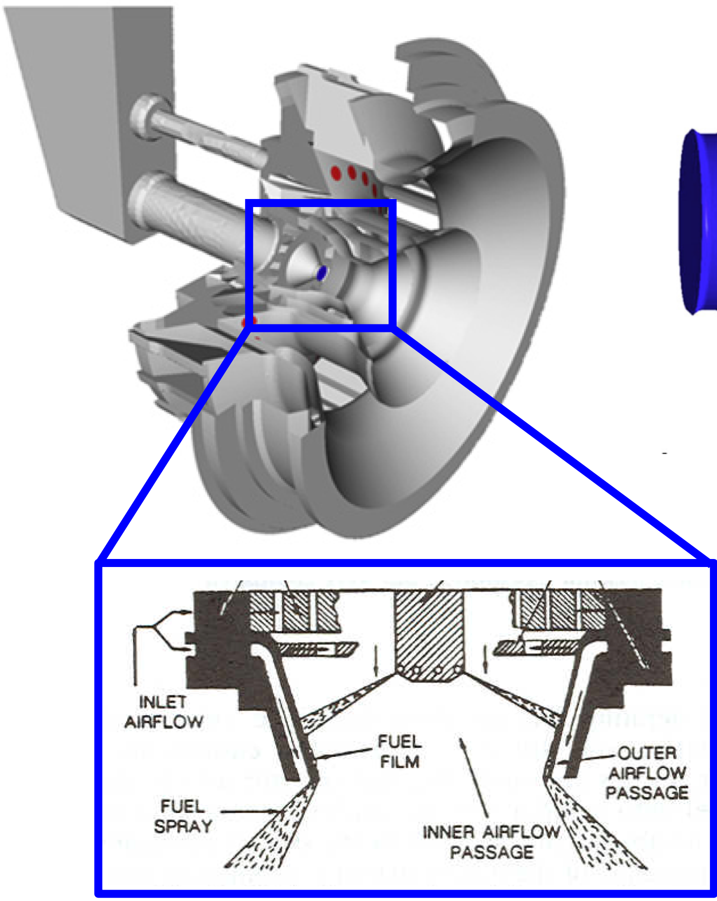


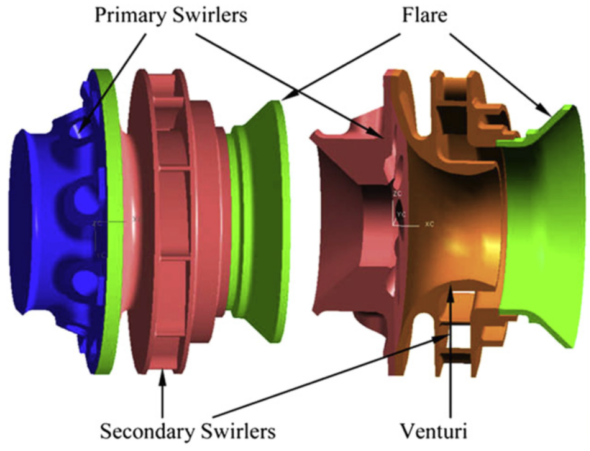
Non-dimensional contours of temperature for two primary configurations for aviation turbine engines: Lean (left) and Rich-Quench-Lean (right)

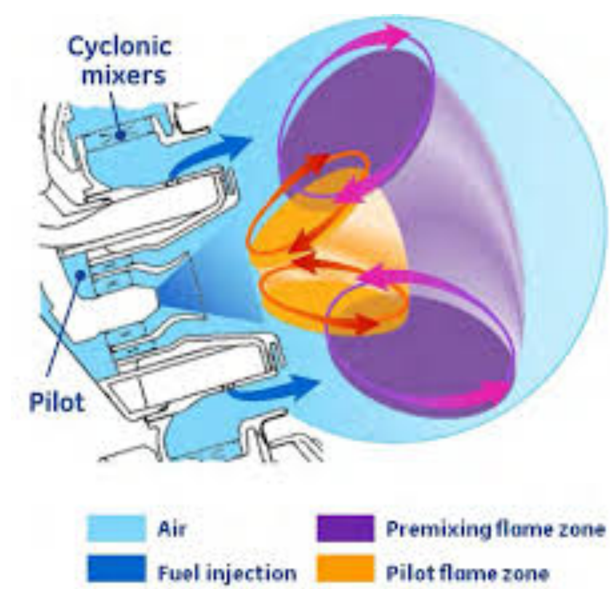
-
- Gas turbine combustors inevitably operate in a ______________________ ______________________ in propulsion applications
    -

Introduction

No two injectors look alike…

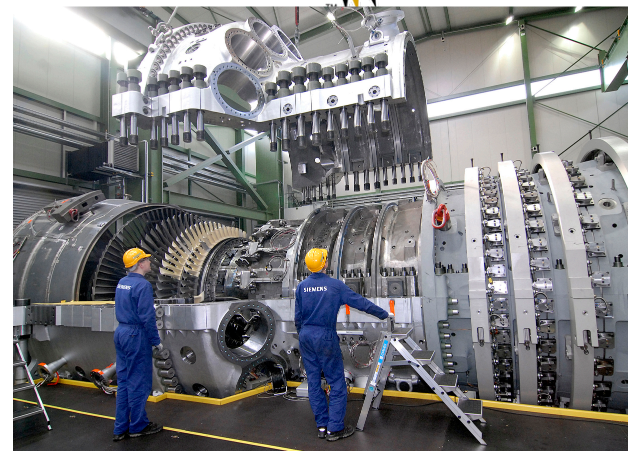


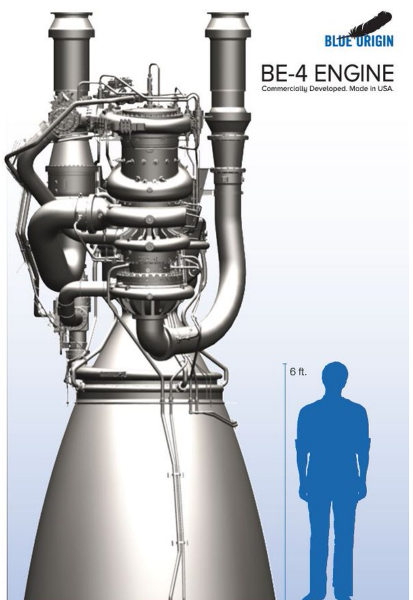


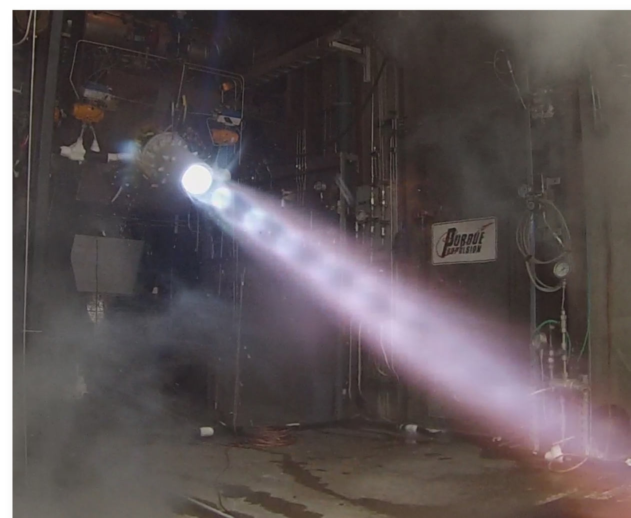


Combustion Engineering

It's just a fire… so how do we ***design*** it?







Combustion Engineering

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Progress over the years…

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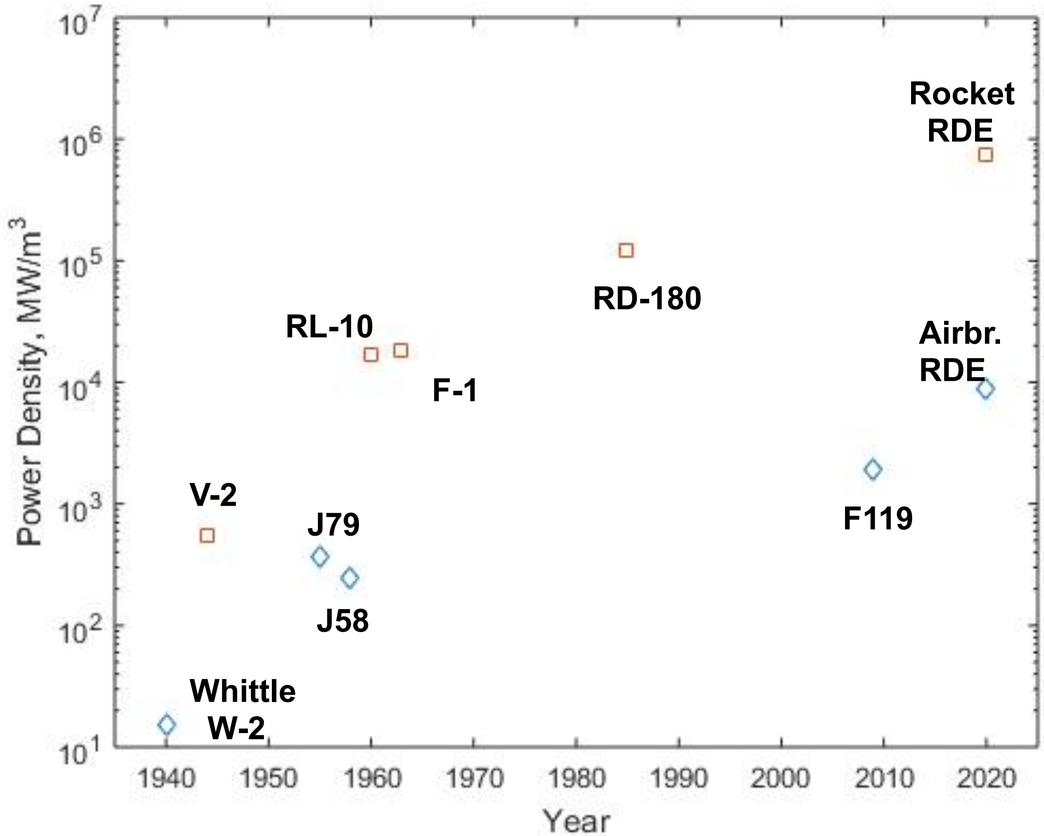
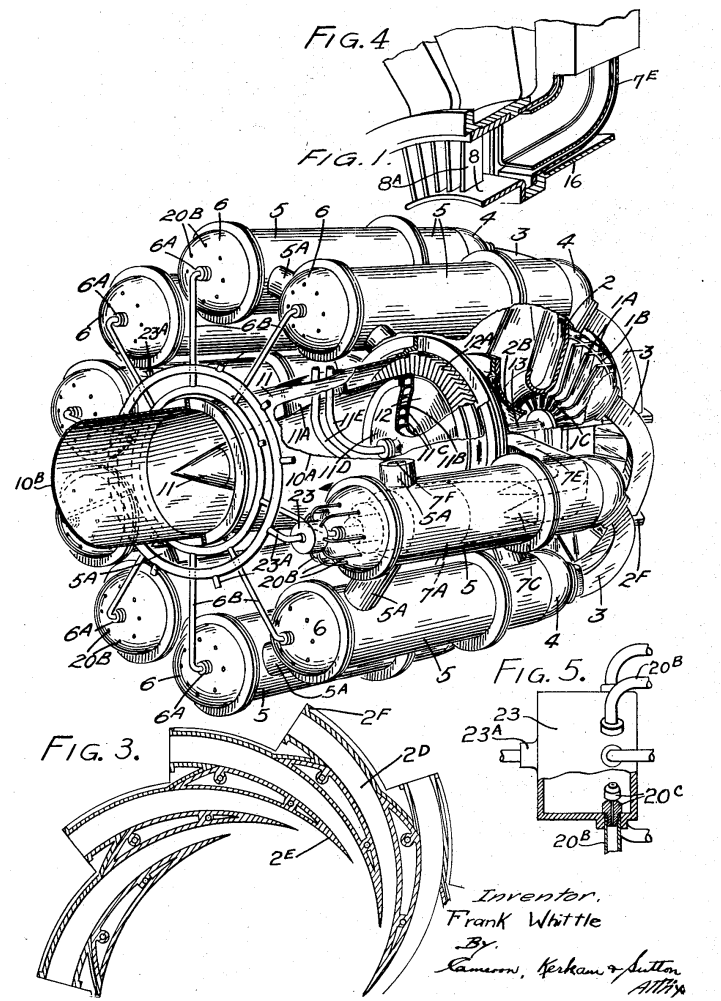


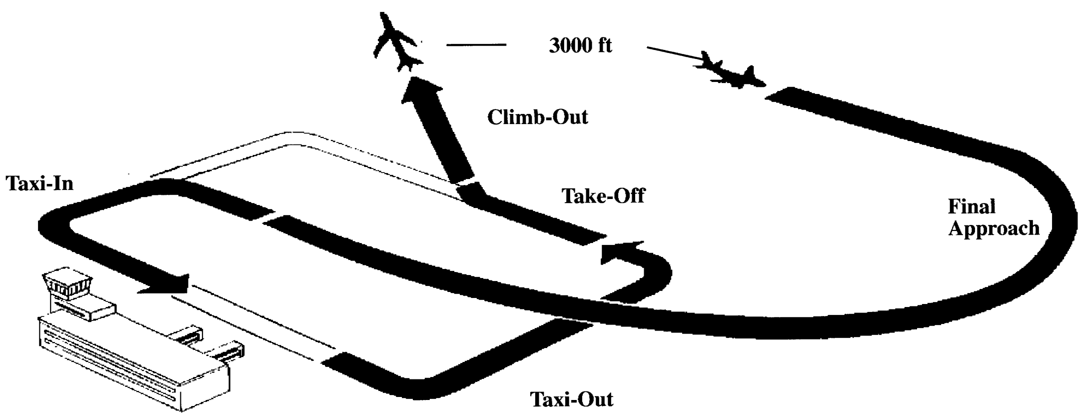


Diagrams from 1941 Whittle Patent

Defining Requirements

Parameter	Take-Off	Cruise
Π_c		
P_3		
T_3		
T_4		
ϕ_O		

- Airlines concerned with ________________________.
  - Predominant mode of operation
- Regulatory agencies address turbojet/turbofan emissions up to 3000 ft.

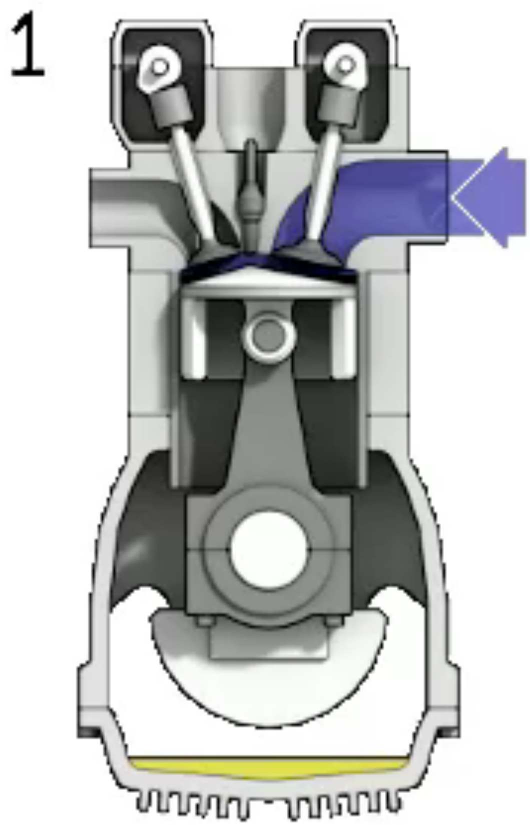


Operating Mode	Thrust (%)	Time (minutes)
Take-Off	100	
Climb-Out	85	
Approach	30	
Ground Idle	7	

ICAO Landing Take-Off (LTO) Cycle – Subsonic Aircraft

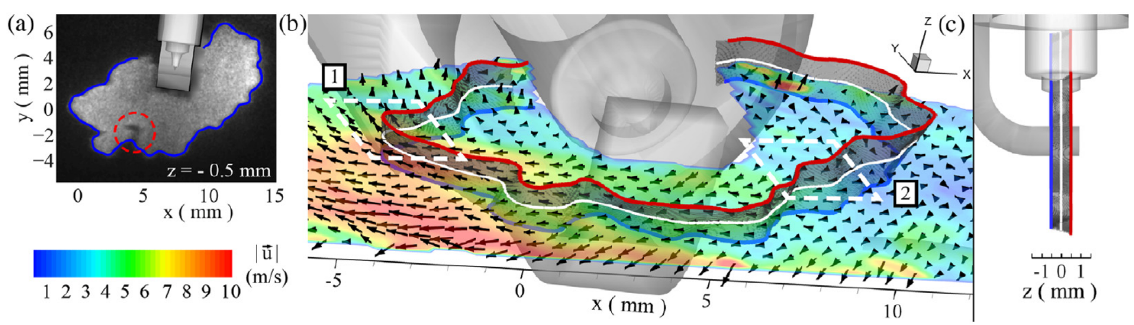
Flame Stabilization

Flame Speed



Courtesy of Wikimedia Commons

- There are two primary ways flames are utilized in practical devices.
  -
  -
- Let's begin by considering the ignition propagation process.
  - Once the fuel and air are mixed in the intake runner, the fresh charge is drawn into the cylinder and ignite in a precisely timed sequence.
  - The flame then propagates from the spark-plug to the cylinder wall, consuming the reactants.



Peterson et al., 2015, Proceedings of the Combustion Institute

Flame Stabilization

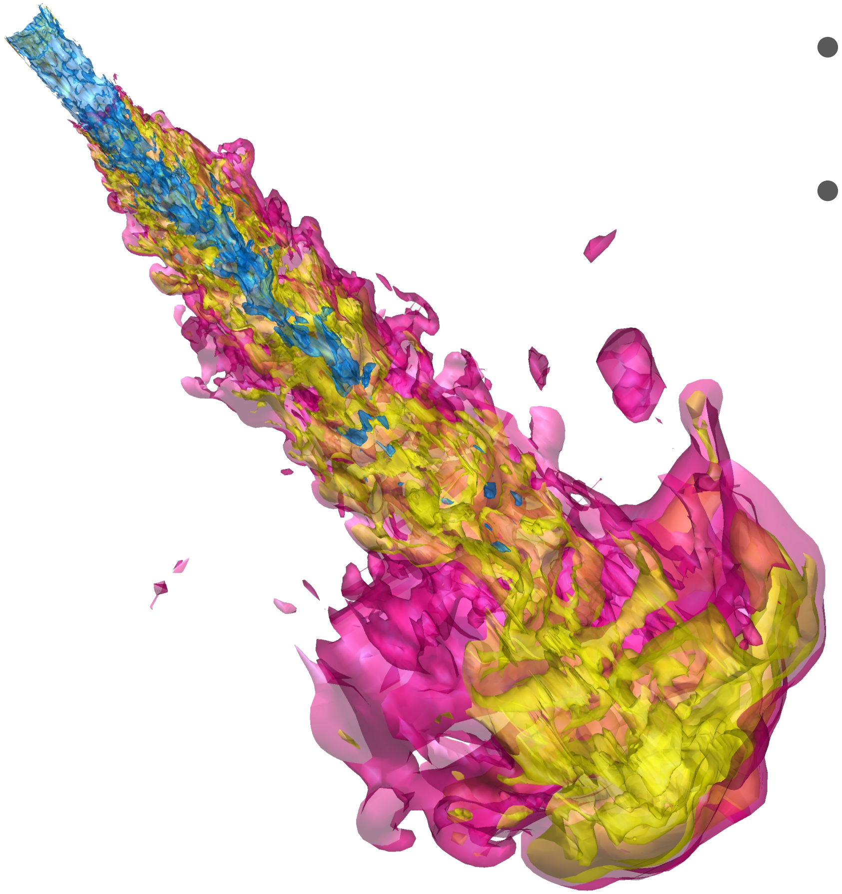
Flame Speed

- We can understand this in a simplified representation, as a flame-surface propagating through a homogeneous mixture of premixed reactants.
  - The flame consumes these reactants at a rate defined as the _______________.
  - The flame speed quantifies the rate at which an un-stretched laminar flame will propagate through a quiescent mixture of unburned reactants.
  - The flame speed is a function of:
  - At the most basic level, we have to design our flow field to achieve adequate mixing performance and a sufficient mean, axial velocity to match the flame speed.

Flame Stabilization

Ignition in ‘steady’ device

Shear Layers

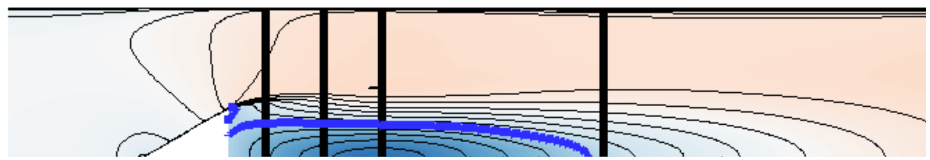


Temperature Isocontours of a Reacting Jet. Courtesy of Joseph Oefelein and Daniel Strong (Sandia National Laboratories)

- Shearing flows provide desirable mixing properties for flame stabilization.
- Often, the reactants are injected into a region adjacent to a recirculation zone that acts as a self-sustaining 'torch' ______________________ _____________________.

Shear Layers

- Shear layers also provide a full range of mean flow velocity for the flame to ‘pick’ where it wants to stabilize.
    -



Bluff-Body Flames

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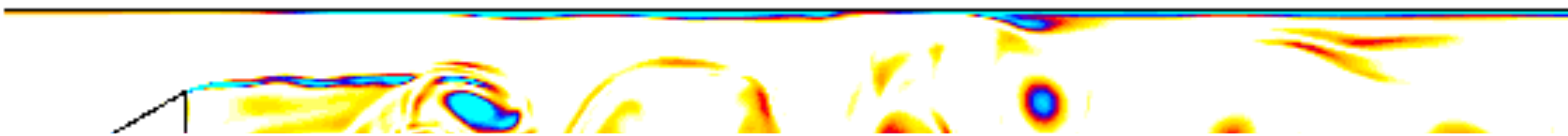
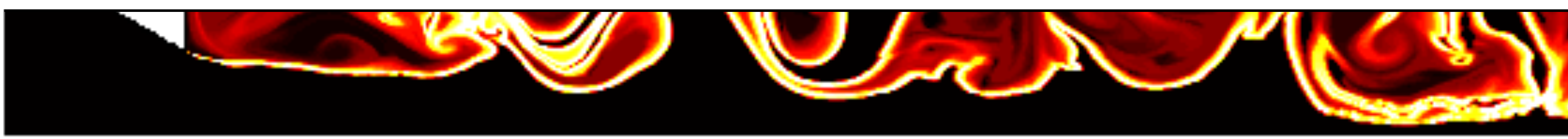
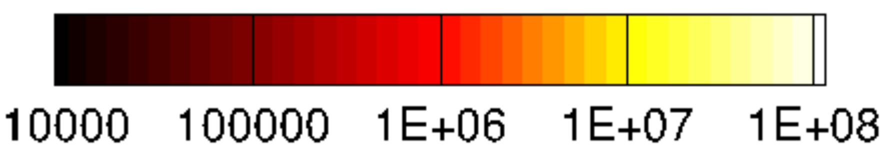
Through-Plane Vorticity (ω_z)



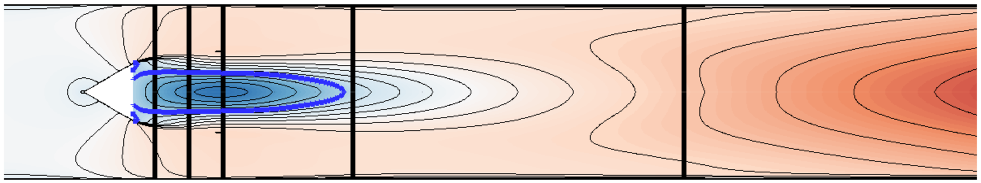




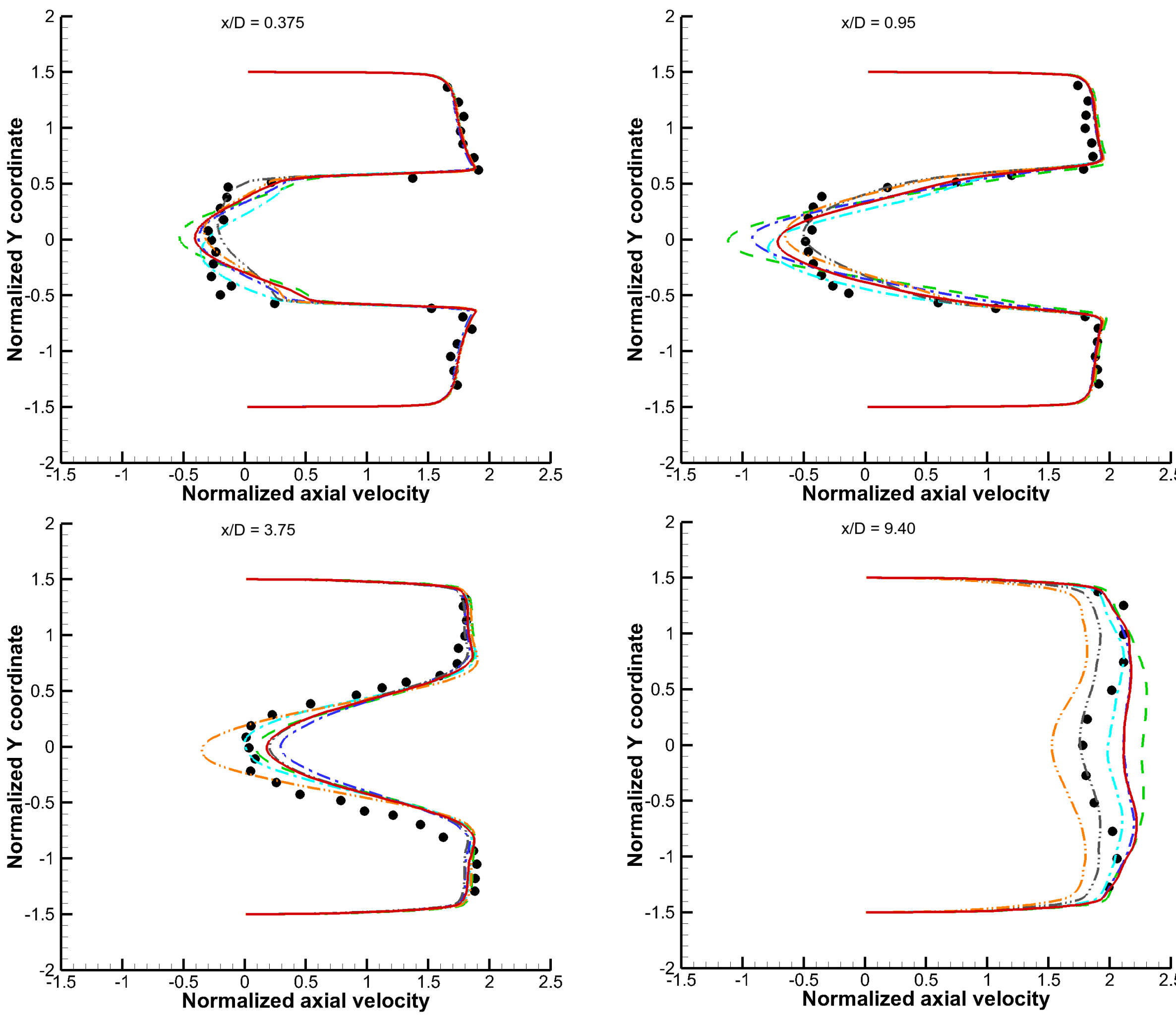
Volumetric Heat Release Rate $[W/m^3]$

Courtesy of Swan Sardeshmukh (Purdue)

Bluff-Body Flames



Contours of Axial Velocity

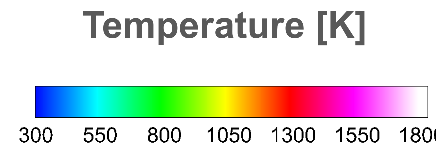


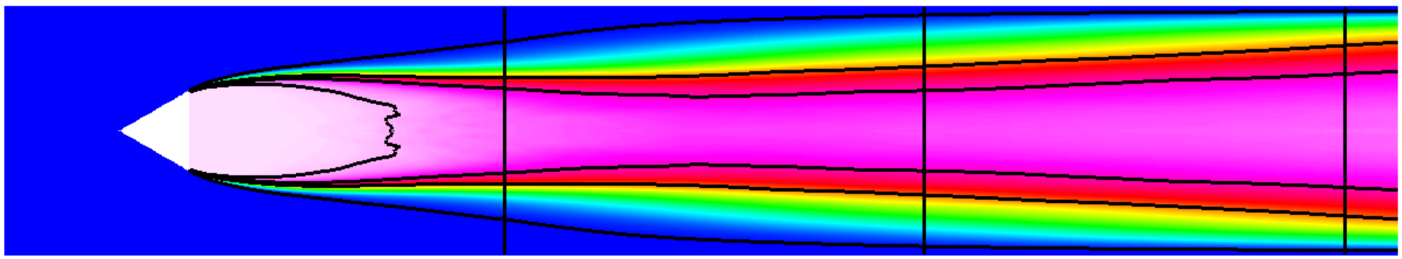
- Positive axial velocity flowing around the bluff body
- Negative axial velocity in the recirculation zone
  - Extending to $x/d \approx 3.75$

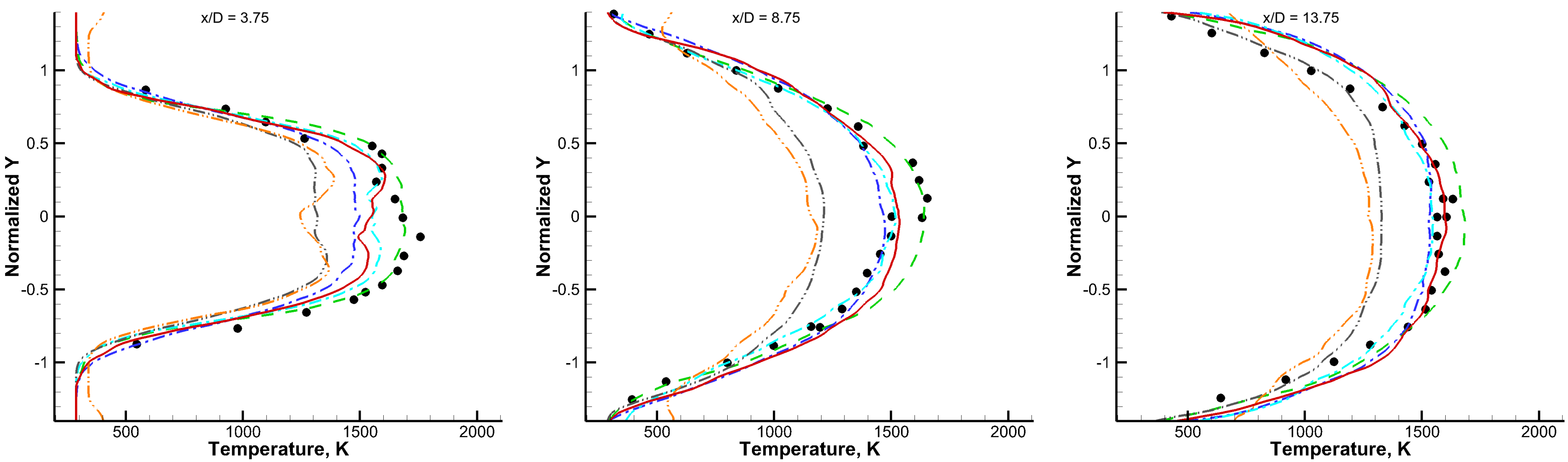
Courtesy of Swan Sardeshmukh (Purdue)

Bluff-Body Flames

- Recirculation zone entrains hot combustion products from the reacting shear layers to provide self-sustaining ignition source.



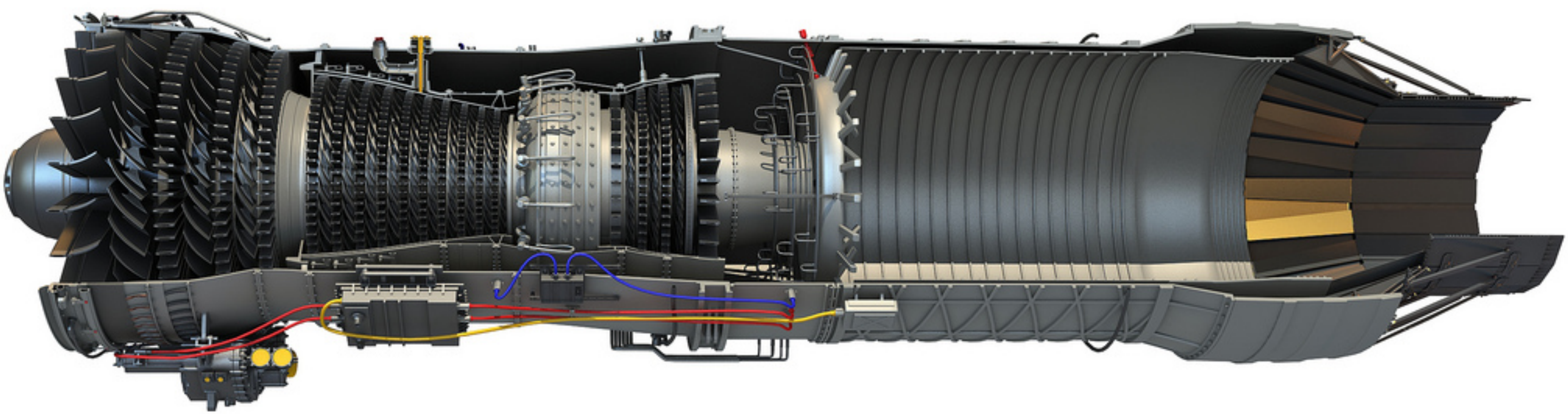




Courtesy of Swan Sardeshmukh (Purdue)

Gas Turbine Combustors

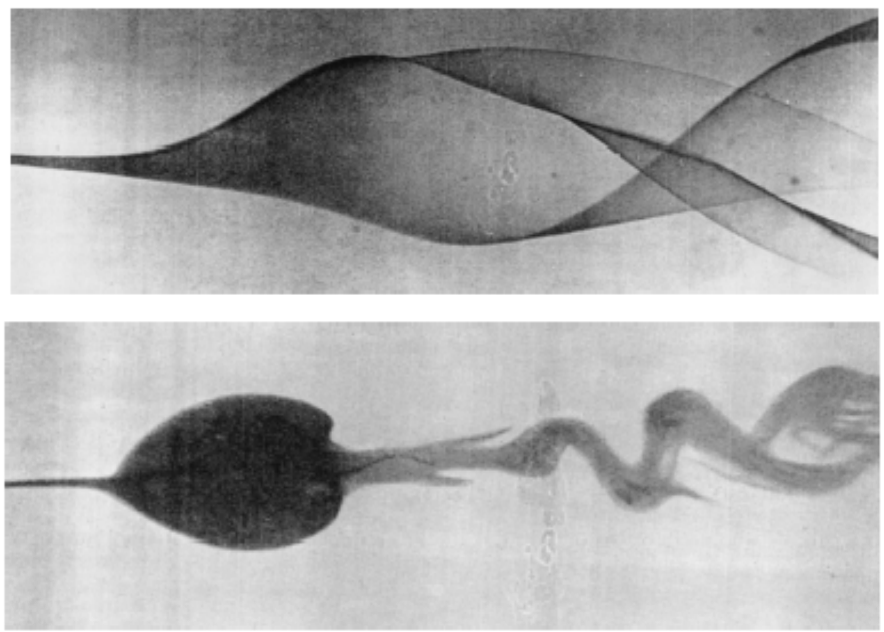
Two Basic Flame Types Found in Engines



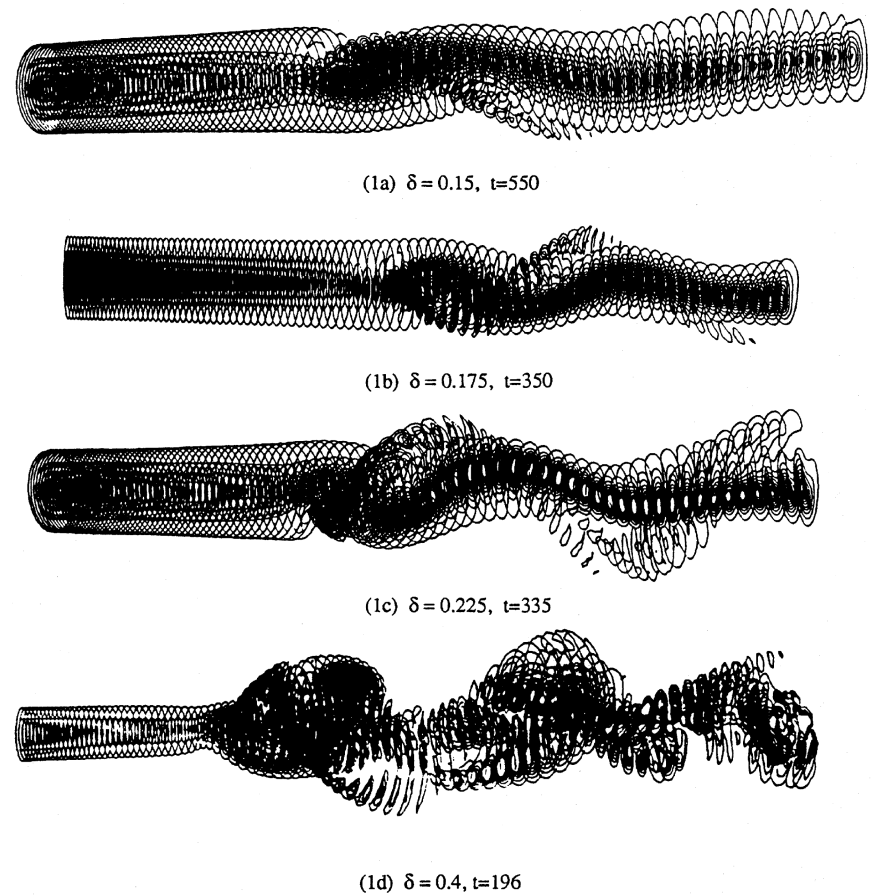
Schematic Diagram of the General Electric J79

Swirling Flows

- Swirling flows have the capability of self-generating these desired flow feature for flame stabilization



Spiral-Type Breakdown (Top) and Bubble-Type Breakdown (Bottom)
Sarpkaya, JFM, 1971

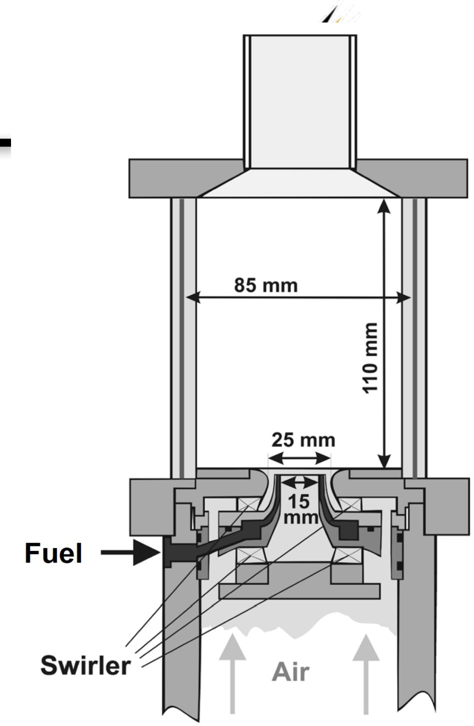


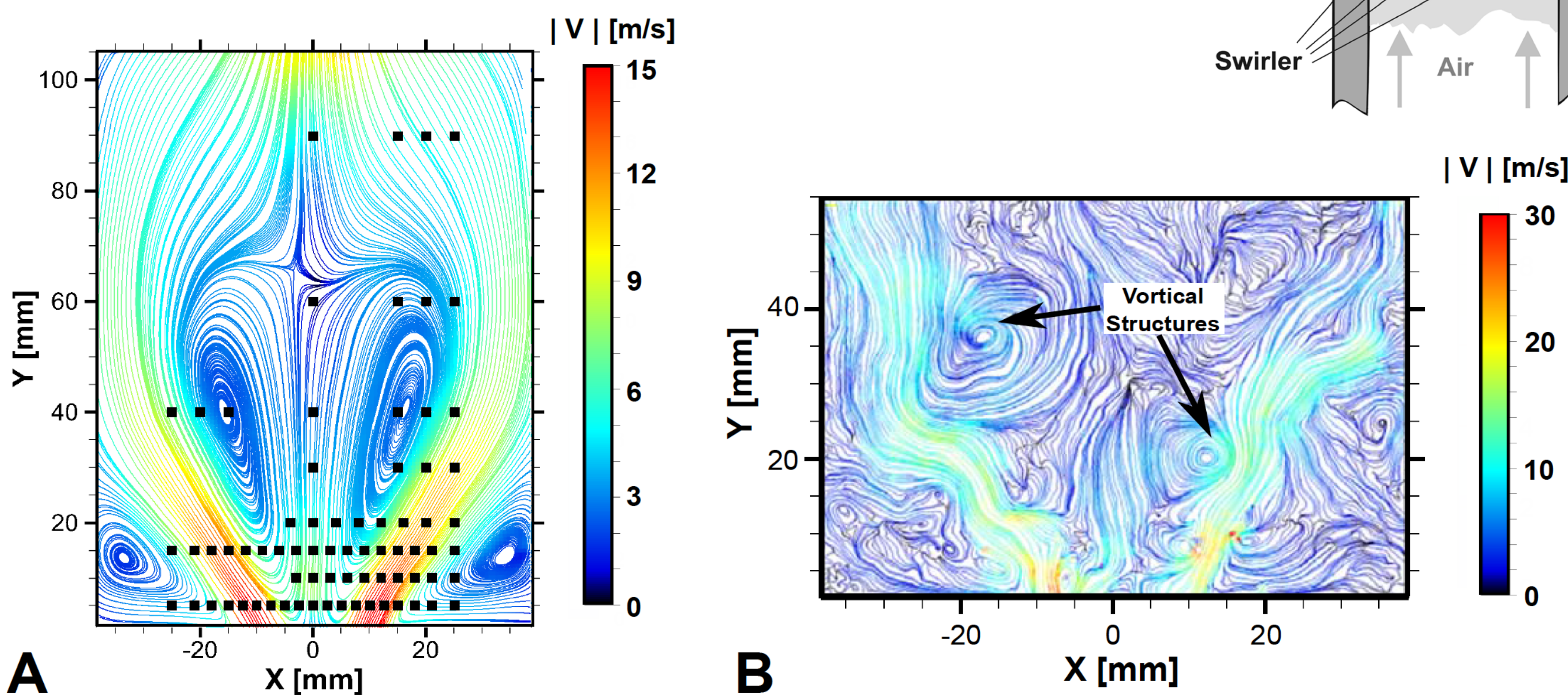
Contours of normalized helicity density with increasing swirl number.
Lucca-Negro and O'Doherty, PECS, 2001

Swirl Combustion

Dual-Swirl Gas Turbine Model Combustor

- Flame stabilization maintained through two mechanisms:
  - Stagnation at the base of the central recirculation zone
  - Shear layer stabilization

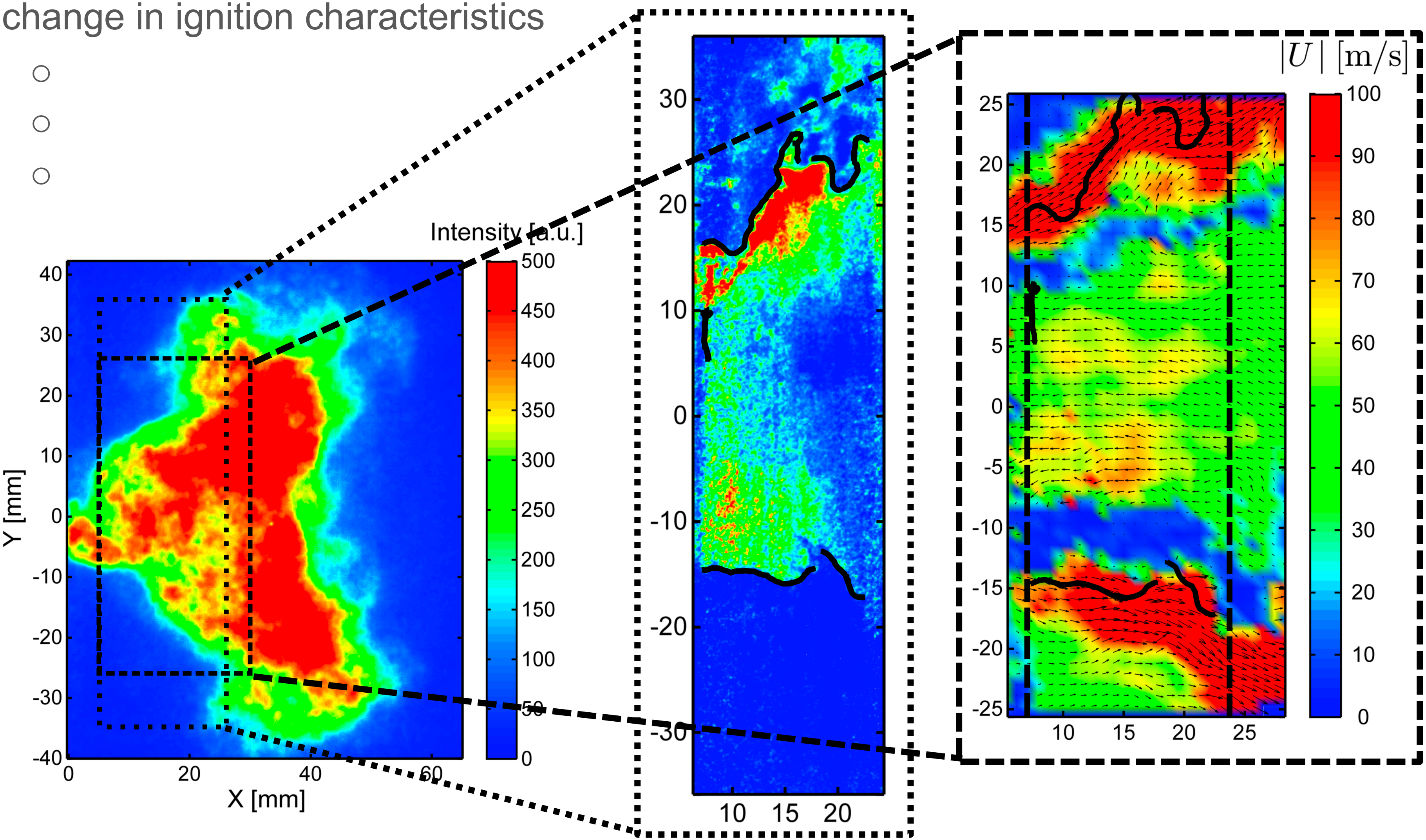




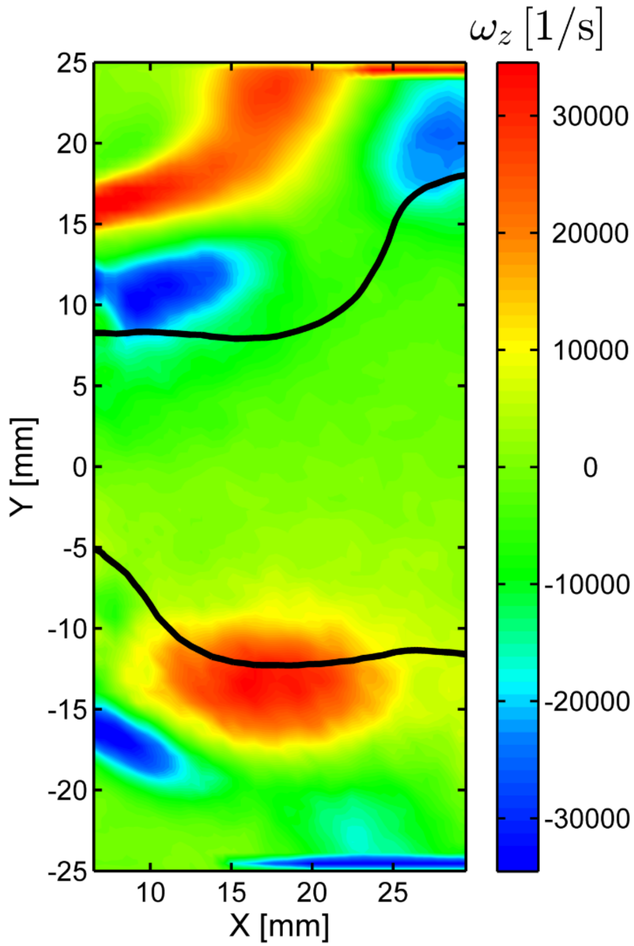
Extracted from Slabaugh, et. al (PIV measurements by Michael Stohr)

Swirl Combustion

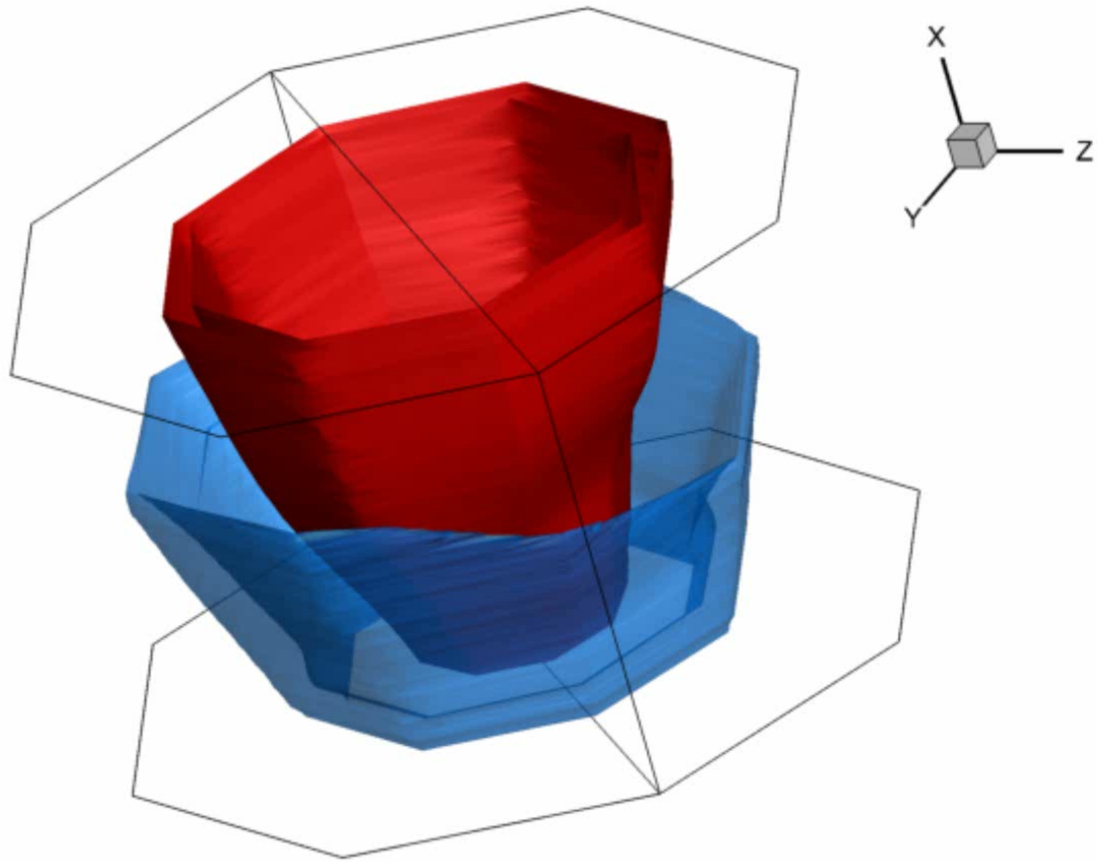
- With increasing power density, there is increased transport, mixing, and a change in ignition characteristics
  -
  -
  -



Swirl Combustion



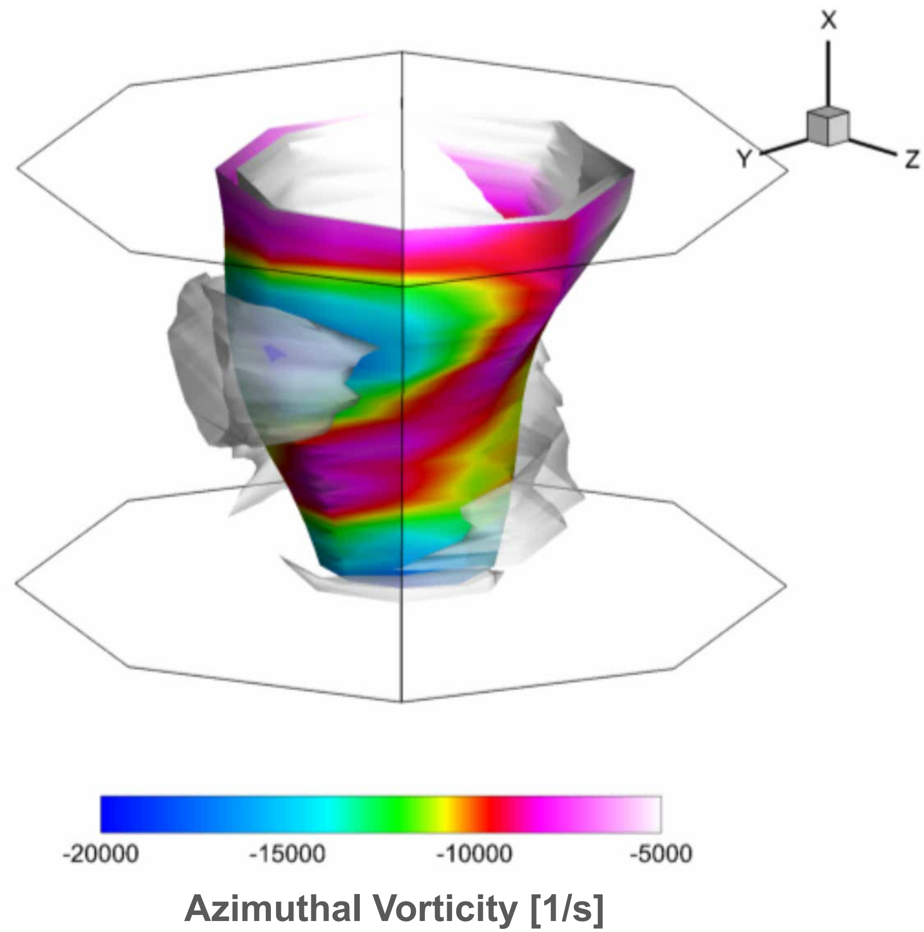
Contours of azimuthal vorticity (ω_z) with stagnation isocontours overlaid (black lines)



Isosurfaces of axial velocity defining the annular reactant jet (blue) and the vortex breakdown bubble (red)

Swirl Combustion

- Rapid mixing and ignition is the result of these well-designed flows.
  - The stagnation layer, specifically the stagnation point at the base of the CRB is the leading edge of the flame.
  - Additional large scale coherent structure further enhance transport of mass, momentum, and heat within the flow.
-
- Other important advantages include:
  -
  -



Summary

- Extremely complex physical processes occurring over a huge range of scales
  - Requires detailed knowledge and engineering intuition to reduce into a manageable problem.

Weight

Emissions

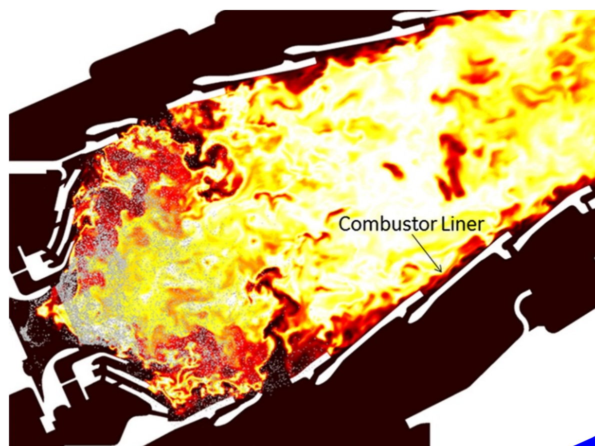
Alternative Fuels

Smoke

Dynamics

Altitude Relight

Reliability



Auto-Ignition

Cost

Fuel Systems

Ground Start

Coking

Exit Profiles

Lean Blow-Out

Pressure Drop

Efficiency