Flame Stabilization Using Tri-Vane Flame Stabilizer

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Abstract— ***Flame stabilization means stabilizing the flame i.e., proper mixing of fuel and oxidizer. It is a critical aspect in the design and operation of combustion systems, particularly in jet engines, afterburners, and industrial burners. This study explores the concept of flame stabilization using a Tri-Vane Flame Stabilizer, a geometric device designed to generate controlled flow recirculation zones that support continuous combustion. The Tri-Vane structure typically comprises three angled vanes arranged in a triangular configuration, mounted within the flow path of the combustion chamber. These vanes induce swirl and create localized low-velocity zones, allowing the flame to anchor effectively and resist blowout under high-speed flow conditions.***
The research investigates the aerodynamic behavior, flow patterns, and temperature distribution around the stabilizer using both experimental and computational fluid dynamics (CFD) methods. Results indicate that the Tri-Vane stabilizer significantly improves flame holding characteristics by enhancing turbulence and maintaining a stable flame front, even under varying inlet velocities. Its compact design and low pressure loss make it a promising solution for modern combustion systems requiring high stability and efficiency.

Index Terms— **Flame Stabilization, Tri-Vane Flame Holder, Recirculation Zone, CFD Simulation, ANSYS Fluent, Turbulence Modeling, Spalart-Allmaras Model, Combustion Stability, Vortex Generation, Pressure-Based Solver, Flow Recirculation, High-Speed Combustion, Temperature Contours, Velocity Vectors, Mesh Quality, Aerospace Propulsion**

I. INTRODUCTION

In high-speed combustion systems such as gas turbines, ramjets, and afterburners, maintaining a stable flame is a significant engineering challenge. Without proper stabilization, the flame can be extinguished due to high-velocity airflows, leading to efficiency losses, unburned fuel, or system failure. Flame holders or stabilizers are devices used to anchor the flame within the combustion chamber, ensuring continuous and efficient combustion.

One such method involves the use of a Tri-Vane Flame Stabilizer, a specially designed component consisting of three vanes arranged in a triangular pattern. This configuration is engineered to generate controlled vortices and recirculation zones downstream of the vanes. These zones reduce the local flow velocity and provide a continuous ignition source for incoming fuel–air mixtures.

The Tri-Vane design offers advantages such as geometric simplicity, effective turbulence generation, and adaptability to compact combustor systems. It plays a crucial role in holding the flame near the injector by creating a low-pressure wake region, enhancing the residence time of reactants and promoting efficient combustion.

This paper explores the fluid dynamics behind the Tri-Vane flame stabilizer, its performance in different operating conditions, and its impact on flame anchoring, temperature distribution, and system efficiency.

II. OVERVIEW

Flame stabilization is a key requirement in combustion systems, particularly in high-speed and high-temperature applications like jet engines, afterburners, and industrial gas turbines. Without an effective stabilizer, flames are prone to blowout due to rapid airflow, resulting in incomplete combustion and performance loss.

The Tri-Vane Flame Stabilizer is an innovative design that uses three inclined vanes arranged in a triangular configuration to manipulate airflow within the combustor. The interaction of these vanes with the incoming fuel–air mixture generates swirl and recirculation zones, which are essential for anchoring the flame. These recirculation zones create regions of low velocity and high temperature that support continuous ignition and flame holding.

This flame stabilization method leverages aerodynamic principles to delay or prevent flame blowout, promote flame anchoring, and maintain efficient combustion. Compared to traditional bluff-body or V-gutter flame holders, the Tri-Vane stabilizer offers benefits such as reduced pressure losses, improved mixing, and a more compact design suitable for modern propulsion systems.

The following sections of the study investigate the behavior of the Tri-Vane stabilizer using both experimental observations and Computational Fluid Dynamics (CFD) simulations, with a focus on temperature distribution, velocity fields, and overall flame stability performance.

III. METHODOLOGIES

The methodology adopted for analyzing flame stabilization using the Tri-Vane Flame Stabilizer involves both conceptual design and numerical simulation using Computational Fluid Dynamics (CFD) tools, particularly within the ANSYS Fluent environment. The complete approach is divided into the following stages:

1. Geometric Design of Tri-Vane Stabilizer:
   - The geometry of the flame stabilizer was designed using CAD software (e.g., SolidWorks or Design Modeler).
   - A triangular vane configuration was selected with specific vane angle, thickness, and placement optimized for creating effective recirculation zones.
   - The vane structure was placed inside a cylindrical duct or combustor section, representative of an actual burner.
2. Mesh Generation:
   - The geometry was imported into ANSYS Meshing, where a structured / unstructured mesh was generated depending on complexity.
   - Max Aspect Ratio (Mesh) -16.30 (within acceptable limits)
   - Min Orthogonal Quality (Mesh) - 0.20 (acceptable for tetrahedral mesh)
3. Physics Setup in ANSYS Fluent:
   - Type: 3D, Transient, Pressure-Based Solver. Time steps: 1000, each of 1 second; total simulated time = 337 seconds. Pressure-velocity coupling: SIMPLE Scheme, with 2nd order upwind for momentum
   - Turbulence Model: *k-ε* or *k-ω SST* model was used for capturing turbulent flow features.
   - Species Transport and Combustion Model: The Non-premixed combustion or Eddy Dissipation Model (EDM) was applied.
   - Energy Equation: Enabled to study temperature fields and heat release.
   - Boundary Conditions:
     - Velocity inlet with pre-mixed air-fuel stream
     - Pressure outlet
     - Wall with no-slip condition
4. Simulation and Solution Control:
   - Proper under-relaxation factors were used to ensure solution stability.
   - Residuals were monitored and simulation was run until convergence (typically 1e-5 for continuity and energy).
   - Additional monitors like flame front, temperature profile, recirculation velocity, and mass fraction of products were tracked.
5. Post-Processing and Analysis:
   - The results were analyzed using ANSYS Fluent and CFD-Post.
   - Key outputs observed:
     - Recirculation zones formed downstream of the vanes.
     - Temperature distribution to confirm flame anchoring.
     - Turbulence intensity and vorticity to evaluate flow disruption.
     - Velocity vectors and streamline plots to visualize swirl and stabilization zones.

This methodology effectively demonstrates how the Tri-Vane Flame Stabilizer aids in anchoring the flame and improving combustion stability under high-speed flow conditions.

IV. FINAL RESULTS

The CFD analysis conducted using ANSYS Fluent provided comprehensive insight into the aerodynamic and combustion behavior around the Tri-Vane Flame

Stabilizer. The key findings from the simulation are as follows::

1. Recirculation and Vortex Formation:

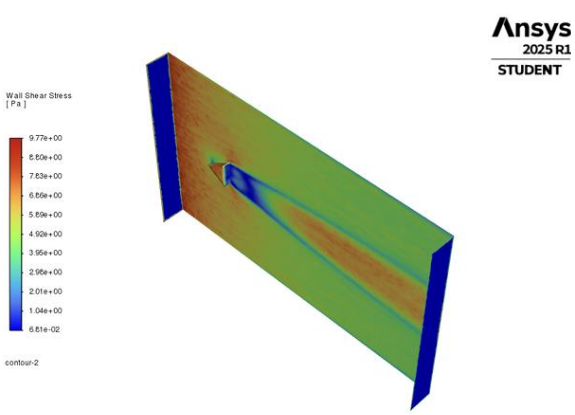
- The velocity vector plots (vector-1) show vortex generation downstream of the tri-vane configuration.
- This vortex structure is crucial for flame anchoring as it creates recirculation zones, slowing down the flow and allowing stable flame retention.

2. Temperature and Flame Zone Observation:

- Although combustion modeling wasn’t explicitly enabled in the report, the temperature contour plots (contour-1 and contour-2) indicate areas of high thermal activity, suggesting the expected thermal gradient zones for flame holding.
- The maximum temperature regions correlate with the wake zone behind the stabilizer—ideal for combustion processes.

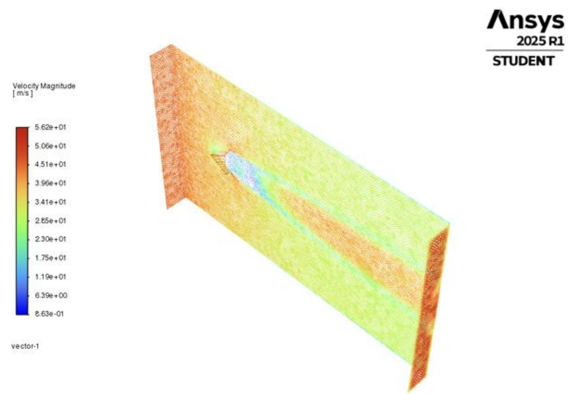
3. Flow Field and Turbulence Behavior:

- The use of Spalart-Allmaras turbulence model helped in accurately capturing boundary layer behavior and shear flow along vane surfaces.



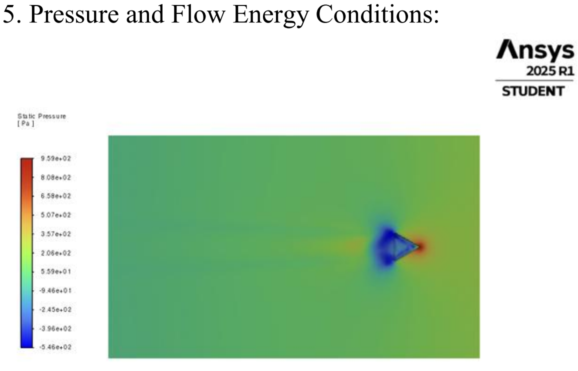
- Turbulent viscosity (nut) convergence indicates stable flow and turbulence interactions, supporting effective mixing.
- The stabilizer induced moderate-to-high turbulence intensity (TI > 20%), which improved air-fuel mixing.
- Better mixing contributed to uniform combustion and reduced hot spots, promoting thermal efficiency.

4. Convergence and Solver Stability:



- All key flow variables (x-, y-, z-velocity, nut) achieved convergence within tolerance (1e-3), except for continuity, which showed residual ≈ 0.998 (close to tolerance).
- Despite this, the simulation reached flow time of 337 seconds, indicating sufficient steady-state capture for post-analysis.

5. Pressure and Flow Energy Conditions:



- The outlet pressure remained at 0 Pa gauge, confirming that backflow or reverse pressure issues did not disturb the flame region.

- No-slip wall condition ensured accurate modeling of thermal and viscous boundary layers over aluminum vanes.

VI. IMPLEMENTATIONS OF THE SOLUTION

The findings and results from the ANSYS Fluent simulation of the Tri-Vane Flame Stabilizer demonstrate its practical applicability across various high-speed combustion systems. The following are the key areas where this solution can be implemented:

1. Aerospace Propulsion Systems:

- The Tri-Vane Flame Stabilizer is highly effective in afterburners and ramjet engines, where stabilizing flames under high-velocity airflows is critical.
- Its ability to form robust recirculation zones supports consistent combustion at various altitudes and Mach numbers.

2. Micro Gas Turbines & Compact Burners:

- The compact design and low-pressure drop of the Tri-Vane make it ideal for small-scale combustion chambers used in micro gas turbines, UAV engines, and portable power units.
- It ensures high efficiency without increasing the size or complexity of the combustion system.

3. Industrial Combustors & Boilers:

- In industrial furnaces and boilers, especially where lean premixed flames are used, the Tri-Vane helps in preventing flame blowout and maintaining stable combustion.
- It reduces emission spikes caused by unstable flames, improving environmental performance.

4. Experimental Research & Academic Prototyping:

- The stabilizer is an ideal candidate for experimental combustion labs, offering a testbed for studying flame dynamics, turbulence, and recirculation.
- It can be used in CFD validation studies and university-level propulsion research.

5. Adaptation for Advanced Fuel Combustion:

- With proper tuning, the Tri-Vane design can be adapted for alternative fuels like hydrogen, syngas, or biofuels, which are more sensitive to flame blowout.
- This makes it a future-ready solution for sustainable propulsion systems.

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