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CFD Investigation of Turbulent Kinetic Energy Distribution in a Scramjet Combustor with PI-Based Fuel Flow Control for Enhanced Combustion Stability

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Abstract: Scramjet (Supersonic Combustion Ramjet) engines are considered one of the most promising propulsion systems for future hypersonic vehicles due to their capability to operate efficiently at Mach numbers greater than 5. However, achieving stable and efficient combustion within the combustor remains a major challenge because of the extremely short residence time of the airflow and complex turbulent flow interactions. Turbulent Kinetic Energy (TKE) plays a crucial role in enhancing fuel-air mixing, flame stabilization, and combustion efficiency in scramjet engines. This research investigates the distribution and behavior of TKE within a hydrogen-fueled scramjet combustor using Computational Fluid Dynamics (CFD) simulations. The flow field, temperature distribution, pressure characteristics, and turbulence parameters are analyzed under hypersonic operating conditions to evaluate their influence on combustion performance.

To improve combustion stability, a closed-loop Proportional-Integral (PI) control system is integrated with the fuel injection mechanism. The controller continuously monitors the combustor temperature and adjusts the hydrogen fuel mass flow rate to maintain a desired temperature setpoint. The CFD simulations are performed using ANSYS Fluent with an appropriate turbulence model, while the PI controller is designed and evaluated through MATLAB/Simulink. The performance of the controller is assessed in terms of temperature regulation, response time, overshoot, and steady-state error. Results demonstrate that regions with higher turbulent kinetic energy promote improved fuel-air mixing and combustion efficiency, while the PI-based fuel flow control effectively reduces temperature fluctuations and enhances overall combustion stability. The proposed methodology provides a combined turbulence-analysis and control-system framework for optimizing scramjet engine performance and offers valuable insights for the development of advanced hypersonic propulsion systems

Index Terms - Scramjet Engine, Hypersonic Propulsion, Turbulent Kinetic Energy (TKE), Computational Fluid Dynamics (CFD), Hydrogen Combustion, Fuel-Air Mixing, Combustion Stability, PI Controller, Fuel Flow Control, Temperature Regulation, Supersonic Combustion, ANSYS Fluent, MATLAB/Simulink, Turbulence Modeling, Hypersonic Flight.

INTRODUCTION

Scramjet (Supersonic Combustion Ramjet) engines are advanced air-breathing propulsion systems designed for hypersonic flight at speeds greater than Mach 5. Unlike conventional jet engines, scramjets maintain supersonic airflow throughout the combustion chamber, enabling efficient operation at extremely high velocities. Due to their potential applications in hypersonic missiles, reusable launch vehicles, and space transportation systems, scramjet engines have become an important area of aerospace research.

One of the major challenges in scramjet operation is achieving stable and efficient combustion within a very short residence time. Effective fuel-air mixing is essential for complete combustion and thrust generation. Turbulence significantly influences the mixing process, and Turbulent Kinetic Energy (TKE) is a key parameter used to evaluate turbulence intensity within the combustor. Higher TKE generally enhances fuel-air mixing and combustion efficiency, while excessive turbulence may lead to flow instability and pressure fluctuations.

Computational Fluid Dynamics (CFD) has become a powerful tool for analyzing flow characteristics, temperature distribution, pressure variation, and turbulence behavior in scramjet engines. Through CFD simulations, researchers can study the distribution of TKE and its effect on combustion performance under different operating conditions.

In addition to flow analysis, maintaining stable combustion is critical for reliable engine operation. A Proportional-Integral (PI) controller can be used to regulate fuel injection based on combustor temperature feedback. The controller continuously adjusts the fuel flow rate to maintain a desired temperature and improve combustion stability. Compared with open-loop systems, PI-based control offers better response and reduced temperature fluctuations.

This research focuses on the CFD investigation of turbulent kinetic energy distribution in a hydrogen-fueled scramjet combustor and the implementation of a PI-based fuel flow control system. The study aims to analyze the relationship between turbulence and combustion performance while evaluating the effectiveness of the PI controller in maintaining stable combustor temperatures and enhancing overall engine efficiency.

OVERVIEW.

Scramjet engines are air-breathing propulsion systems capable of operating at hypersonic speeds above Mach 5. Their performance depends heavily on efficient fuel-air mixing and stable combustion within the combustor. Turbulence plays a crucial role in enhancing the mixing process, and Turbulent Kinetic Energy (TKE) is an important parameter used to quantify turbulence intensity and evaluate combustion characteristics.

This research investigates the distribution of TKE within a hydrogen-fueled scramjet combustor using Computational Fluid Dynamics (CFD). The study analyzes velocity, pressure, temperature, and turbulence fields to understand the effect of TKE on fuel-air mixing and combustion stability. Higher turbulent kinetic energy is expected to improve mixing efficiency and combustion performance by increasing interaction between fuel and incoming air.

To further enhance engine stability, a Proportional-Integral (PI) controller is integrated into the fuel injection system. The controller uses combustor temperature as a feedback signal and continuously adjusts the fuel mass flow rate to maintain the desired operating temperature. This closed-loop control approach helps reduce temperature fluctuations, improve combustion stability, and optimize engine performance.

METHODOLOGIES

The present study investigates the distribution of Turbulent Kinetic Energy (TKE) in a hydrogen-fueled scramjet combustor and evaluates the effectiveness of a PI-based fuel flow control system for improving combustion stability. The methodology consists of the following steps:

Step 1: Geometry Development

A three-dimensional scramjet combustor model is developed using SolidWorks or ANSYS Space Claim. The model includes the inlet section, isolator, fuel injector, combustion chamber, and nozzle. The geometry dimensions are selected based on standard scramjet configurations available in the literature.

Step 2: Mesh Generation

The geometry is imported into ANSYS Meshing for grid generation. A fine mesh is created near the fuel injector, wall boundaries, and combustion region to accurately capture turbulence and flow gradients. Grid independence analysis is performed to ensure that the results are independent of mesh size.

Step 3: CFD Model Setup

The meshed model is imported into ANSYS Fluent. The pressure-based solver is selected along with the energy equation and species transport model. Hydrogen is used as the fuel, while air acts as the oxidizer. The k–ω SST turbulence model is employed to predict turbulent flow behavior and calculate turbulent kinetic energy.

Step 4: Boundary Conditions

The following boundary conditions are applied:

- Inlet Velocity: Corresponding to Mach 5–7
- Inlet Temperature: 1200–1500 K
- Inlet Pressure: 1–3 MPa
- Fuel Type: Hydrogen
- Fuel Injection: Through transverse injector
- Outlet Condition: Pressure outlet
- Wall Condition: No-slip adiabatic wall

Step 5: CFD Simulation

The simulation is initialized and iterated until convergence is achieved. Residual values below 10^{-6} are considered acceptable. The flow field is analyzed under different fuel flow rates and operating conditions.

Step 6: Turbulent Kinetic Energy Analysis

The distribution of turbulent kinetic energy inside the combustor is examined using contour plots. Key parameters analyzed include:

- Maximum TKE
- Average TKE
- Turbulence intensity
- Fuel-air mixing region
- Shock-wave interaction zones

The relationship between TKE and combustion performance is investigated.

Step 7: Temperature and Combustion Analysis

Temperature contours, pressure distribution, velocity fields, and species concentration plots are generated. Combustion efficiency and flame stabilization characteristics are evaluated to determine the influence of turbulence on engine performance.

Step 8: PI Controller Design

A Proportional-Integral (PI) controller is developed in MATLAB/Simulink. The controller receives combustor exit temperature as the feedback signal and compares it with a predefined temperature setpoint.

The PI control law is expressed as:

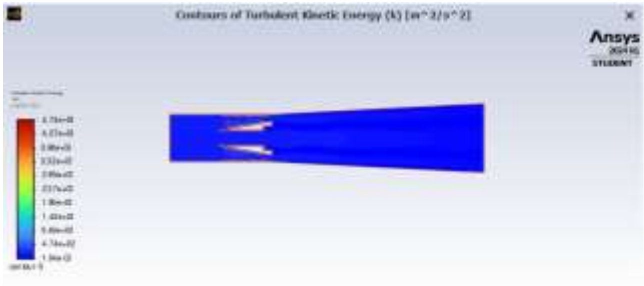
$$\mathbf{u(t)= k_c e(t) + k_2 \frac{1}{\tau I} \int_0^t e(\tau) d\tau}$$

where:

- u(t) = Control signal
- e(t) = Temperature error
- K_c = Proportional gain
- τ_I= Integral gain

FINAL RESULTS

The CFD simulation successfully predicted the flow behavior, temperature distribution, pressure variation, and turbulent kinetic energy (TKE) characteristics inside the scramjet combustor under hypersonic operating conditions. The results showed that the highest TKE values occurred near the fuel injection region and in areas of strong shear layer interaction, indicating enhanced turbulence and fuel-air mixing. Increased turbulent kinetic energy promoted rapid mixing of hydrogen fuel with incoming air, resulting in improved combustion efficiency and more uniform temperature distribution throughout the combustor.



The temperature contours revealed stable combustion with peak temperatures concentrated within the primary combustion zone. Pressure distribution remained within the expected operating range, while velocity contours confirmed the maintenance of supersonic flow throughout the combustor. The analysis demonstrated that regions with higher TKE contributed significantly to flame stabilization and combustion enhancement.

The PI controller effectively regulated the hydrogen fuel mass flow rate based on combustor temperature feedback. Compared to the uncontrolled system, the controlled system exhibited reduced temperature fluctuations and improved thermal stability. The controller quickly responded to temperature deviations by adjusting fuel injection rates, thereby maintaining the desired temperature setpoint with minimal steady-state error.

Performance evaluation showed that the PI-controlled combustor achieved faster stabilization, lower overshoot, and improved combustion consistency. The controlled system also demonstrated better fuel utilization and reduced risk of combustion instability under varying operating conditions.

IMPLEMENTATIONS OF THE SOLUTION

The implementation of this research was carried out through the integration of Computational Fluid Dynamics (CFD) analysis and a PI-based fuel flow control system. Initially, a three-dimensional scramjet combustor geometry was developed using CAD software and imported into ANSYS Fluent for numerical simulation. The computational domain was discretized using a refined mesh to accurately capture flow behavior, turbulence characteristics, and combustion phenomena.

Hydrogen fuel was injected into the supersonic airflow, and simulations were performed under hypersonic operating conditions. The k–ω SST turbulence model was employed to analyze the distribution of Turbulent Kinetic Energy (TKE), velocity, pressure, and temperature within the combustor. The simulation results were used to identify regions of intense turbulence and evaluate their influence on fuel-air mixing and combustion performance.

To improve combustion stability, a Proportional-Integral (PI) controller was designed in MATLAB/Simulink. The combustor exit temperature was selected as the feedback parameter, while the hydrogen fuel mass flow rate served as the control variable. The controller continuously compared the measured temperature with the desired setpoint and adjusted the fuel injection rate accordingly.

The CFD model and control system were integrated through a feedback mechanism, enabling real-time regulation of combustor temperature. When temperature deviations occurred, the PI controller automatically modified the fuel flow rate to restore the desired operating condition. The performance of the controller was evaluated using response characteristics such as settling time, overshoot, and steady-state error.

The implementation demonstrated that combining turbulence analysis with a closed-loop PI control strategy effectively enhanced fuel-air mixing, maintained stable combustion temperatures, and improved the overall performance of the scramjet engine. This approach can be further extended to advanced intelligent control systems for future hypersonic propulsion applications.

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