© September 2026 | IJIRT | Volume 13 Issue 4 | ISSN: 2349-6002

AI based Scramjet Combustor With PI/PID based control system

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***Abstract*—Scramjet engines are advanced air-breathing propulsion systems designed for hypersonic flight above Mach 5. Stable and efficient combustion is challenging because the airflow remains supersonic and the available residence time is extremely short.**

The supplied analyzes velocity, pressure, temperature and turbulence fields using CFD. The PI controller monitors combustor temperature and adjusts hydrogen fuel mass flow to maintain a desired setpoint. Reported results indicate that higher-TKE regions promote fuel-air mixing and combustion efficiency, while PI-based fuel-flow control reduces temperature fluctuations and improves stability.

The supplied study investigates turbulent kinetic energy (TKE) in a hydrogen-fueled scramjet combustor using Computational Fluid Dynamics. Velocity, pressure, temperature and turbulence fields are analyzed to understand fuel-air mixing and combustion stability.

A closed-loop Proportional-Integral controller regulates hydrogen fuel mass flow using combustor temperature feedback. The reported results indicate that higher-TKE regions promote mixing and combustion efficiency, while PI control reduces temperature fluctuations.

Keywords and Study Scope-

Keywords: Scramjet Engine; Hypersonic Propulsion; Turbulent Kinetic Energy; Computational Fluid Dynamics; Hydrogen Combustion; Fuel-Air Mixing; Combustion Stability; PI Controller; Fuel Flow Control; Temperature Regulation; Supersonic Combustion; ANSYS Fluent; MATLAB/Simulink; Turbulence Modeling; Hypersonic Flight.

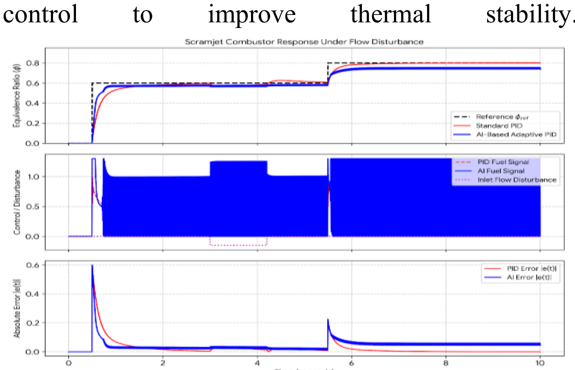
This report expands the supplied four-page research material into a structured 50-page academic document without introducing unsupported numerical simulation results.

***Index Terms*—Introduction, Scramjet Engine Fundamentals, Hypersonic Combustion Challenges, Turbulent Kinetic Energy, CFD in Scramjet Research, PI-Based Fuel Flow Control, Study Motivation, Research Objectives, Scope of the WorkGeometry Development, Mesh Generation, CFD Model Setup, Boundary Conditions, Simulation Procedure, TKE Analysis Method, Temperature and Combustion Analysis, PI Controller Design, Closed-Loop Control, CFD-Control Integration, Results, TKE Results, Temperature Results, Pressure and Velocity Results, Control Performance, Fuel-Air Mixing, Combustion Stability, Implementation, Discussion, Advantages, Limitations, Future Scope, Engineering Significance, Methodology Summary, Results Summary, Integrated Interpretation, Practical Considerations, Academic Contribution, Conclusions, References, Appendix and Source Notes**

I. INTRODUCTION

Scramjet, or Supersonic Combustion Ramjet, technology is an important area of aerospace propulsion research for hypersonic flight. The supplied study describes scramjets as air-breathing propulsion systems designed for speeds greater than Mach 5.

Unlike conventional jet engines, scramjets maintain supersonic airflow through the combustion chamber. This enables very-high-speed operation but makes fuel injection, mixing and flame stabilization difficult. The research focuses on TKE distribution in a hydrogen-fueled combustor and the use of PI-based fuel-flow control to improve thermal stability.



II. SCRAMJET ENGINE FUNDAMENTALS

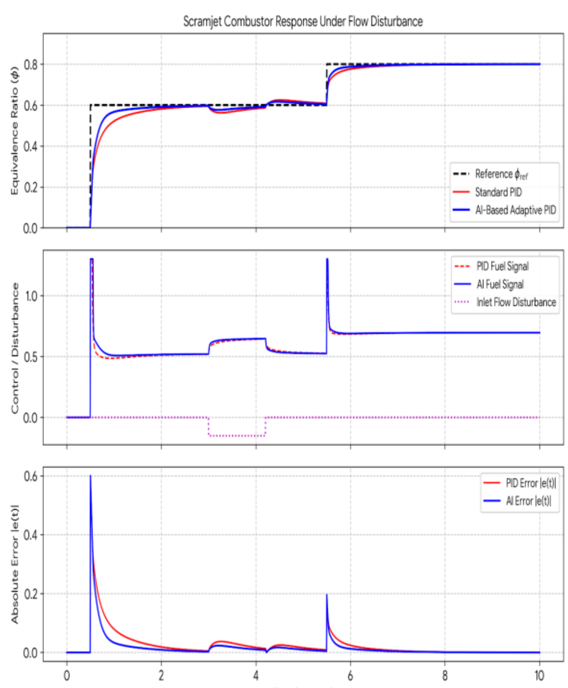
A scramjet uses atmospheric oxygen rather than carrying oxidizer. Its principal computational regions in the supplied methodology are the inlet section, isolator, fuel injector, combustion chamber and nozzle.

A scramjet processes atmospheric air through an inlet and burns injected fuel while the internal flow remains supersonic.

- Inlet: captures and compresses incoming high-speed air.
- Isolator: provides a flow region between inlet and combustor.
- Fuel injector: introduces hydrogen into the supersonic airflow.
- Combustion chamber: supports rapid mixing and heat release.
- Nozzle: expands hot gases to generate useful thrust.

The inlet processes incoming hypersonic air. The isolator provides a flow region between inlet and combustor. Hydrogen is introduced through a transverse injector, mixing occurs in the combustor, and the nozzle provides the downstream flow path.

The supplied methodology explicitly identifies the inlet, isolator, fuel injector, combustion chamber and nozzle as the main geometry components.



III. HYPERSONIC COMBUSTION CHALLENGES

The source emphasizes the short residence time of airflow as a central difficulty. Fuel must mix with air and react rapidly while the flow remains supersonic. Turbulence therefore has a strong influence on the quality and rate of fuel-air interaction.

Stable combustion is also necessary for reliable operation. The supplied study links excessive turbulence with possible flow instability and pressure fluctuations, while identifying appropriately high TKE as beneficial for mixing.

1. Develop a hydrogen-fueled scramjet combustor model.
2. Generate a refined computational mesh.
3. Use ANSYS Fluent to calculate velocity, pressure, temperature, species and turbulence fields.
4. Use the k–ω SST model to predict turbulence and TKE.
5. Identify high-TKE regions and relate them to fuel-air mixing.
6. Evaluate combustion and temperature characteristics.
7. Develop a PI controller in MATLAB/Simulink.
8. Adjust hydrogen fuel mass flow using closed-loop control.
9. Evaluate stabilization, overshoot and steady-state error.

IV. TURBULENT KINETIC ENERGY

Turbulent Kinetic Energy is a key parameter used to evaluate turbulence intensity within the combustor. The study examines maximum TKE, average TKE, turbulence intensity, fuel-air mixing regions and shock-wave interaction zones.

Higher TKE generally enhances fuel-air mixing because it increases interaction between hydrogen and incoming air. The source also cautions that excessive turbulence may contribute to instability and pressure fluctuations.

Turbulent kinetic energy is a central variable because it represents the intensity of turbulent motion. In the combustor, turbulence affects the interaction between injected hydrogen and incoming air.

The supplied paper states that higher TKE generally promotes fuel-air mixing and combustion efficiency, while excessive turbulence may lead to instability and pressure fluctuations.

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

V.CFD IN SCRAMJET RESEARCH

Computational Fluid Dynamics is used in the supplied study to analyze flow characteristics, temperature distribution, pressure variation and turbulence behavior. CFD makes it possible to examine the spatial distribution of TKE and its relationship with combustion performance.

The methodology uses ANSYS Fluent with the energy equation, species transport and the k–ω SST turbulence model.

The meshed model is imported into ANSYS Fluent. The supplied study uses a pressure-based solver, energy equation and species transport model. Hydrogen is the fuel and air is the oxidizer.

- Solver — Pressure-based ANSYS Fluent
- Energy — Energy equation enabled
- Species — Species transport
- Fuel — Hydrogen
- Oxidizer — Air
- Turbulence — k–ω SST

The k–ω SST model is used to predict turbulent flow behavior and calculate TKE.

VI. PI-BASED FUEL FLOW CONTROL

The supplied study integrates a Proportional-Integral controller into the fuel injection system. Combustor exit temperature is used as feedback and hydrogen fuel mass flow is the control variable.

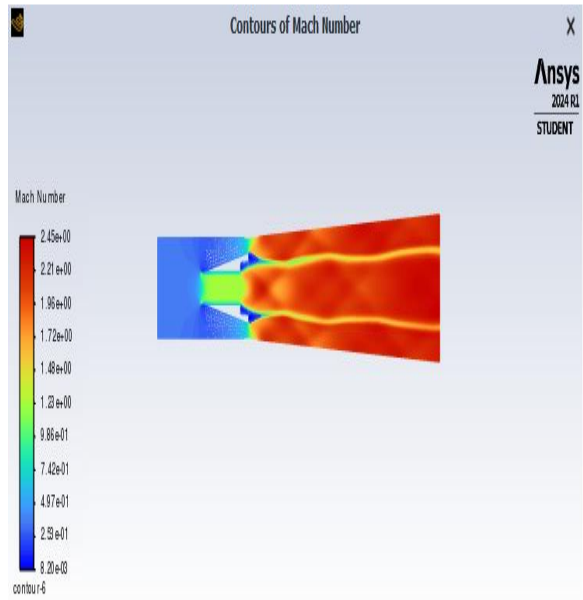
The controller compares measured temperature with a predefined setpoint and adjusts fuel flow. Performance is evaluated using temperature regulation, response time, overshoot, settling behavior and steady-state error.

A Proportional-Integral controller is developed in MATLAB/Simulink. It receives combustor exit temperature as feedback and compares it with a predefined temperature setpoint.

The proportional term responds to present error, while the integral term accounts for accumulated error. The control signal changes hydrogen fuel mass flow.

- u(t): control signal
- e(t): temperature error
- Kc: proportional gain
- Integral term: accumulated error contribution

Numerical controller gains are not supplied in the source material and are therefore not invented.



VII. STUDY MOTIVATION

The motivation comes from the need to combine understanding of turbulent mixing with active combustion stabilization. CFD alone can describe the flow field, but the supplied study adds feedback control to regulate temperature.

The combined approach is intended to enhance fuel-air mixing, maintain stable combustion temperatures and improve overall scramjet performance.

VIII. RESEARCH OBJECTIVES:

The supplied methodology supports the following objectives:

• Develop a three-dimensional hydrogen-fueled scramjet model.

• Generate a refined mesh.

• Predict flow, temperature, pressure, species and turbulence.
• Study TKE distribution and mixing regions.
• Analyze combustion characteristics.
• Design a PI controller in MATLAB/Simulink.
• Regulate hydrogen fuel mass flow using temperature feedback.
• Evaluate stabilization, overshoot and steady-state error.

IX. SCOPE OF THE WORK

The scope covers geometry development, mesh generation, CFD model setup, boundary conditions, simulation, TKE analysis, temperature and combustion analysis, PI controller design, and integration of CFD findings with closed-loop fuel-flow control.
The supplied document does not provide complete geometry dimensions, mesh statistics or numerical PI gains. This expanded report therefore preserves the source-supported level of detail rather than inventing missing values.

X. GEOMETRY DEVELOPMENT

The methodology states that a three-dimensional scramjet combustor model is developed using SolidWorks or ANSYS Space Claim. The model includes inlet, isolator, fuel injector, combustion chamber and nozzle.

Geometry dimensions are selected based on standard scramjet configurations available in the literature. The supplied ANSYS image is included in the report as a visual representation of the computational geometry.
The supplied geometry shows a long flow passage with an upstream region, an internal injector-related feature and a downstream divergent region.

- Upstream region: inlet-side flow path.
- Central feature: fuel-injection and local flow interaction region.
- Downstream passage: mixing and combustion flow region.
- Divergent end: nozzle-side flow path.

The computational domain must resolve the supersonic flow, shock interactions, fuel injection and turbulent mixing.

XI. 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 capture turbulence and flow gradients.

Grid-independence analysis is performed to ensure that important results are not dependent on mesh size. The supplied source does not give exact cell count or element-quality statistics.
The geometry is imported into ANSYS Meshing. The supplied methodology calls for fine mesh near the fuel injector, wall boundaries and combustion region.

- Refine the injector region.
- Refine wall-adjacent regions.
- Refine combustion and shear-layer regions.
- Check mesh quality.
- Perform grid-independence analysis.

Grid-independence analysis helps ensure that important CFD results are not strongly dependent on mesh size.

XII. 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 and air as the oxidizer.
The k–ω SST turbulence model is employed to predict turbulent flow behavior and calculate turbulent kinetic energy.
The meshed model is imported into ANSYS Fluent. The supplied study uses a pressure-based solver, energy equation and species transport model. Hydrogen is the fuel and air is the oxidizer.

- Solver — Pressure-based ANSYS Fluent
- Energy — Energy equation enabled
- Species — Species transport
- Fuel — Hydrogen
- Oxidizer — Air
- Turbulence — k–ω SST

The k–ω SST model is used to predict turbulent flow behavior and calculate TKE.

XIII. BOUNDARY CONDITIONS

The supplied boundary conditions are:
• Inlet velocity corresponding to Mach 5–7.

• Inlet temperature of 1200–1500 K.
• Inlet pressure of 1–3 MPa.
• Hydrogen fuel.
• Transverse fuel injector.
• Pressure outlet.
• No-slip adiabatic wall.

These are ranges stated by the source; a single operating point is not assumed.

- Inlet velocity: Mach 5–7
- Inlet temperature: 1200–1500 K
- Inlet pressure: 1–3 MPa
- Fuel: Hydrogen
- Fuel injection: Transverse injector
- Outlet: Pressure outlet
- Wall: No-slip, adiabatic

These are the operating ranges stated in the supplied material. A unique operating point is not invented here.

XIV. SIMULATION PROCEDURE

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

Post processing includes velocity, pressure, temperature, species concentration and TKE distributions.

XV. TKE ANALYSIS METHOD

The TKE analysis uses contour plots to examine the distribution of turbulent kinetic energy inside the combustor. Key parameters are maximum TKE, average TKE, turbulence intensity, fuel-air mixing regions and shock-wave interaction zones.

The relationship between TKE and combustion performance is then investigated.

XVI. 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.

The reported results describe stable combustion with peak temperatures concentrated in the primary combustion zone.
Temperature contours, pressure distribution, velocity fields and species concentration plots are generated to evaluate combustion behavior.

The reported results show stable combustion with peak temperatures concentrated in the primary combustion zone. Increased TKE supports rapid fuel-air mixing and contributes to a more uniform temperature distribution.

- Temperature contours identify thermal patterns.
- Peak temperature indicates the primary combustion zone.
- Temperature uniformity helps assess stability.
- Exit temperature is used as the PI feedback signal.

XVII. PI CONTROLLER DESIGN:

A PI controller is developed in MATLAB/Simulink. It receives combustor exit temperature as feedback and compares it with a predefined temperature setpoint.

The supplied notation defines u(t) as the control signal, e(t) as temperature error, Kc as proportional gain and I as integral gain. The source does not provide numerical controller gain values.

A Proportional-Integral controller is developed in MATLAB/Simulink. It receives combustor exit temperature as feedback and compares it with a predefined temperature setpoint.
The proportional term responds to present error, while the integral term accounts for accumulated error. The control signal changes hydrogen fuel mass flow.

- u(t): control signal
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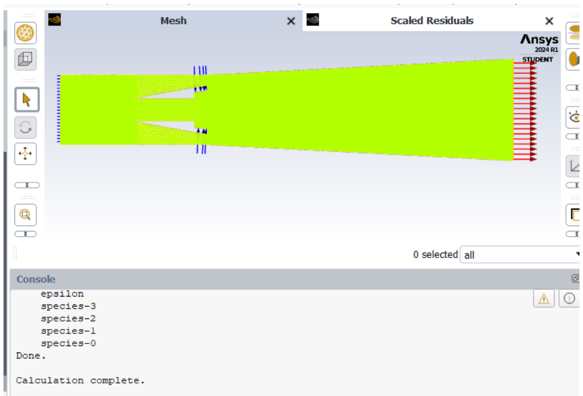
- Kc: proportional gain
- Integral term: accumulated error contribution
  Numerical controller gains are not supplied in the source material and are therefore not invented.



XVIII. CLOSED-LOOP CONTROL

The closed-loop system continuously monitors combustor temperature. When the measured temperature differs from the desired setpoint, the controller changes hydrogen fuel mass flow.

This feedback mechanism is intended to reduce temperature fluctuations, improve combustion stability and maintain the desired operating condition. The closed-loop strategy is intended to reduce temperature fluctuations, improve thermal stability and maintain the desired operating condition

XIX. CFD-CONTROL INTEGRATION

The CFD model and control system are integrated through a feedback mechanism. The CFD model provides the physical understanding of flow and thermal behavior, while the PI controller provides a means of regulating fuel flow based on temperature.

The implementation evaluates settling time, overshoot and steady-state error.

XX. RESULTS

The supplied final results state that CFD successfully predicted flow behavior, temperature distribution, pressure variation and TKE characteristics under hypersonic conditions.

The highest TKE values occurred near the fuel-injection region and areas of strong shear-layer interaction. These regions indicate enhanced turbulence and fuel-air mixing.

XXI. TKE RESULTS

The reported TKE distribution shows strong turbulent activity around the fuel injection region and shear layers. Increased TKE promoted rapid mixing of hydrogen with incoming air.

The source associates this enhanced mixing with improved combustion efficiency and more uniform temperature distribution.

XXII. TEMPERATURE RESULTS

Temperature contours revealed stable combustion with peak temperatures concentrated within the primary combustion zone.

The supplied findings indicate that the PI controller helped maintain the desired temperature setpoint and reduced temperature fluctuations compared with the uncontrolled system.

XXIII. PRESSURE AND VELOCITY RESULTS:

The supplied results report that pressure distribution remained within the expected operating range. Velocity contours confirmed maintenance of supersonic flow throughout the combustor.

These observations support the interpretation that the computational model captured the principal hypersonic flow characteristics described by the study.

XXIV. CONTROL PERFORMANCE

The PI-controlled system exhibited reduced temperature fluctuations and improved thermal stability. The controller responded to temperature deviations by adjusting the fuel injection rate.

The reported performance included faster stabilization, lower overshoot, minimal steady-state error and improved combustion consistency.

XXV. FUEL-AIR MIXING

Fuel-air mixing is central to scramjet combustion because hydrogen must interact rapidly with incoming air. The supplied research connects high-TKE regions with enhanced interaction between fuel and air.

The injector and shear-layer regions are therefore important areas for interpreting the TKE contours and combustion behavior.

XVI. COMBUSTION STABILITY

Combustion stability depends on maintaining an appropriate thermal condition while preserving effective mixing. The study reports that turbulence analysis combined with PI control improved stability.

The controller acts when temperature deviates from the desired setpoint, adjusting fuel flow to restore the operating condition.

XVII. IMPLEMENTATION

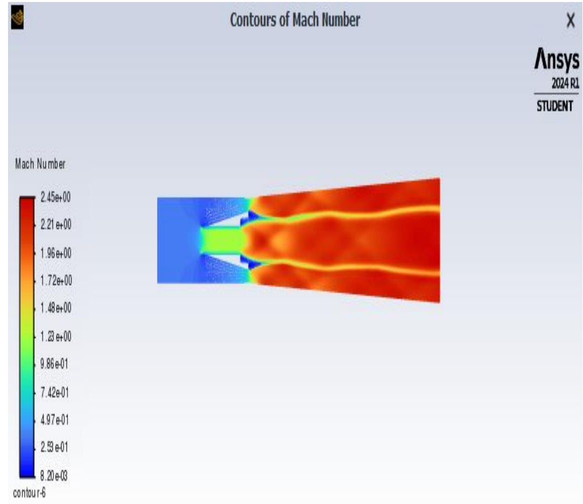
Implementation begins with development of a three-dimensional CAD model and import into ANSYS Fluent. A refined mesh is used to resolve flow, turbulence and combustion phenomena.

Hydrogen is injected into the supersonic airflow. The k–ω SST model is used to analyze TKE, velocity, pressure and temperature. MATLAB/Simulink is used for PI controller design.

XXVIII. DISCUSSION

The central finding of the supplied study is the relationship between turbulent kinetic energy and combustion performance. Regions with higher TKE provide stronger mixing, which supports combustion enhancement.

The second major finding is that feedback control improves thermal stability by continuously adapting fuel mass flow to the measured combustor temperature.



XXIX. TURBULENT KINETIC ENERGY

Turbulent kinetic energy is a central variable because it represents the intensity of turbulent motion. In the combustor, turbulence affects the interaction between injected hydrogen and incoming air.
The supplied paper states that higher TKE generally promotes fuel-air mixing and combustion efficiency, while excessive turbulence may lead to instability and pressure fluctuations.

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

XXX. ADVANTAGES

The combined CFD-control framework provides several advantages:
• Detailed numerical analysis of internal flow.
• Visualization of turbulence and mixing regions.
• Temperature-based active stabilization.
• Reduced temperature fluctuations.
• Improved combustion consistency.
• A framework that can be extended toward advanced control systems.

XXXI. LIMITATIONS

The supplied source does not provide all numerical details that would normally accompany a full CFD report. Exact geometry dimensions, mesh cell counts, grid-independence values, detailed contour legends and numerical PI gains are not included in the parsed material.

Accordingly, this report does not invent those missing values.

XXXII. FUTURE SCOPE

The source explicitly states that the approach can be further extended to advanced intelligent control systems for future hypersonic propulsion applications.

Future studies based on additional data could investigate alternative operating conditions, injection arrangements and advanced control strategies.

XXXIII. BOUNDARY CONDITIONS

- Inlet velocity: Mach 5–7
- Inlet temperature: 1200–1500 K
- Inlet pressure: 1–3 MPa
- Fuel: Hydrogen
- Fuel injection: Transverse injector
- Outlet: Pressure outlet
- Wall: No-slip, adiabatic

These are the operating ranges stated in the supplied material. A unique operating point is not invented here.

XXXIV. ENGINEERING SIGNIFICANCE

The study is significant because scramjet operation requires both efficient mixing and stable combustion at hypersonic speed. TKE analysis provides a way to identify regions of strong turbulent interaction.

Adding PI-based control connects physical flow analysis with an active operating strategy.

XXXV. METHODOLOGY SUMMARY

The complete supplied methodology can be summarized as:

1. Geometry development.
2. Mesh generation.
3. CFD model setup.
4. Boundary-condition definition.
5. CFD simulation.
6. TKE analysis.
7. Temperature and combustion analysis.
8. PI controller design.
9. Integrated feedback implementation.
10. Performance evaluation.

XXXVI. RESULTS SUMMARY

The source reports that high-TKE regions occur near fuel injection and strong shear layers. Higher TKE promotes rapid hydrogen-air mixing and improved combustion efficiency.

The temperature field shows stable combustion, pressure remains within the expected range, and velocity remains supersonic. PI control reduces temperature fluctuations and improves stability.

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XXXVII. INTEGRATED INTERPRETATION

Taken together, the reported findings indicate a chain of effects: fuel injection creates mixing and shear-layer interactions; turbulence produces regions of elevated TKE; increased TKE enhances fuel-air interaction; improved mixing supports combustion; and temperature feedback allows the controller to regulate fuel flow.

This integrated interpretation is the central engineering message of the supplied work.

XXXVIII. PRACTICAL CONSIDERATIONS

For practical CFD implementation, the supplied methodology emphasizes mesh refinement near important gradients, convergence monitoring and analysis under different fuel flow rates and operating conditions.

For control implementation, temperature measurement and reliable fuel-flow actuation are essential because the PI controller depends on feedback and adjustment of the hydrogen mass flow rate.

XXXIX. ACADEMIC CONTRIBUTION

The supplied work combines turbulence analysis and control-system design in one scramjet study. Rather than treating CFD and control independently, it links the combustor thermal response to fuel-flow regulation.

The approach provides a structured framework for examining both physical combustion behavior and dynamic stabilization.

XXXX. CONCLUSION

The supplied study demonstrates a combined CFD and PI-control framework for a hydrogen-fueled scramjet combustor. ANSYS Fluent is used to study flow, temperature, pressure, species and TKE, while MATLAB/Simulink is used for controller design.

The reported results show that high-TKE regions near fuel injection and shear layers promote mixing and combustion enhancement. PI control reduces temperature fluctuations and improves thermal stability.

REFERENCES

[1] ResearchGate source listed in the supplied material: Effects of Simulated Surface Roughness on Flow Characteristics in Symmetrical Airfoil.

[2] Chakraborty, Utsav, and Disha Chakraborti. “Investigating Flame Stabilization using Chakraborty/U-Shape Flame Holder.”

[3] Chakraborty, Utsav, and Subhadip Paul. “Influence of Surface Roughness on Symmetric Airfoil Flow Properties and Reynolds Number.” (2024).

[4] Prasad, G., Chakraborty, U., Matete, E.S., Marwaha, K.S. and Vero, R., 2025. Innovation of bio-inspired materials for next-generation defense applications. In *Innovative Materials for Next-Generation Defense Applications: Cost, Performance, and Mass Production* (pp. 145-180). IGI Global Scientific Publishing.

[5] *Satellite Monitoring Of Ocean Resources Using UPI (Utsav-Prasanna-Indira) Remote Senser*

APPENDIX AND SOURCE NOTES:

The supplied source is a four-page JAAFR article published in Volume 4, Issue 6, June 2026. It contains the research title, abstract, introduction, overview, methodology, final results, implementation, acknowledgement and references.

FINAL SOURCE-BASED SUMMARY

The supplied research concludes that integrating CFD-based turbulence analysis with closed-loop PI fuel-flow control can enhance scramjet combustion stability. The CFD analysis identifies the relationship between TKE, fuel-air mixing, temperature and supersonic flow, while the PI controller uses combustor temperature feedback to regulate hydrogen fuel mass flow.

The reported implementation demonstrates reduced temperature fluctuations, faster stabilization, lower overshoot and improved combustion consistency. The source also identifies future extension toward advanced intelligent control systems for hypersonic propulsion.