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MICRO COMBUSTOR ANALYSIS OF HYDROGEN

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Abstract: This study presents a detailed investigation of hydrogen combustion characteristics in a micro-scale combustor, with emphasis on optimizing flame stability, thermal management, and combustion efficiency for compact energy applications. Computational and experimental analyses are conducted to evaluate the effects of critical parameters, including inlet velocity, equivalence ratio, and combustor geometry, on micro-scale flame dynamics and heat transfer mechanisms. The results demonstrate that strategic modifications in combustor design—such as the integration of swirl-inducing features and cavity-based flame holders—significantly enhance reactant residence time and thermal performance. Furthermore, the study identifies optimal operating regimes that achieve stable combustion while minimizing heat losses, making the system suitable for micro-thermophotovoltaic (μ-TPV) applications requiring high energy density. The findings contribute to advancing microscale combustion technology by providing key insights into flame anchoring, heat recirculation, and efficiency enhancement in constrained geometries.

Keywords: Micro-combustion, Hydrogen combustion, Flame stability, Heat transfer, Combustion efficiency, Micro-thermophotovoltaic (μ-TPV), Residence time, Swirl flow, Cavity flame holder, Compact energy systems.

I. INTRODUCTION

A combustor serves as the heart of many energy systems, enabling controlled fuel combustion to generate power or thrust. Found in gas turbines, jet engines, and industrial power plants, its primary function involves mixing fuel—such as natural gas, kerosene, or hydrogen—with compressed air and igniting the mixture to produce high-energy exhaust gases. These gases either drive turbine blades for electricity generation or create propulsion in aircraft. Modern combustors are engineered for peak thermal efficiency while minimizing nitrogen oxides (NOx) and carbon monoxide (CO) emissions through lean-burn designs, staged combustion, and advanced cooling techniques like film cooling and thermal barrier coatings. Their robust construction allows them to withstand extreme temperatures exceeding 1,500°C, making material selection and heat management critical aspects of their design.

The growing demand for compact power solutions has spurred the development of micro-combustors, which are revolutionizing portable energy systems. These millimetre-scale devices enable applications in micro-drones, wearable electronics, and micro-power generators by offering exceptional energy density. However, their small size introduces challenges like excessive heat loss due to high surface-to-volume ratios and flame instability from shortened gas residence times. Researchers are addressing these issues through innovative approaches like catalytic combustion (using platinum or palladium coatings), Swiss-roll heat-recirculating designs, and porous media combustion to stabilize flames and improve thermal efficiency. Some experimental micro-combustors even operate on alternative fuels like ammonia or biofuels, expanding their potential in green energy systems.

While traditional combustors prioritize large-scale power output and emission control, micro-combustors focus on overcoming miniaturization barriers for portable applications. Both types benefit from ongoing advancements in computational fluid dynamics (CFD) modeling, additive manufacturing for complex geometries, and novel materials like ceramic matrix composites. As global energy needs evolve, combustor technology continues to adapt—whether scaling up for cleaner power plants or scaling down for next-generation microelectronics. The future may see hybrid systems combining both technologies, offering scalable solutions from megawatt power stations to pocket-sized energy devices, all while meeting increasingly strict environmental standards.

II. MICRO-COMBUSTOR

A micro combustor is a small-scale combustor designed for use in micro-engine systems, such as micro gas turbines, portable power devices, or microelectromechanical systems (MEMS). Essentially, it functions similarly to a regular combustor but is miniaturized for compact applications where space, weight, and efficiency are critical.

Combustors are designed to ensure efficient burning, minimal emissions, and effective heat management. Their design is crucial for the overall performance of engines and power generation systems. A combustor is a critical component in many energy systems, responsible for the process of burning fuel to release energy in the form of heat. It plays a vital role in engines, turbines, power plants, and a range of industrial applications. The main function of a combustor is to provide a controlled environment for the combustion of fuel (e.g., natural gas, hydrogen, or liquid fuels) and air (oxygen) in order to produce heat or power.

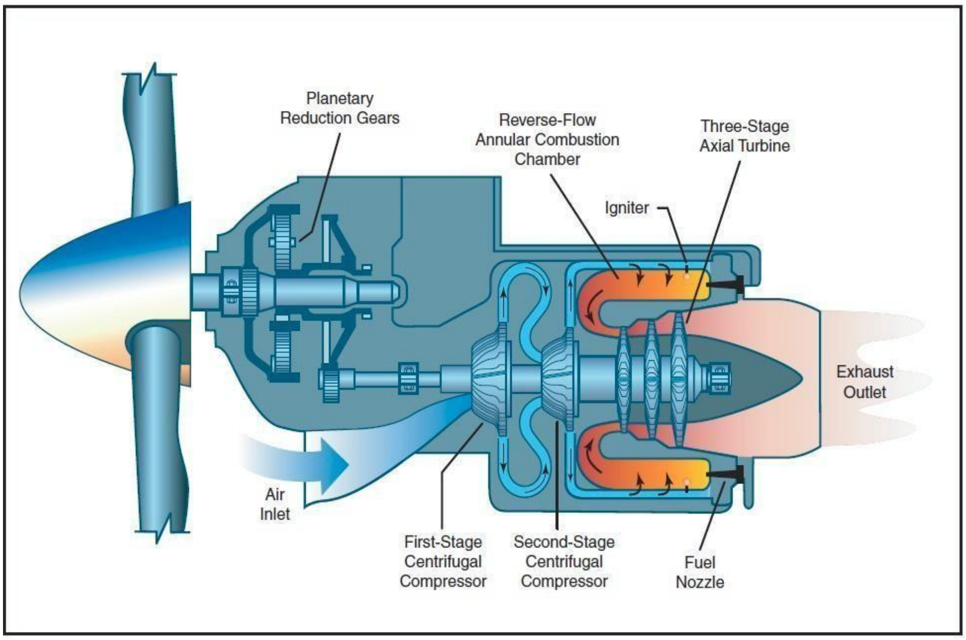

Figure 1 Micro combustor

Micro-combustors are revolutionizing portable power systems as ultra-compact combustion devices. These miniature powerhouses enable exciting applications across multiple fields - they can run pocket-sized generators for outdoor equipment, extend flight durations for micro-drones, and power precision laboratory instruments. However, engineers face significant hurdles in developing these tiny combustion systems. The primary challenges include maintaining stable flames in spaces sometimes smaller than a coin, preventing excessive heat loss due to the high surface-to-volume ratio, and ensuring complete fuel combustion to minimize emissions. To overcome these obstacles, researchers are implementing innovative solutions like advanced ceramic materials that withstand extreme temperatures, intricate heat-recirculating channel designs, and specialized catalytic coatings that enhance combustion efficiency. The development of micro-combustors is particularly significant as they promise to deliver higher energy density than conventional batteries, with some experimental hydrogen-powered versions producing only water vapor as exhaust. Remarkably, cutting-edge micro-combustor prototypes have achieved such miniaturization that multiple units could fit on a single fingernail, demonstrating the incredible potential of this technology for future portable power applications. Current research continues to push the boundaries of what these microscopic combustion systems can achieve, potentially transforming how we power small-scale devices across numerous industries.

PROCESS OF COMBUSTOR:

Micro-combustors perform the same fundamental function as their larger counterparts but require specialized engineering solutions to overcome scale-related challenges. The process begins with air intake through micron-scale channels, where specialized micro-compressors or pressure differentials create the necessary compression ratios typically between 3:1 to 10:1. Fuel delivery systems achieve remarkable precision using MEMS-based piezoelectric injectors for liquids or porous

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metal diffusers for gases, with flow rates carefully regulated by micro-valves capable of millisecond response times.The mixing process presents unique challenges at this scale, where engineers employ innovative solutions like herringbone micro-channels or micro-pillar arrays to achieve complete fuel-air mixing within extremely short residence times of 0.1-5 milliseconds. Ignition systems must be equally precise, utilizing micro-plasma discharges or catalytic glow plugs that can reliably ignite mixtures with as little as 0.1mJ of energy. Once ignited, maintaining combustion stability requires specialized flame anchoring techniques such as cavity-stabilized recirculation zones or micro-pin arrays that create controlled vortices.

Thermal management becomes critical in these compact systems, addressed through multi-layer insulation schemes and advanced cooling methods like micro-channel liquid cooling or transpiration through porous walls. The high-velocity exhaust gases (100-300 m/s) can then drive various energy conversion systems, from miniature turbines to thermophotovoltaic cells, though engineers must carefully balance efficiency against the inherent challenges of microscale operation. Current research focuses on pushing the boundaries of what's possible in micro-combustion, with developments like 3D-printed ceramic combustors and AI-controlled adaptive systems showing particular promise for improving performance while maintaining the size and weight advantages that make micro-combustors so valuable for portable power applications.

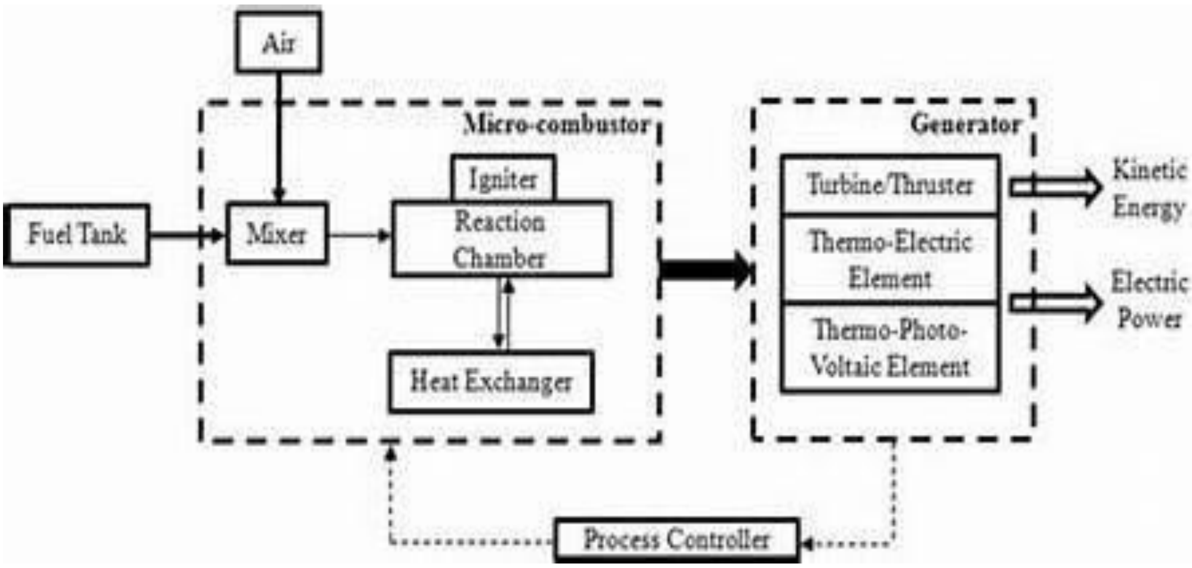

Figure 2 Process chain

ROLES OF MICRO-COMBUSTORS IN MICRO-POWER GENERATION:

Micro-combustors serve as the powerhouse for next-generation portable energy systems, enabling compact and efficient power solutions across multiple sectors. Their unique capabilities address critical challenges in three fundamental areas:

- **High-Efficiency Energy Conversion**

Micro-combustors achieve exceptional energy density through precision combustion in miniature chambers, converting up to 30% of fuel's chemical energy directly into usable power. Unlike conventional batteries, these systems maintain constant power output as long as fuel is supplied, with energy densities 5-10 times greater than lithium-ion batteries. Advanced designs incorporate catalytic combustion and heat-recirculating geometries that push thermal efficiencies beyond 85% in some configurations, while maintaining flame stability in chambers as small as 1cm³.

- **Versatile Power System Integration**

These components form the core of multiple micro-power solutions:
Micro-turbine generators producing 10-500W for UAVs and portable equipment
Hybrid power packs combining combustion with thermoelectric conversion
MEMS energy systems delivering milliwatt power for sensors and micro-robotics
Their fuel flexibility spans hydrogen, hydrocarbons, and biofuels, with modern designs automatically adjusting combustion parameters for optimal performance across different fuel types through integrated sensors and control algorithms.

- **Sustainable Distributed Energy Solutions**

Micro-combustors enable clean, off-grid power with several environmental advantages:
60-90% lower NOx emissions than conventional generators through flameless combustion modes
Carbon-neutral operation when using bio/synthetic fuels
Waste heat recovery systems that boost total efficiency to >90% in cogeneration setups
Emerging applications include hydrogen-powered medical devices and solar-fuel hybrid systems for remote monitoring stations, demonstrating their role in the transition to sustainable energy

III. LITERATURE REVIEW

Ronney (2003) [1]
He was among the first to explore the unique characteristics of flame propagation in micro-channels, identifying the importance of conductive heat loss to walls that can lead to flame quenching. His work laid the foundation for flame stability analysis in miniaturized systems.

Maruta, K. (2011) [2]
He investigated the various combustion regimes in narrow channels, including weak flames, repetitive extinction and ignition (FREI), and stable flame propagation. His group classified these regimes based on wall heat loss, equivalence ratio, and inlet velocity. He performed experimental studies with premixed hydrogen-air flames in micro-tubes, showing that hydrogen's high diffusivity and low ignition energy support stable combustion in smaller geometries compared to hydrocarbons.

Peter D. Ronney (2003) [3]
Ronney studied flame quenching and stabilization in micro-channels using hydrogen. He introduced the concept of quenching diameter and how wall heat losses affect combustion. His findings are essential in designing micro combustors that avoid flame extinction and ensure efficient operation, particularly in micro-scale power and propulsion systems.

Kazuhiro Maruta (2011) [4]
Maruta explored combustion regimes in narrow channels, identifying phenomena like Flame Repetitive Extinction and Ignition (FREI). His regime maps for hydrogen-air mixtures helped clarify flame behavior under varying conditions. This research greatly impacted the stability and control strategies for hydrogen combustion in micro-scale applications like micro-reactors and sensors.

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Alan H. Epstein (1997) [5]
Epstein led the MIT micro-gas turbine project, integrating silicon-based hydrogen micro-combustors with MEMS turbines. He conceptualized compact, high-power-density systems capable of portable energy generation. His work was pioneering in demonstrating the viability of hydrogen as a clean fuel in micro-scale power technologies, such as micro-UAVs and electronics

IV. DESIGN AND DEVELOPMENT

Design of combustion chamber
The current paper describes the study of the micro combustion chamber's numerical analysis. In order to design the combustion chamber, design constraints must be satisfied. The compressor and turbine work must be considered to determine the overall size. Combustion inlet requirements and compressor exit conditions depend on each other, which must be considered when designing a combustor.

In order to design the combustion chamber for a gas turbine engine, two considerations must be used. Major combustion chamber dimensions consider aerodynamics and chemical for the casing and liner design of Swiss role-type combustion chambers for small gas turbine applications. The commercial CFD package ANSYS CFX performs the CFD simulation for the intended chamber

1) Geometry of the Combustor

- Shape: Common geometries include straight-channel, U-shaped, annular, and cavity-based combustors.
- Size: Microscale dimensions (1–10 mm); the small volume affects residence time and flame stabilization.
- Aspect Ratio: Impacts heat recirculation and flow development.

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2) Fuel and Air Injection System

- Premixed vs. Diffusion Flame: Premixing is preferred in micro combustors for stable and clean combustion.
- Injector Design: Swirlers or jet-in-crossflow injectors help mix hydrogen and air efficiently.
- Backflow Prevention: Flashback is a risk with hydrogen; use of flame arresters or porous media can help.

3) Flame Stabilization Techniques

- Recirculation Zones: Swirling flow or bluff bodies create zones of low velocity to hold the flame.
- Wall Heat Recirculation: Heat feedback from walls helps preheat the mixture and stabilize the flame.
- Catalytic Coating: Helps stabilize flame at lower temperatures and smaller scales.

4) Material Selection

- Thermal Stability: Must withstand high flame temperatures (1800–2200 K).
- Oxidation Resistance: Especially important for hydrogen combustion.
- Low Thermal Conductivity: Helps reduce heat loss (e.g., ceramics or coated metals).

5) Thermal Management

- High Surface-to-Volume Ratio: Leads to high heat losses—must be minimized by insulation or heat recuperation.
- Wall Cooling: Sometimes needed to protect components but must be balanced to avoid flame quenching.
- Combustor Wall Coatings: Ceramic or refractory coatings reduce heat loss and increase durability.

6) Reaction Mechanisms and Kinetics

- Fast Reactions: Hydrogen combusts rapidly; kinetic models (like GRIMech) are used in simulations.
- Flammability Range: Hydrogen has a wide flammability range (4– 75%)—helps ignition but increases flashback risk.

7) Combustion Efficiency

- Equivalence Ratio: Optimal values (usually 0.8–1.2) ensure complete combustion with minimal emissions.
- Residence Time: Needs to be long enough for full combustion but short enough to reduce heat loss.

8) Emissions

- NOx Formation: Even though hydrogen combustion is clean, high temperature NOx must be monitored.
- Water Vapor: Main product—must be considered in post-processing or condensation control.
- Heat feedback from walls helps preheat the mixture and stabilize the flame.

9) Ignition Method

- Spark Plug: Common but consumes power.
- Hot Surface/Igniter Coil: More compact and suitable for MEMS.
- Catalytic Ignition: Enables cold-start and low-temperature operation.
- Ceramic or refractory coatings reduce heat loss and increase durability.

10) 3.2.10 Simulation and Optimization Tools

- CFD Tools (e.g., ANSYS Fluent): Used to model combustion, fluid flow, and thermal behavior.

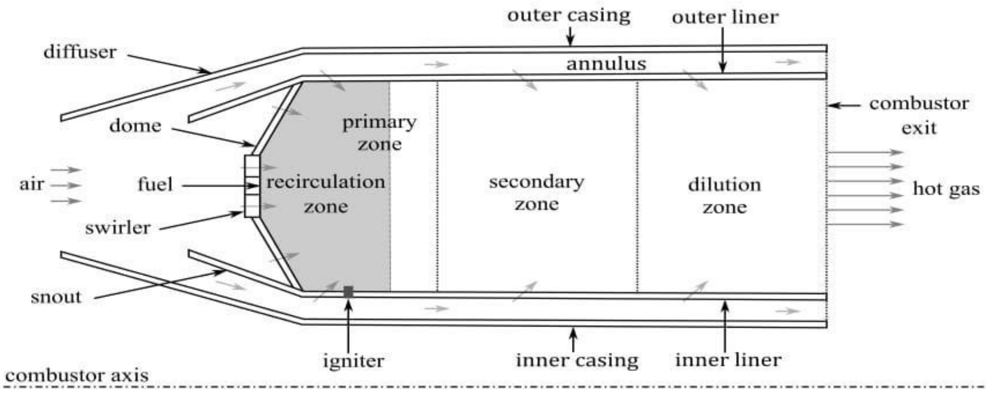

Figure 3 Design of Micro combustor

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PROPERTIES OF MICRO COMBUSTOR:

Parameters	Value
Combustor type	Straight channel
Combustor length	300 mm
width	50 mm
Fuel	Hydrogen
Air-fuel mixing	Premixed
Inlet temperature	300k
Operating pressure	1 atm

Calculations:

1.Wall Thickness:

$$t= \frac{P.r_i}{\sigma_{allowable}}$$

where:

- Internal pressure P= (1×10^5)
- Radius r= $0.005\ m$
- $\sigma_{allowable}$=50×10^6Pa

t= $\frac{151987\times0.005}{50\times10^6} \cong 0.0152$ mm

2. Combustion Reaction:

=$2H_2$+O_2+$2H_2$O

- Enthalpy of combustion, ΔH_comb = −286 kJ/mol H_2
- Molar mass of H_2 = **2.016 g/mol**

3.Molar Flow Rate of Hydrogen:

$$nH_2 = \frac{m\dot{H}_2}{MH_2}$$

$$= \frac{0.0005}{0.002016}$$

= 0.248mol/s

4.Heat Released per Second:

Q=n˙H2×ΔHcomb

=0.248×286=70.93Kw

5.Air requirement:

From: 2H2+O2→2H2O⇒1mol H2:0.5mol O2

Air contains 21% O_2 by volume ⇒ 1 mol O_2 needs 4.76 mol air

˙nair=0.248×0.5×4.76=0.59mol/s air

Mass of air:

m˙air=0.59mol/s×28.97g/mol≈0.0171kg/s

ANSYS Fluent: Species Model Setup Guide

ANSYS is a powerful engineering simulation software used to analyze and solve problems related to structures, heat transfer, fluid flow, electromagnetics, and Multiphysics. It helps engineers design and optimize products without physical prototypes by using computer-based simulations. Common modules include ANSYS Mechanical (for structural analysis), ANSYS Fluent and CFX (for fluid flow and combustion), and ANSYS Workbench (for integrated simulation workflows).

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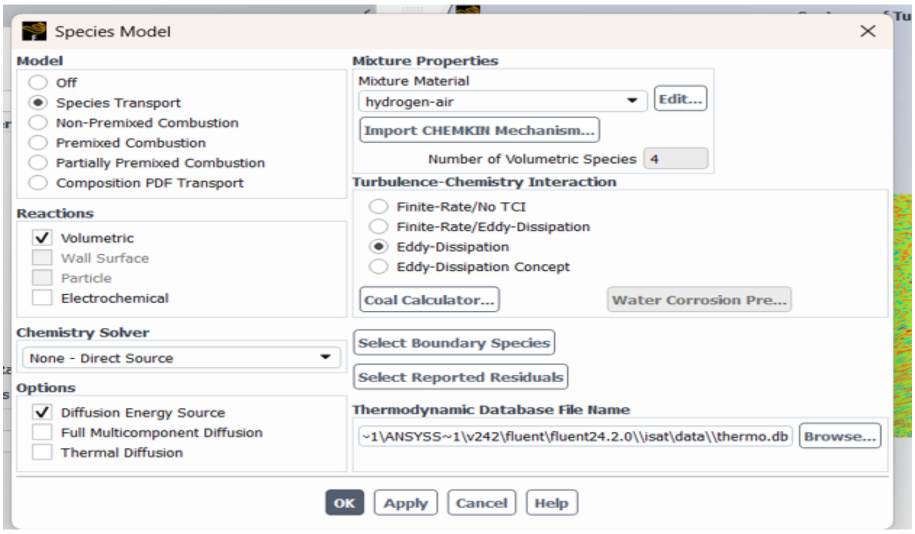

Figure 4 Ansys fluent

Model selection:

• Species Transport: Enables resolution of species mass conservation equations without a predefined reaction model.
• Non-Premixed Combustion: Used when fuel and oxidizer enter separately and mix within the domain (typically modelled with PDF transport).
• Premixed Combustion: Assumes reactants are fully mixed before combustion; uses flame let models or progress variables.
• Partially Premixed Combustion: Combines premixed and non-premixed features, suitable for turbulent flames with partial pre-mixing.
• Composition PDF Transport: Solves a probability density function for mixture fraction and scalar dissipation, crucial in turbulent combustion.
Mixture Properties:
• Mixture Material: Defines the working fluid, here "hydrogen-air", which governs thermodynamic and transport properties (Cp, viscosity, etc.).
• Edit...: Allows you to define custom species, their transport coefficients, and thermodynamic.
• Import CHEMKIN Mechanism: Used to load detailed chemical reaction mechanisms in CHEMKIN format, allowing modeling of complex reactions.
• Number of Volumetric Species: Specifies the count of gaseous chemical species solved via the species conservation equations.

Turbulence–Chemistry Interaction:

• Finite-Rate/No TCI: Solves Arrhenius-based reaction rates without considering turbulence effects (purely laminar combustion).
• Finite-Rate/Eddy-Dissipation: Considers both finite-rate kinetics and turbulent mixing limits (Damköhler number-driven model).
• Eddy-Dissipation: Fast chemistry assumption; reaction rate is limited by turbulent mixing only (suitable for highly turbulent, fast-burning flames).
• Eddy-Dissipation Concept (EDC): A more accurate closure model that resolves reaction rates within fine structures of turbulent eddies (includes micro-mixing and chemical timescales).

Reactions:
• Volumetric: Bulk-phase chemical reactions (gas-phase combustion).
• Wall Surface: Surface catalysis or heterogeneous reactions.
• Particle: Used in multiphase flows involving reacting particles (e.g., coal combustion).
• Electrochemical: For simulating fuel cells or batteries involving ionic transport and electrode reactions.

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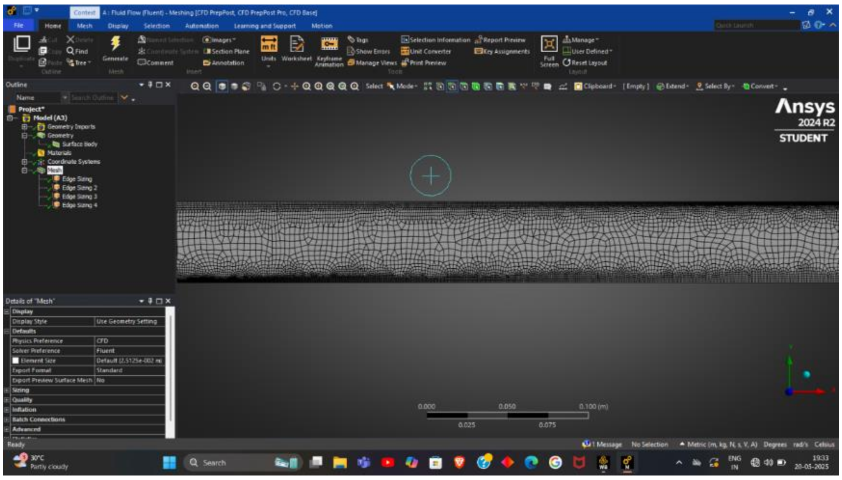

Figure 5 Meshing

Scaled Residuals:

In ANSYS Fluent, scaled residuals quantify the normalized imbalance in governing equations (mass, momentum, energy, etc.) during iterative solving. They serve as convergence indicators, ensuring solution stability. Lower residuals imply improved numerical accuracy, especially critical in capturing complex flow behavior like turbulence, heat transfer, and chemical reactions in fluid dynamics.

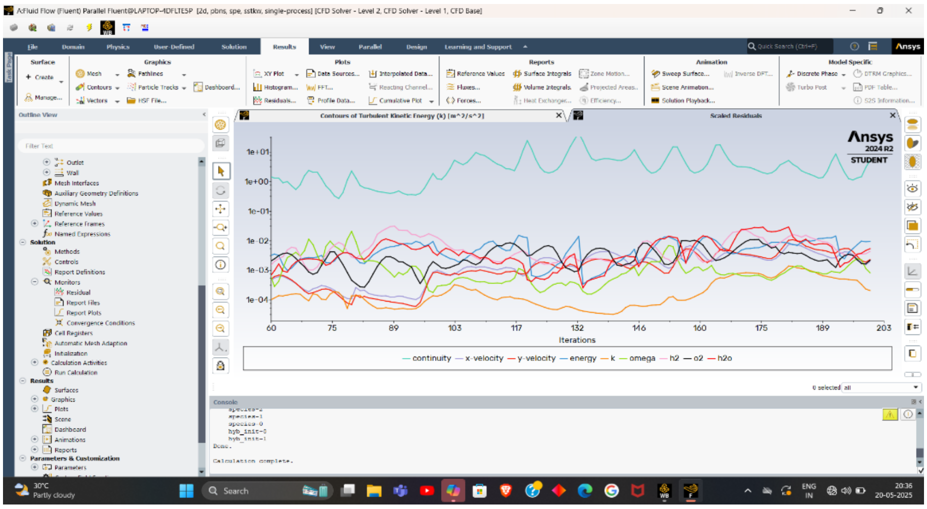

Figure 6 Scaled residuals

During the simulation of the combustor model in ANSYS Fluent (2024 R2 Student Edition), the convergence behavior was monitored using scaled residual plots. These residuals represent the imbalance in the governing equations - mass, momentum, energy, turbulence, transport.

Governing Equations Solved:

The simulation involved the solution of:

- Continuity equation (mass conservation)
- Momentum equations (x- and y-velocity components)
- Energy equation (thermal energy distribution)
- Turbulence equations: *k* (turbulent kinetic energy) and *ω* (specific dissipation rate), based on the k-ω SST turbulence model
- Species transport equations for H_2, O_2, and H_2O to model the combustion process

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Residual Behavior:

The residual plot in Figure [X] (insert image number here) shows the variation of residuals over approximately 200 iterations.

- The continuity residual remained relatively high ($\sim 10^0 – 10^1$), indicating a persistent imbalance in the mass conservation equation. This is common in reacting flow simulations where rapid changes in density and temperature occur due to combustion.
- The x- and y-velocity residuals showed fluctuating but generally reducing trends, stabilizing below 1-2 in most cases.
- The energy residual remained below 1e-3 after ~120 iterations, suggesting a reasonably accurate prediction of temperature distribution.
- The turbulence residuals (k and ω) fluctuated due to turbulence–chemistry interaction but trended toward acceptable convergence limits.
- Species residuals (H_2, O_2, H_2O) showed high initial variation due to active combustion reactions but began to stabilize after ~150 iterations.

V. RESULTS AND DISCUSSIONS

DYNAMIC PRESSURE DISTRIBUTION

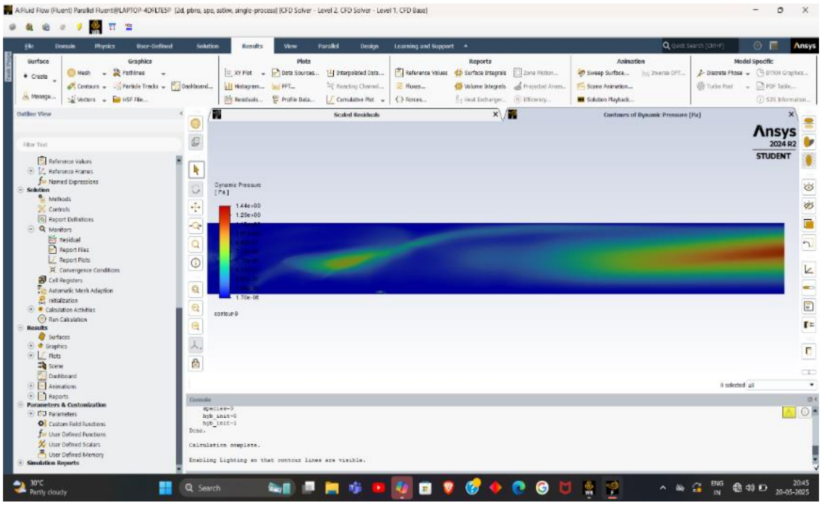

Figure 7 Dynamic pressure distribution

The image displays the contour plot of dynamic pressure (Pa) inside a 2D combustor geometry in ANSYS Fluent 2024 R2 Student Edition. Dynamic pressure represents the kinetic energy per unit volume of the flowing fluid and is crucial in analysing high-velocity flows and combustion dynamics. The contour shows a pressure rise in the downstream region, likely due to combustion-induced expansion and velocity increase. The blue region indicates low dynamic pressure, whereas the red region near the outlet shows higher dynamic pressure, corresponding to increased velocity. This distribution helps validate the combustor's performance and flow behaviour under reacting flow conditions.

VELOCITY MAGNITUDE CONTOUR PLOT:

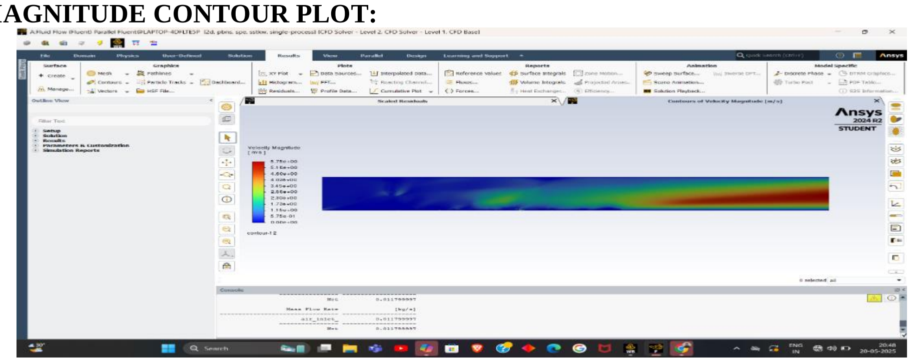

Figure 8 velocity magnitude contour plot

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The image presents the velocity magnitude contour plot from a 2D combustor simulation in ANSYS Fluent 2024 R2 Student Edition. Velocity magnitude represents the speed of fluid particles at various points within the domain. The contour clearly shows velocity increasing from inlet to outlet, where red regions indicate higher velocities (~5.75 m/s) and blue regions represent low-speed zones. These variations result from combustion-induced expansion and flow acceleration. Recirculation and turbulence are visible in the mid-section, contributing to efficient mixing of air and fuel. The velocity distribution is vital in analyzing flame stabilization, combustion efficiency, and pressure drop in the combustor. A velocity magnitude plot in ANSYS shows the speed of fluid flow at various points using colour contours. It helps visualize flow behaviour, identify high or low velocity zones, detect recirculation or stagnation, and optimize design. It's essential for analysing airflow, combustion, or cooling performance in simulations.

CONTOUR PLOT OF STATIC TEMPERATURE:

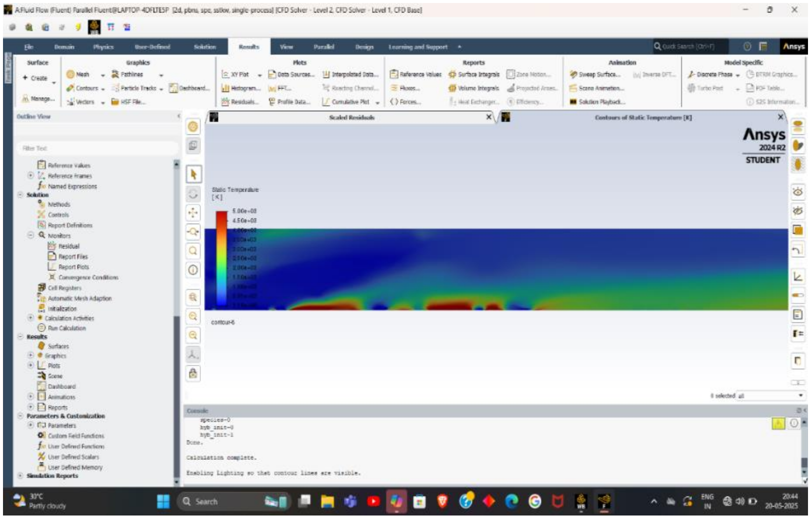

Figure 9 Contour plot for static temperature

The image illustrates a contour plot of static temperature in a combustor simulation conducted using ANSYS Fluent 2024 R2 Student Edition. Static temperature represents the actual temperature of the fluid without accounting for its kinetic energy, making it crucial in combustion analysis. In this 2D domain, the temperature distribution indicates combustion zones, flame stabilization regions, and post-combustion heat release. Red areas signify high-temperature zones nearing 5000 K, corresponding to active combustion, while blue regions show cooler areas (~1100 K) near the walls and air inlet.

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