A New Approach to Computational Combustion Analysis of Pre-Chamber Pulsejet Combustor Using Ansys Fluent

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Abstract—**The pulsejet received a lot of attention during World War II; it operates at subsonic speed, but the technology has never lived up to expectations about performance. Recently, a renewed interest in this technology has led to an upsurge in pulsejet research and experimentation. Recent advancements include attempts to use a pulsejet as a combustor for a gas turbine engine, the use of pulsejets to create greater power, and the ability of pulsejets to function at supersonic speeds. Reference studies validate that pre-chamber combustion is effective in gasoline IC engines. In this project, a pre-chamber was incorporated into a pulsejet combustor, and combustion analysis was carried out using the CFD simulation software ANSYS Fluent. A pre-chamber is a small chamber typically mounted on top of the main chamber, having a fuel inlet, air inlet, and spark plug. Its volume is 2.4% of the main combustion chamber. Extremely fuel-rich mixture inside the pre-chamber in order to form a low-temperature torch in the form of incomplete combustion products, instead of a flame. On success, the following flame establishment results in pressure increase with an expulsion force that makes partially burnt products ejected out of the pre-chamber into the main chamber, air-fuel in main chamber's is a lean mixture. Combustion efficiency was determined from the mass fractions of fuel species and combustion product species.**

Index Terms—**Propulsion, Combustion, Computational Fluid Dynamics, Pulsejet Engine, Modeling.**

I. INTRODUCTION

The pulsejet engine is mechanically simple design but inherently unstable propulsion system that generates thrust intermittently in a cycle of air intake, combustion, and exhaust. The engine configuration comprises an inlet diffuser, check valves, combustion chamber, and exhaust tube. Fuel is injected after the valves and is mixing with the incoming air. When ignited, the combustion produces high pressure, that closing the check valves and exhausting exhaust gases through exhaust tube. When the gases are exhausted, they leave behind a vacuum that opens the valves again, allowing fresh air to enter and repeat the process [1]. This self-repeating process is based on the Kadenacy Effect, which explains the pressure oscillations in the combustion chamber due to the inertia of the gases being pushed out. The effect acts to draw in fresh air and fuel into the chamber, thus sustaining the combustion cycle without the need for constant external ignition [2]. The pulsejet engine features a simple operating mechanism, but its relatively low combustion efficiency limits its practical applications.

1.1 Development of Pre-chamber in Reciprocating IC Engines

In an effort to increase combustion efficiency further, pre-chamber combustion methods have been researched extensively in IC engines. Initial pre-chamber engine development involved the Ricardo Three Valve Engine that improved power delivery through the provision of separate air and fuel-air mixture valves, thereby eliminating throttling losses [3]. Development also involved a pre-chamber with a large interconnecting passage that was aimed at directing flames into the main chamber, thus improving combustion efficiency through better flame propagation [4]. Additionally, the employment of small nozzle diameters produced high-velocity jets that were better positioned to burn lean mixtures, thus increasing overall efficiency [5]. Inclusion of a stand pipe within the pre-chamber nozzle served to prevent fouling of the spark plug, while tangential nozzle holes

allowed for better mixing and lower deposit formation [6].

Later advancements included the use of the LAG-Ignition method, which utilized an extremely rich mixture in the pre-chamber to create a low-temperature torch of chemically reactive species, thereby allowing ignition without the formation of a classical flame [7]. A second pre-chamber design placed the spark plug near the interconnecting channel, allowing combustion products to flow directly into the main chamber; this was not significantly to improve efficiency [8]. The development of the Turbulent Jet Ignition (TJI) system later allowed stable operation at low ignition energies and high air-fuel ratios, with improved efficiency over conventional systems [9].

1.2 *Pre-chamber in Pulsejet Combustor*

Introducing a pre-chamber into a pulsejet combustor significantly improves combustion efficiency by ensuring consistent and reliable ignition. The pre-chamber design improves fuel-air mixing and generates high-velocity jets that promote effective flame propagation into the main chamber. This leads to more complete fuel combustion, thereby boosting the overall performance of the pulsejet combustor under various operating conditions.

II. METHODOLOGY

In this project, the dimensions of the main parts of the pre-chamber and main combustor were determined using fundamental and derived equations from references. The design and combustion analysis of the pre-chamber pulsejet combustor were performed to evaluate its combustion efficiency. Initially, the geometry of the pulsejet combustor and pre-chamber was designed and modelled using Ansys Design Modeller. An unstructured mesh was generated to discretize the computational domain, ensuring precise capture of flow physics and combustion phenomena.

Boundary conditions, including inlet velocity, temperature, and species concentrations, were defined based on the pulsejet operating condition. Simulations were executed using Ansys Fluent software, with solution convergence closely monitored to ensure numerical residuals stability. Post-processing techniques were applied to analyze results through contour plots and species concentrations at the inlet

and outlet. The combustion efficiency was calculated based on the burnt and unburnt species concentrations at the outlet, providing a comprehensive assessment of the system's performance.
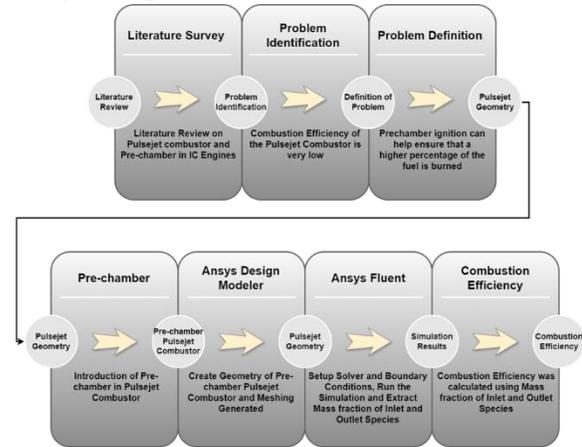

Figure 1: Methodology

2.1 *Description of Pre-Chamber Combustion System*

The pre-chamber combustion system, also known as pre-chamber ignition or pre-chamber spark ignition, is a method used in some internal combustion. Here's how it typically operates:

2.1.1 Pre-Chamber Design: In this system, each cylinder has its own small pre-chamber adjacent to the main combustion chamber. The pre-chamber is connected to the main combustion chamber by one or more small orifices or passages like nozzles.

2.1.2 Fuel Injection: Fuel is injected into the pre-chamber during the compression stroke of the engine cycle. The fuel-air mixture in the pre-chamber is typically richer than the air-fuel mixture in the main combustion chamber.

2.1.3 Ignition: A spark plug or other ignition source ignites the fuel-air mixture in the pre-chamber shortly before the main combustion event. This creates a flame kernel or small flame front within the pre-chamber.

2.1.4 Combustion Initiation: The flame kernel rapidly expands into the main combustion chamber through the orifices or passages, igniting the leaner mixture present there. This results in the simultaneous ignition of the entire mixture in the main combustion chamber.

2.1.5 Main Combustion: Once ignited, the fuel-air mixture in the main combustion chamber undergoes

rapid combustion, generating the power stroke of the engine.

This system is commonly used in certain types of spark-ignition engines, particularly in applications where combustion stability and efficiency are critical, such as in high-performance engines or engines operating under variable load conditions.

III. GEOMETRICAL DESIGN OF PRE-CHAMBER PULSEJET COMBUSTOR

The pulsejet engine design is founded on extensively tested relationships between dimensions, thrust(F), and mixture ratios. The pulsejet required take-off thrust of 2700N, and 3300N during flight. The combustor diameter (Dc) was determined to be 0.53m, and the combustion chamber length (Lc) is 0.53m. A 30-degree angle was implemented to connect the combustion chamber with the tailpipe, enhancing internal flow dynamics [15].
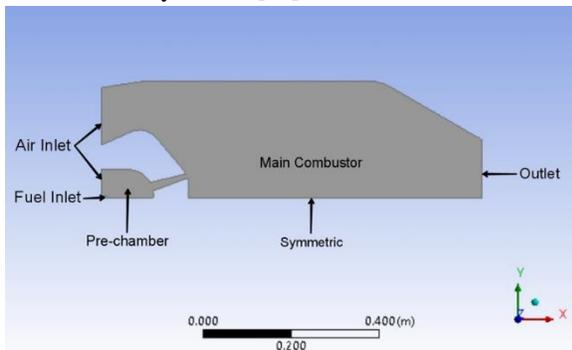

Figure 2: Pre-chamber Pulsejet Geometry

The pre-chamber design of the pulsejet combustor significantly influences combustion efficiency (η_c). Increasing the pre-chamber volume from 1.4% to 2.4% of the main chamber's volume notably reduces the flame development angle and combustion duration while enhancing initial heat release. Expansion of the pre-chamber volume up to 2.4% also significantly improved combustion efficiency, although further expansion was less effective [10]. The pre-chamber has a volume of 0.0028m³, which is 2.4% of the main chamber's 0.1169m³. It features a cylindrical design with a 0.135 m diameter, a 0.06 m length, and a rounded front with a 0.065 m radius. A nozzle connects the prechamber and main chamber, which is 2:1 ratio accelerates pre-combustion flame efficiently

within the main chamber. These design parameters are shown in table 1.

Table 1: Design Parameters of Pre-Chamber Pulsejet Combustor

Parameters	Formula	Results
Thrust (F)	F	3300 N
Engine Diameter or Combustion Chamber Diameter (Dc)	$Dc = 9.1619 \times 10^{-3} \sqrt{F}$	0.53 m
Combustion Chamber Length (Lc)	Lc = Dc	0.53 m
Joint the Combustion Chamber with Tailpipe		30°
Volume of Main Combustor (Vm)	$Vm = (\pi/4)Dc^2 \times Lc$	0.1169m³
Volume of Pre-chamber (Vp)	Vp = 0.024 x Vm	0.0028m³
Diameter of the Pre-chamber (Dp)	Dp	0.1350m
Length of the Pre-chamber (Lp)	Lp	0.06m
Pre-chamber Front Diameter		0.065
Convergent Nozzle jet ratio		2:1

IV. NUMERICAL ANALYSIS OF PRE-CHAMBER PULSEJET COMBUSTOR

The detailed 2D surface geometry of the pre-chamber implemented pulsejet combustor was created using Ansys Design Modeler, as illustrated in Figure 2, based on the specified design parameters. The geometry includes key components such as the air inlet, fuel inlet, main combustor, and pre-chamber, with all dimensions provided in SI units (meters and degrees). A high-quality computational mesh was generated using Ansys Fluent's meshing capabilities, employing structured meshing techniques. So, approximately 1.5 million was chosen as the optimum grid size and was used for whole study. This process incorporated boundary layer refinement and mesh adaption strategies to accurately capture flow

gradients and combustion phenomena, ensuring reliable results for subsequent simulations.

4.1   Governing Equations

The Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations were used to solve the computational model using the finite volume approach. These equations govern the conservation of mass, momentum, and energy in the flow field. The equations are stated as follows:

A. *Mass Conservation Equation:*

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

This equation ensures the conservation of mass within the control volume by accounting for temporal and convective changes in density (ρ) and velocity (u).

B. *Momentum Conservation Equation:*

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) = -\nabla p + \nabla \cdot (\mu \nabla u) + S$$

This equation describes the balance of forces, including pressure gradients (p), viscous stresses (with dynamic viscosity μ), and external forces (S) acting on the fluid.

C. *Energy Conservation Equation:*

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot \left(u(\rho E + p)\right) = \nabla \cdot (k \nabla T) + \Phi$$

Here, E represents the total energy per unit mass, k is the thermal conductivity, T is the temperature, and Φ denotes the viscous dissipation term. This equation ensures energy conservation by accounting for convection, conduction, and viscous effects.

These governing equations were discretized using the finite volume approach to solve the flow and combustion parameters in the pulsejet combustor correctly.

4.2   Boundary Conditions

A pressure-based solver with absolute velocity and transient conditions was selected to capture the unsteady behavior of the flow and combustion processes effectively. The energy equation was activated to account for heat transfer, and the k-epsilon turbulence model was employed to simulate the turbulent flow characteristics accurately. The mesh was refined near the boundaries to capture gradients efficiently, ensuring that the numerical solution would be both stable and reliable.

The combustion was simulated by using the species transport method along with the eddy dissipation turbulence to efficiently model the reaction kinetics of methane and air mixtures. A spark ignition was applied to the pre-chamber to bring about ignition of the combustion, which lasted for 0.01 seconds. Once this ignition period was over, the combustion proceeded automatically, depending upon the chemical kinetics of the mixture and its turbulent flow behavior. This configuration was essential in order to represent the transition from ignition to sustained combustion accurately.

The boundary conditions were defined with precise parameters to replicate realistic operating conditions. The air inlet temperature was set to 450 K, while the fuel inlet temperature was 650 K. For the composition, a methane mass fraction of 1 and an oxygen mass fraction of 0.23 were specified to represent a stoichiometric mixture initially. The flow parameters included an air velocity of 125 m/s and a fuel pressure equivalent velocity of 106.95 m/s, ensuring a proper mixture and flow rate for combustion. Referring to the combustion mixtures, the pre-chamber was designed to contain a rich fuel mixture at an equivalence ratio of 14.5:1 for the purpose of initial ignition. The main combustor, operated on a lean mixture at an equivalence ratio of 40:1 for efficient combustion and reduced emissions. This disparity between the pre-chamber and main combustor mixtures was required to replicate the staged combustion process accurately. These accurately specified conditions enabled careful investigation of the combustion process, temperature profile, and flow pattern within the pulsejet combustor.

V. RESULTS AND DISCUSSION

The pre-chamber pulsejet combustor analysis validated the role of inlet species concentration in determining combustion efficiency and product formation. The inlet mass fraction of methane (CH_4) was kept at 1.0000, i.e., the use of pure methane as a fuel, while that of oxygen (O_2) was 0.2329 and is equal to atmospheric levels. The appropriate concentrations were essential in replicating the combustion environment in Ansys Fluent. The high methane concentration ensured the rich fuel supply to the pre-chamber and enabled the aggressive combustion process during the initial stage. Meanwhile, the concentration of oxygen was high enough to maintain

the oxidation reactions to ensure the conversion of methane into combustion products.

The ANSYS Fluent simulation provided a complete account of the species concentrations at the exit. The mass fraction at the exit for carbon dioxide (CO_2) was 0.0338, which was typical of the presence of fully oxidized carbon as a complete combustion product. The mass fraction for carbon monoxide (CO) was 0.0499, which indicated the fact that the fuel had undergone incomplete combustion due to incomplete mixing or insufficient time for combustion. The mass fraction for water vapor (H_2O) was 0.0493, which was consistent with the combustion products for methane. The values indicate the complexity of the combustion process with both complete and incomplete combustion paths. One notable finding was the relatively high mass fraction of unburnt methane (CH_4) at the outlet, recorded at 0.2898. This unreacted methane was subsequently directed to the next component, the tailpipe, where additional combustion occurred. The detailed results are summarized in Table 2: Species Mass Fractions.

Table 2: Inlet and Outlet Species Mass Fractions

S.No	Species (Inlet & Outlet)	Mass Fractions
1.	CH_4 - in	1.0000
2.	O_2 - in	0.2329
3.	CH_4 - out	0.2898
4.	CO_2 - out	0.0338
5.	CO - out	0.0499
6.	H_2O - out	0.0493

5.1   Combustion Efficiency

The inlet conditions were defined with methane mass fraction 1.0000 and oxygen mass fraction 0.2329, supplying rich fuel supply and adequate oxygen for the combustion process. The outlet species concentrations were in terms of mass fraction, with it being 0.0338 for carbon dioxide (CO_2), 0.0499 for carbon monoxide (CO), and 0.2898 for unburnt methane (CH_4). The values above affirm the presence of complete as well as incomplete combustion products and conclude that fuel-air mixing and combustion behavior was not completely optimized.

The lower heating values (LHV) of methane (50MJ/kg) and carbon monoxide (10MJ/kg) were used to evaluate the energy content of the unburnt fuel,

which was found to be 35.4662MJ/kg. This is an indication of the impact of incomplete combustion on combustor performance. Increasing the combustion process to reduce the amounts of unburnt methane and CO would significantly enhance energy conversion efficiency.

In terms of combustion efficiency, the pre-chamber pulsejet combustor achieved 31.067%, showing a slight improvement compared to the 30% efficiency without the pre-chamber. The marginal increase suggests that the pre-chamber was assisting in enhanced fuel-air mixing and the stabilization of the combustion process to ensure more efficient fuel utilization. However, the relatively low efficiency suggests the need for further optimization of pre-chamber design and operation conditions for increased complete combustion and improved energy conversion efficiency.

VI. CONCLUSION AND FUTURE WORK

This project explored the design and performance of a pre-chamber pulsejet combustor, inspired by pre-chamber concepts commonly used in internal combustion engines. The pre-chamber was customized to fit the unique needs of the pulsejet combustor, with its volume set at 2.4% of the main chamber, aiming to boost combustion efficiency by improving fuel-air mixing.

The outlet mass fractions of CO_2, CO, H_2O, and unburnt CH_4 at 0.0338, 0.0499, 0.0493, and 0.2898, respectively. The relatively high amount of unburnt methane suggested that the fuel wasn't completely burned, pointing to challenges in mixing and combustion efficiency. The unburnt fuel also represented a significant loss of potential energy, indicating areas for improvement.

The combustion efficiency was found to be 31.067%, which is only slightly better than the 30% efficiency without the pre-chamber, which means 1.067% relatively increased. These results highlight the importance of further refining the pre-chamber design to make the combustor more efficient and less polluting, providing a solid starting point for future research.

To improve the performance of the pre-chamber pulsejet combustor, further research could focus on optimizing the pre-chamber geometry to enhance fuel-air mixing and improve combustion. Adjusting the

pre-chamber volume might also lead to higher combustion efficiency. Additionally, exploring advanced turbulence models and conducting experimental validation would provide deeper insights into the combustion dynamics, helping to refine the design for better efficiency.

VII. ACKNOWLEDGMENT

NOMENCLATURE

LAG	'Lavinia Aktyvatsia Gorenia (Ignition method)
URANS	Unsteady Reynolds-Averaged Navier Stokes
ρ	Density of the Fluid
u	Velocity
p	Pressure
μ	Viscosity
S	External Force
E	Energy per unit mass
k	Thermal Conductivity
T	Temperature

Φ	Viscosity Dissipation
F	Thrust Force
Dc	Combustor Diameter
Lc	Combustor Length
η_c	Combustion Efficiency
LHV	Lower Heating Value
Vm	Volume of the Main Combustor
Vp	Volume of the Pre-chamber
Dp	Diameter of the Pre-chamber
Lp	Length of the Pre-chamber

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