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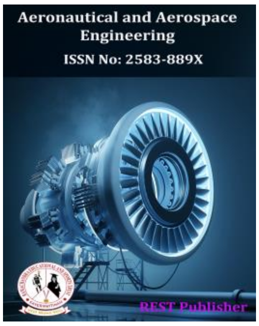

Flow Dynamics and Design Optimization of Rotating Detonation Engine

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Abstract: *Rotating Detonation Engines (RDEs) have attracted considerable attention because of their promise for improved efficiency and lower fuel usage compared to traditional propulsion systems. The performance of RDEs hinges on the complex interactions between combustion flow dynamics, the stability of detonation waves, and the design of the combustion chamber. This research offers a design and analysis of the essential physics behind detonative combustion, examining crucial factors like pressure distribution, wave movement, and the mixing of fuel and air. In addition, the study delves into practical design enhancements aimed at boosting wave stability, minimizing thermal stresses, and increasing the durability of materials. By connecting computational models with experimental results, this report illuminates the pathway towards making RDEs a practical option for aerospace and defence applications.*

Keywords: *RDE, Detonation, Injectors, Nozzle, Fuel & Oxidizer.*

1. INTRODUCTION

A Rotating Detonation Engine (RDE) is an advanced propulsion system that uses continuous detonation waves to generate thrust. Unlike regular engines, it burns fuel in shockwaves, making it more efficient. RDEs promise higher power, lower fuel consumption, and compact designs, making them ideal for future.

1.1 Purpose and Functionality:

1.1.1 Purpose Higher Efficiency:

Uses detonation waves for combustion, reducing fuel wastage.

- Compact Design: Smaller and lighter than conventional engines, ideal for space and defense applications.
- Increased Thrust: Generates more power with the same amount of fuel.
- Future-Ready Propulsion: A step towards next-gen hypersonic and reusable spaceflight.

1.1.2 Functionality

- Detonation-Based Combustion: Instead of slow burning, it creates high-speed shockwaves for thrust.
- Continuous Operation: Unlike pulse detonation engines, RDE maintains a steady combustion process.
- Works with Multiple Fuels: Can run on hydrogen, methane, or conventional jet fuels.
- Lower Heat Loss: More energy is converted into thrust, reducing engine cooling requirements.
- Scalability: Can be adapted for missiles, fighter jets, and even space propulsion.

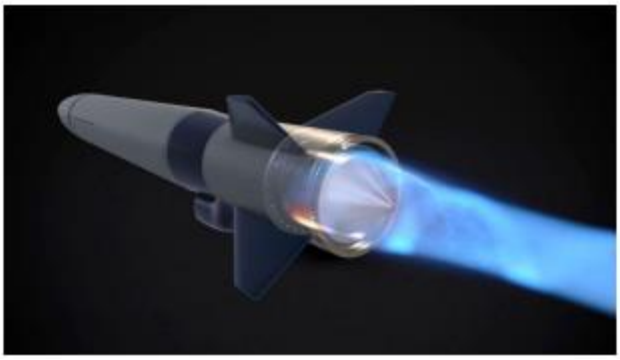

FIGURE 1. Conceptual RDE

2. DESIGN METHODOLOGY

2.1 Component Design

- Combustion Chamber: Designed with annular geometry for continuous detonation wave propagation.
- Injector Placement: Oxidizer Injector Angle: 20°–45°
- Nozzle Design: Aerospike nozzle to maintain flow efficiency at various altitudes.
- Material Selection: Titanium alloy or SS 316 based on high temperature and pressure tolerance.

2.2 Propulsion System Setup

- Fuel Type: Liquid hydrocarbon-based monopropellant or Petrol or Aviation Fuel
- Oxidizer: Liquid oxygen or equivalent.
- Injection System: Pintle injector used for optimized mixing and combustion stability & Spark Plug Igniter
- Control System: ESP32 microcontroller for flow regulation, ignition control, and real-time monitoring

2.3 Computational Modelling

- CFD Simulation Platform: ANSYS Fluent and/or Open FOAM. Fig 1. 1 Conceptual RDE
- Pre-processing: Geometry modeling and meshing with fine grid near injector and detonation regions.
- Boundary Conditions: Inlet: Specified pressure and fuel-air mixture ratio. Outlet: Pressure, Velocity Outlet Wall: Adiabatic/no-slip conditions. 2.4 Experimental Setup
- Engine Casing: Titanium/SS 316
- Sensors: Load Cell: For thrust measurement. K-Type Thermocouple: Exhaust temperature. BMP280/MPX5700: Chamber pressure.
- Control Systems: Remote ignition and fuel flow control via wireless ESP32-based system.
- Safety: Blast-proof suit and remote shutdown fail-safe included.

3. DESIGN & OPTIMIZATION

The design and optimization of a Rotating Detonation Engine (RDE) involve precise engineering of various subsystems to ensure efficient detonation propagation, optimal fuel-oxidizer mixing, thermal management, and structural integrity. This chapter elaborates on the design rationale, component-level analysis, material selection, injector design, and performance optimization techniques adopted in this study.

3.1 Design Objectives

- To achieve continuous and stable detonation within the combustion chamber.
- To ensure efficient atomization and mixing of fuel and oxidizer.
- To maintain thermal and structural stability of engine components.
- To design a compact and scalable engine suitable for aerospace applications.
- To enhance Specific Impulse (Isp), Thrust & thrust-toweight ratio (TWR)

3.2 Combustion Chamber

- Type: Annular chamber design.
- Function: Allows continuous propagation of detonation waves around the annular path.

- Dimensions: Length – 215 mm, Diameter – 110 mm.
- Cooling: Integrated cooling channels around the chamber walls.

3.3 Nozzle

- Type: Aerospike nozzle.
- Advantage: Efficient at varying altitudes, compact design.
- Function: Converts high-pressure detonation products into axial thrust.

FIGURE 2. RDE Design

4. SIMULATION ANALYSIS

Simulation Setup

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

Continuity Equation

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g}$$

Navier Stokes Equation

Performance Metrics

- Simulated Thrust Output: 850N
  - Specific Impulse (ISP): ~290 seconds
  - Combustion Efficiency: >98%
  - Detonation Behaviour: Simulation confirmed smooth, high-speed rotating waves with minimal instabilities.

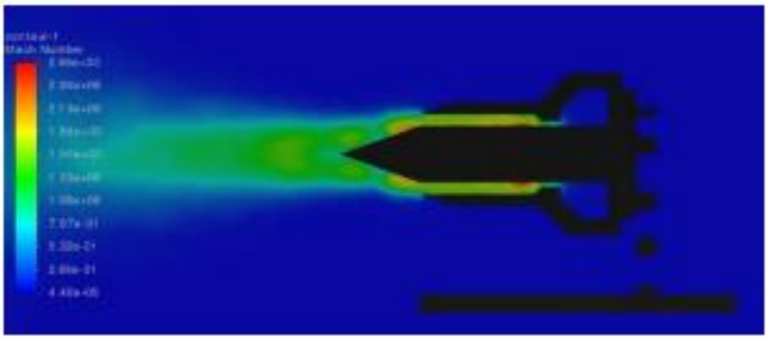

FIGURE 3. Velocity Contour

4 Testing & Optimization

4.1 Components

- Engine (Assembled)
- Fuel & Oxidizer Injector connectors
- One Way no return fuel valves
- Pneumatic Automatic Flow Control Valves (Programmable with Throttle Control Compatible)
- One way no return valves (for fuel & oxidizer tank)
- Pressure Tank (Fuel – pressure fed)
- Pressure Tank (Oxidizer – pressure fed)
- Stationary Support Structures (for the components)
- Load Cell Test Platform Integrated with Support Structures
- Temperature & Pressure Sensor integrated engine case
- Engine Run Test read-data tracking system with real time results output
- Remote Start integrated setup with fail safe system
- Blast Proof Suits • Safety Measurements Kit

5. APPLICATIONS

Aerospace Propulsion:

- RDEs offer higher efficiency and specific impulse compared to conventional combustion engines, making them attractive for next generation aircraft and space propulsion systems.
- They could reduce fuel consumption and emissions while increasing range and payload capacity for aircraft.

FIGURE 4.

Rocket Propulsion:

- In rocket engines, RDEs promise improved thrust-toweight ratios and potentially lower costs associated with manufacturing and operation.
- Their simplicity and potential for scaling make them viable for small satellite launch vehicles and larger orbital missions.

Power Generation:

- RDEs could be adapted for power generation, particularly in combined cycle power plants, where their high efficiency and fuel flexibility could offer advantages over traditional gas turbines.

Marine Propulsion:

- In naval applications, RDEs could power nextgeneration ships, offering improved efficiency and operational range.
- They may also reduce the environmental footprint of maritime operations by lowering emissions.

Industrial Applications:

- RDEs could find use in industrial applications requiring high-efficiency and reliable power generation, such as remote power stations or offshore platforms**.**

6. CONCLUSION

This project investigated the combustion flow dynamics and structural optimization of a Rotating Detonation Engine (RDE)— a next-generation propulsion system designed to outperform conventional rocket and jet engines. Through the integration of computational simulations, advanced injector design, and control system engineering, a functional and scalable RDE prototype was conceptualized and partially validated under simulated conditions.

- Introduced a simulation validated RDE model that can be scaled and tested physically.
- Developed a control architecture for real-time operation and fail-safe testing, integrating modern IoT tools.
- Proposed an optimized injector configuration specifically suited for small-scale experimental detonation engines.
- Provided a robust numerical framework for future students or researchers to replicate and expand upon detonation-based propulsion research.
- This paper demonstrates that Rotating Detonation Engines (RDEs) hold transformative potential for future aerospace propulsion.

By achieving efficient, compact, and high thrust combustion using detonation waves, RDEs can surpass traditional engines in terms of fuel efficiency, thrust to-weight ratio, and scalability. The success of this study lies in bridging theoretical detonation dynamics with practical engineering solutions through intelligent design, simulation, and system integration.

This work lays the groundwork for continued innovation in detonation-based propulsion, serving as a blueprint for both academic research and industrial prototyping.

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