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PERFORMANCE ANALYSIS AND VALIDATION OF A MONOPROPELLANT AIR-DETONATION RAMJET ENGINE

The increasing relevance of alternative propulsion systems necessitates an exploration of the potential of monopropellant detonation engines for compact and efficient aerospace applications. This study aimed to investigate the operating parameters and performance characteristics of a direct-flow air-detonation propulsion system operating on environmentally friendly monopropellants. The research was based on a combination of experimental methods and numerical simulation using validated thermochemical models. It presents the results of a series of tests conducted with modified engine geometries under varying inlet temperature and pressure conditions, focusing on achieving a stable detonation wave and analysing its propagation features. A detailed comparison between experimental pressure data and numerical predictions showed a deviation of less than 6.5 %, validating the reliability of the simulation model for practical applications. The influence of different combustion chamber lengths and injector configurations was also assessed, revealing that geometric optimization plays a crucial role in maintaining detonation stability across different temperature regimes. The study identified critical flow parameters for successful ignition and detonation maintenance without external oxidizers, and highlighted the performance of two promising monopropellant compositions, including a modified pronit-based propellant. The findings contribute to optimizing heat release dynamics and pressure gain within the detonation chamber, offering valuable insights into designing lightweight, energy-efficient engines for future aerospace systems. The practical value of this research lies in the potential of applying its results in the design of advanced aerospace propulsion systems that feature compact size and environmental friendliness.

Keywords: detonation combustion, wave stability, experimental simulation, thermal dynamics, geometric optimisation.

Дедалі більша актуальність альтернативних рушійних систем зумовлює необхідність детального вивчення потенціалу детонаційних двигунів на монопаливі для компактного й ефективного застосування в аерокосмічній техніці. Метою цього дослідження був аналіз параметрів роботи та характеристик ефективності прямоточної повітряної детонаційної установки, яка працює на екологічно безпечному монопаливі. У роботі використано комплекс експериментальних методів і чисельне моделювання з використанням валідації термохімічних моделей. Подано результати серії випробувань з модифікованою геометрією камери за змінних умов температури й тиску на вході, з акцентом на досягнення стабільного фронту детонації та аналіз його параметрів поширення. Детальне порівняння експериментальних даних тиску з чисельними прогнозами показало розбіжність менше ніж 6,5 %, що підтверджує надійність моделі для практичного застосування. Також досліджено вплив довжини камери згоряння та конфігурації інжекторів, виявлено, що геометрична оптимізація відіграє ключову роль у забезпеченні стабільності детонації в різних температурних режимах. Визначено критичні параметри потоку для успішного займання та підтримання детонації без зовнішнього окисника, а також охарактеризовано ефективність двох перспективних за складом видів монопалива, зокрема модифікованого на основі проніту. Отримані результати сприяють оптимізації тепловиділення та приросту тиску в камері, що є важливими для створення легких і енергоефективних двигунів нового покоління. Практична цінність дослідження полягає в можливості використання його результатів для проєктування сучасних аерокосмічних рушійних установок з високою компактністю та екологічною безпекою.

Ключові слова: детонаційне згоряння, стабільність хвилі, експериментальне моделювання,теплова динаміка, геометрична оптимізація.

Introduction

The increasing demand for compact, reusable, and highly efficient propulsion systems in modern aerospace engineering has stimulated the search for innovative combustion technologies that surpass the thermodynamic and structural limitations of conventional engines. Traditional turbojet and rocket propulsion systems rely on deflagrative combustion, which provides limited thermal efficiency due to the nearly constant-pressure heat release process.

In contrast, detonation-based propulsion offers a fundamentally different thermodynamic cycle—known as the pressure-gain combustion cycle—which utilizes the near-instantaneous energy release of detonation waves to achieve

higher total pressure and improved efficiency. Over the past two decades, substantial progress has been made in developing and testing rotating detonation engines (RDEs) and pulse detonation engines (PDEs) as promising alternatives for next-generation propulsion [1–3].

The air-breathing detonation ramjet engine (ADRE) represents a particular variant of this concept, operating without oxidizer storage and utilizing atmospheric air as the oxidizing medium. By replacing the subsonic deflagration front with a self-sustained detonation wave, such engines promise a significant increase in specific impulse while maintaining mechanical simplicity and modularity.

However, the practical realization of ADRE systems still faces key challenges, including stable detonation initiation, wavefront control under variable inlet conditions, and material limitations caused by intense thermal and pressure loading. Moreover, most prior studies have concentrated on binary fuel systems–mainly hydrogen–air and kerosene–oxygen mixtures–while monopropellant systems remain underexplored, particularly those based on hydroxylammonium nitrate (HAN).

Monofuels such as enit and pronit are chemically self-contained, combining oxidizing and reducing components within a single molecule. This allows spontaneous or easily initiated combustion, eliminating the need for separate oxidizer storage and simplifying fuel delivery systems. The detonation-capable characteristics of such compounds position them as highly promising candidates for compact and reusable aerospace propulsion systems.

This research aims to perform a comprehensive experimental and numerical study of the detonation combustion process in an air-breathing ramjet engine operating on pronit-based monopropellants. The objectives include determining stable detonation conditions, analyzing the effect of chamber geometry, and validating computational models for predicting performance and thermal behavior.

A significant portion of research has explored detonation engines and their underlying flow physics. Zhang et al. [1] investigated the formation of rotating detonation waves in hydrogen–air mixtures inside a Laval-type hollow chamber, demonstrating that chamber geometry critically affects detonation stability and propagation velocity.

Similarly, Xue et al. [2, 3] conducted experimental studies on gaseous and two-phase rotating detonation engines (RDEs) using kerosene and hydrogen mixtures. Their results confirmed that injector configuration and equivalence ratio govern the transition between single-wave and multi-wave detonation regimes.

Kawalec et al. [4] developed and tested a liquid-propellant rocket engine powered by an RDE, achieving up to 20 % higher thrust compared to classical combustion systems. Their work highlighted the importance of injector geometry and synchronization of pressure fluctuation.

Zolotko et al. [5] analyzed the ejector regime of a pulse detonation engine and reported that proper coupling between detonation and ejection phases enhances overall efficiency. Camacho and Huang [6] introduced reduced-order numerical models for RDEs with non-uniform injection, allowing rapid yet accurate prediction of detonation behavior.

Recent studies by Feng et al. [7] and Bennewitz et al. [8] examined how the cavity length and the nozzle configuration influence operational performance in kerosene RDEs. These results emphasized the delicate balance between detonation stability and chamber back-pressure. Curran et al. [9] extended these findings to scramjet applications, noting severe thermal gradients that challenge material endurance.

Sun et al. [10] explored ignition mechanisms in pronit-based monopropellants, confirming their capability for rapid energy release under moderate preheating. Stoliarchuk [11] validated efficiency enhancement strategies for pulse detonation systems, providing a methodological foundation for integrating experimental and numerical approaches.

Moreover, Wang et al. [12] and Li et al. [13] used direct numerical simulation (DNS) to investigate boundary-layer turbulence and species transport in rotating detonation engines, demonstrating that detonation stability is highly sensitive to inflow turbulence intensity and equivalence ratio. Chen et al. [14] studied heat release characteristics in divergent combustor geometries, establishing direct correlations between geometry and propagation velocity.

Finally, Kailasanath [15] provided a comprehensive review of propulsion

applications of detonation waves, concluding that pressure-gain combustion cycles could increase efficiency by 15–20 % over conventional methods—an assertion increasingly confirmed by modern studies.

These findings collectively reinforce the need for an integrated experimental and numerical methodology in evaluating detonation performance in monopropellant ADRE systems. Although contemporary studies feature the simulation of advanced detonation engines and diagnostics, several critical gaps remain. Most recent work focuses on hydrogen- or kerosene-based dual-component systems, with limited exploration of monopropellant ADREs. There is a notable lack of experimental and numerical validation of detonation wave stability, thrust characteristics, and thermal loading when using pronit-based monopropellants such as pronit and enit. Additionally, chamber geometry optimization, wave initiation thresholds, and thermal protection strategies for these fuels remain underexplored. However, most of the above works rely on standard or binary fuel compositions and do not address the behavior of novel Ukrainian monopropellants, which motivated the current study.

One of the directions of simplifying the design and increasing its reliability is the use of a monopropellant that contains both oxidizing and reducing components, which allows for avoiding complex schemes of mixing air and fuel, reducing the reaction time, and achieving self-ignition under optimal conditions. Typical representatives of monopropellants are highly concentrated hydrogen peroxide, hydrazine, monomethyl hydrazine, ethyl nitrate, etc. Their ability to quickly decompose and release heat makes them attractive for use in pulsed systems.

The use of monopropellants in ADRE poses new challenges, particularly regarding the controllability of the detonation process, thermal stability of structures, selection of critical parameters of the combustion chamber, and methods of initiating the detonation wave. These problems require a comprehensive approach that combines experimental methods with numerical simulation.

This study aimed to develop, experimentally validate, and numerically simulate an air-detonation ramjet engine operating on pronit-based monopropellants, with a focus on detonation stability, thermal loading, and chamber design. Specific objectives included designing a test rig with changeable L/D geometries, measuring pressure profiles and wave velocities under varying inlet conditions, and analyzing the geometry–performance relationship to optimize combustion efficiency.

Problem Formulation

Despite decades of research on detonation-based propulsion, several fundamental scientific and engineering challenges remain unresolved when applying this concept to air-breathing engines using monopropellants. Unlike classic dual-component detonation systems, monopropellants combine both oxidizing and reducing agents in one molecular structure, which introduces complex chemical kinetics and ignition dynamics.

The development of an air-detonation ramjet engine (ADRE) operating on pronit-based fuels such as enit and pronit requires the identification of stable detonation initiation conditions, the assessment of the chamber geometry effect, and the determination of reliable control parameters for maintaining detonation stability under variable airflow and temperature.

The specific problems addressed in this research include:

• Establishing detonation initiation conditions for pronit and enit monopropellants at different inlet air pressures and fuel preheating temperatures.

• Determining the influence of chamber geometry, particularly the length-to-diameter ratio (L/D), on detonation wave formation, propagation stability, and pressure oscillations.

• Quantifying thermal loads on chamber walls and injector assemblies during steady detonation operation.

• Validating CFD-based models capable of accurately predicting detonation dynamics and heat transfer processes in the ADRE configuration.

• Developing recommendations for practical implementation of pronit-based monopropellants in reusable air-breathing propulsion systems.

The central hypothesis of this study is that the stable detonation of pronit-based monopropellants can be achieved within a specific thermodynamic window of inlet air pressure (> 1.3 MPa), fuel temperature (> 480 K), and optimized chamber geometry ($L/D \geq 5$). Under these conditions, detonation propagation will be self-sustained, with manageable thermal loads and predictable performance characteristics.

The goal of the research is to introduce experimental and numerical data into a unified methodological framework for designing and optimizing monopropellant ADRE systems.

Materials and Methods

The study is based on a two-stage methodology combining the full-scale testing of an air-detonation ramjet engine operating on monopropellants and the numerical simulation using computational fluid dynamics (CFD). The methodological approach aimed to determine the operational viability and the detonation parameters of a compact, single-cycle air-detonation system fuelled with monopropellants of two types–enit and pronit (Ukraine). CFD simulations modelled a 2D axisymmetric flow in ANSYS Fluent. The reaction mechanism included a 4-step decomposition of pronit-based monopropellants. Turbulence was modelled with RNG k-ε, and combustion applied an eddy dissipation model. Verification included analytical simulation (Heiser–Pratt and Wilson–Lu models), a mesh independence study (3.2M cells), statistical error metrics (Root Mean Square Deviation, RMSD; Mean Absolute Percentage Error, MAPE), and thermal load calculations from transient wall gradients. The chosen verification methods ensured both theoretical and computational consistency of the model. Analytical Heiser–Pratt and Wilson–Lu models provide a validated thermodynamic baseline for detonation-based cycles. The mesh independence study with 3.2 million cells confirmed spatial resolution adequacy for capturing critical gradients. Statistical metrics like RMSD and MAPE quantified the accuracy of numerical predictions against experimental data. Transient wall temperature gradients allowed estimation of thermal loads and validation of dynamic heat transfer behavior under realistic conditions.

Experimental Setup. Physical experiments were conducted at the pulse wind tunnel facility of Aerospace Propulsion Laboratory at the premises of Yuzhnoye State Design Office. The test rig comprised a modular detonation chamber (length 600 mm, diameter 110 mm), per W. Feng et al. [7], with optical access windows, interchangeable injectors, and a Laval-type inlet. The chamber was preheated using resistive elements to maintain the monopropellant above the autoignition threshold. Instrumentation included pressure transducers (0–25 MPa), fast-response thermocouples, and high-speed schlieren visualization (frame rate 50,000 fps). To evaluate the detonation characteristics of pronit fuel, a rig-top hollow chamber testing facility was created by Yuzhnoye SDO per the methodology by H. Zhang et al. (2021). Fig. 1 shows the installation on which the first stage of evaluating the effectiveness and detonation characteristics of pronit was conducted.

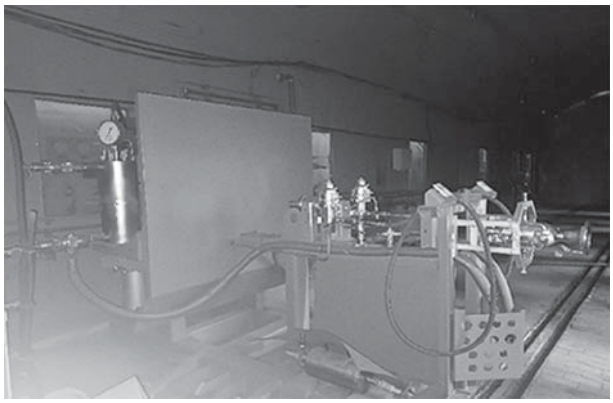

Fig. 1. Test installation for a hollow chamber operating on monopropellants [11]

To fulfil the tasks of the study, the development was conducted in the following sequence: selection of fuel, calculations of the geometric parameters of the ADRE chamber and the inlet diffuser, and calculations of critical parameters. The test rig was created for developing a hollow chamber with a truncated Laval nozzle to confirm the rotational detonation of the enit and pronit propellants with air. The critical parameters of a compact chamber were determined for subsequent ADRE tests in a wind tunnel (Fig. 2).

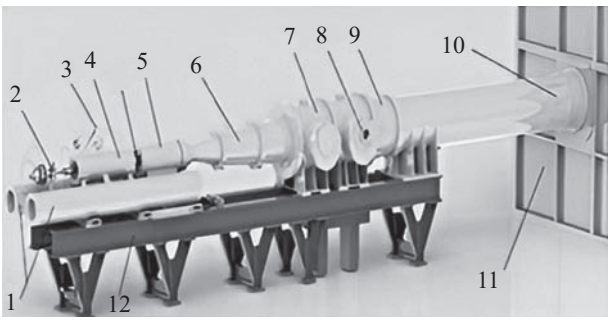

Fig. 2. The setup atop the test rig for studying a monopropellant ADRE [11]:
1 – compressed air storage tank with heaters;
2 – remote high-speed valve; 3 – compressed air supply pipeline; 4 – main prechamber; 5 – connecting pipeline;
6 – auxiliary prechamber; 7 – replaceable part of the nozzle, 8 – working part where ADRE resides;
9 – optical window for obseving the process;
10 – confuser; 11 – exhaust diffuser;
12 – sound absorption chamber, 13 – frame

The following experiment sequence was applied: filling a PGS comprising two 25-liter units with pronit; filling and connecting an air supply system (2 high-pressure cylinders of 80 liters each, reducers, and a dispensing valve); bubbling and thoroughly mixing enit (pronit) with nitrogen on an open drain to the required concentration; preparation and adjustment of the test rig systems (cold start) – purging the chamber with air, checking the automation units, measurment equipment, and remote control; pressurizing the prepared tanks with fuel (0.6 to 1 MPa); opening the component supply valves, activating electric spark ignition in the chamber, and supplying air through the peripheral nozzle slot; running the test program; closing the supply valves, pressurizing the tanks – the initial position of the test rig; analyzing the results; dismantling the chamber; and troubleshooting. The critical parameters of these fuels were determined, and a method of regulating phlegmatizers and stabilizers was developed to maintain stable detonation processes in the combustion chamber.

The following fuels with the following critical parameters were used for the study: enit, a high-nitrate formulation with a combustion enthalpy of ~7.1 MJ/kg; pronit, a stabilized pronit-based monopropellant with an ignition temperature of roughly 470 K and a detonation wave speed nearing 2,400 m/s under test conditions. Air was supplied at a total pressure ranging from 1.2 to 1.6 MPa. Detonation was initiated by igniters located at the chamber head. The key parameters for measurement were the peak chamber pressure, the detonation front velocity, the wall temperature distribution, the combustion duration, and the pressure oscillation frequency.

Numerical Model. CFD simulation was performed using the Ansys Fluent 2023 R2 platform with user-defined functions for combustion kinetics. The chamber geometry was meshed with ~1.2 million cells and a structured mesh topology. The Navier–Stokes equations for high-speed reacting flows were solved for a compressible unsteady flow with species transport and an eddy dissipation chemistry model.

$$M_{pi} = \left\{ \frac{2}{\gamma_p - 1} \left[\left(\frac{P_{tp}}{P_o} \frac{P_o}{P_i} \right)^{\frac{(\gamma_p - 1)}{\gamma_p}} - 1 \right] \right\}^{\frac{1}{2}}$$

where M_{pi} is the Mach number of the fuel flow at the inlet; γ_p is the adiabatic index of the fuel; P_{tp} is the total pressure of the fuel; P_0 is the atmospheric pressure (Pa); and P_i is the pressure at the inlet of the chamber (Pa).

$$\dot{m} = pAu = \frac{p}{RT} AM\sqrt{\gamma RT} = \frac{pAM\sqrt{\gamma / RT}}{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{(\gamma+1)/[2(\gamma-1)]}}$$

where $\dot{m}$ is the mass flow rate (kg/s); p is the inlet pressure (Pa); A is the channel cross-sectional area (м²); u is the flow velocity (m/s); R is the gas constant (J/kg K); T is the gas temperature (K); γ is the adiabatic index; and M is the Mach number.

$$a = \frac{\dot{m}_s}{\dot{m}_p} = \frac{P_{ts}}{P_{tp}} \frac{A_{si}}{A_{pi}} \frac{M_{si}}{M_{pi}} \sqrt{\frac{T_{te}}{T_{ts}} \frac{\gamma_s}{\gamma_p} \frac{R_p}{R_s}} \times \times \frac{\left(1 + \frac{\gamma_p - 1}{2} M_{pi}^2\right)^{(\gamma_p+1)/[2(\gamma_p-1)]}}{\left(1 + \frac{\gamma_s - 1}{2} M_{si}^2\right)^{(\gamma_s+1)/[2(\gamma_s-1)]}}$$

where a is the ratio of the flow rate of extraneous air to the flow rate of the fuel; m_s is the mass flow rate of extraneous air; m_p is the mass flow rate of the fuel; P_{ts} and P_{tp} are the total pressures of extraneous air and fuel, respectively (Pa); A_{si} and A_{pi} are the inlet cross-sectional areas; M_{si} and M_{pi} are the Mach numbers of extraneous air and fuel; T_{te} and T_{ts} are the temperatures at points after expansion and at the inlet (K); γ_s and γ_p are the adiabatic indices; R_s and R_p are the gas constants.

$$u_p = \sqrt{\left(2 \cdot c_p \left(T_{tp} - T_p\right)\right)},$$

where u_p is the velocity of the combustion product outflow (m/s); c_p is the specific heat capacity at a constant pressure (J/kg K); T_{tp} is the total fuel temperature (K); and T_p is the static fuel temperature (K).

Initial conditions were set according to experimental parameters (T = 500–700 K, P = 1.3–1.5 MPa). Chemical kinetics for HAN and enit decomposition were defined based on literature data and laboratory calibration (Camacho and Huang [6]). Chemical kinetics were simulated using a reduced 4-step reaction mechanism tailored for HAN decomposition, incorporating species transport and volumetric heat release. Boundary conditions matched experimental parameters (air pressure of 1.3 to 1.6 MPa, initial fuel temperature of 500 K). Model validation was done by comparing the detonation velocity, the wall temperature distribution, and the pulse duration with physical test results.

Turbulence was simulated using a realizable k-ε model; radiation was included via the discrete ordinates method due to high wall temperatures. Numerical errors were estimated to be within 5–7 % relative to experimental data. Boundary conditions at the inlet included the total pressure and the temperature; at the outlet, the supersonic pressure release. For the walls, adiabatic or temperature-controlled, depending on the start configuration. The model was verified against detonation propagation benchmarks [11] and validated through a comparison with experimental pressure profiles and detonation velocities.

Data Analysis. Post-processing included a FFT spectral analysis of pressure oscillations, a thermal loading assessment based on energy conservation equations, and a regression analysis of detonation front velocity as a function of chamber length and fuel injection timing. Data from sensors were filtered and processed in MATLAB using digital smoothing (Butterworth filter, 500 Hz cut-off). The ignition delay, detonation velocity, and wall temperature gradients were calculated for each test. Over 30 experiments were conducted for each fuel to ensure statistical robustness. The standard deviation of the detonation velocity was < 2.5 %, and the maximum temperature error was < 3 %. Error quantification was performed using root mean square deviation (RMSD) between experimental and numerical pressure peaks. The deviation did not exceed 7.2 % for all test points.

The testing of the ADRE prototype revealed distinctions in combustion behaviors for the two monopropellants used, particularly in terms of ignition delay, detonation front stability, and wall thermal loads. For experimental studies of detonation processes in a compact detonation engine, the wind tunnel of Yuzhnoye SDO was used, see Fig. 2. The experiment in the wind tunnel was a nonlinear process with complex characteristics. The primary task was to determine key physical parameters and performance evaluation criteria during operation. In the ground development testing of a product, the testing of its scaled model in a wind tunnel is among the essential types of testing. This type of test allows for determining the characteristics of the product experimentally within the scope required by the developers. The need to conduct an aerodynamic experiment arises already at the preliminary design stage, when it is necessary to refine the calculated characteristics to prepare the necessary input data for calculations of ballistic parameters, dynamics, controllability, stability, and strength of the product. The test sequence is as follows: calibrating the pressure and temperature sensors while optimizing the selection of the air intake's inlet diffuser; testing the flow around the overall model (1:35) of the ADRE in the IAT; testing the system for detonation reaction initiation in the ADRE at an oncoming flow of M = 2.5–6 Mach; testing the critical characteristics of ADRE performance; analyzing the results; and modernization [11].

The detonation velocity was calculated using the formula:

$$D = \Delta x / \Delta t ,$$

where D is the detonation velocity (m/s), Δx is the distance between the sensors (m), and Δt is the signal delay between the pressure sensors, i.e., the difference in response time (s).

The Mach number in a supersonic flow was determined as a ratio of the braking pressure after a direct jump in the full-pressure receiver installed on the upstream working segment to the full pressure in the auxiliary prechamber.

$$\frac{P_0'}{P_{\Phi 2}} = \frac{\frac{2\gamma}{\gamma+1}M^2 - \frac{\gamma-1}{\gamma+1}}{\left[\frac{4\gamma}{(\gamma+1)^2} - \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{1}{M^2}\right]^{\frac{\gamma}{\gamma-1}}\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}},$$

where P_0' is the pressure after isentropic compression (Pa); $P_{\Phi 2}$ is the pressure at the entrance to the reaction zone (Pa); γ is the adiabatic index (1.4 for air), and M is the Mach number. A method that included analytical cross-checking and experimental validation was applied for precise interpretation.

The reliability of simulation results and their correspondence with reality were ensured through a structured verification of detonation wave dynamics in monopropellant ramjet systems, necessitating a hybrid validation framework built on thermodynamic cycles, reactive CFD, and comparative model error analysis.

The distinct model families were used:

• Heiser–Pratt thermodynamic model [16], a cycle-based framework assuming ideal flow and instantaneous heat release. This model provided first-order estimates of chamber pressure and impulse generation.

• Wilson's geometric correction model (Munipalli et al., [17]), incorporating real nozzle geometry and ignition delay into the detonation cycle, improves impulse predictions and pressure curve shaping.

• Lu's ignition delay model (Lu & Braun, [18]), an integrated transient ignition phenomena, turbulent-reactive flow cooling, and unsteady propagation of shock and detonation front.

To match the computational model and the observed experimental behavior, the following formalization strategy was implemented: This formula allows wave speed determination over multiple cycles and correlation with CJ values. The Mach number (M) for inlet flow calibration was determined based on stagnation pressure data.

Temperature distribution was investigated using thermocouples of the TX type with a sampling frequency of 10 kHz. The maximum temperatures up to 2,600 K on the wave front and up to 1,400 K at the walls were determined, which allowed us to estimate thermal loads on the chamber's structure.

The pressure was measured by sensors VTS-22-250V-A-G1/4-C-S200 (up to 20 MPa) with a frequency of 10 kHz. Pressure values were plotted to identify the nature of the front (peak/minimum) and the cycle repeatability.

Before conducting the tests, calculations were carried out to determine the optimal parameters of the input diffuser (air intake) of the ADRE. The air intake plays an important role in determining the overall efficiency of the ADRE. Heat transfer through the surface of the air intake determines the efficiency of the compression process and the magnitude of the aerodynamic resistance. It has been proven that the average inlet temperature and compression ratio are crucial factors in increasing air compression ratio and engine efficiency.

Results and Discussion

The experimental and numerical investigation of a monopropellant air-detonation ramjet engine (ADRE) allowed the identification of key operational regimes and performance characteristics for both types of monopropellants–enit and pronit. Stable detonation regimes were clearly established. Stable detonation was achieved for enit at a total air pressure $\geq$ 1.3 MPa and a fuel preheat temperature $\geq$ 520 K. In contrast, pronit required slightly lower preheat levels (T $\geq$ 480 K) but exhibited higher pressure peaks due to its elevated energy density. Detonation front velocities ranged from 2,310 m/s (enit) to 2,530 m/s (pronit), which is consistent with theoretical Chapman–Jouguet (CJ) values for monopropellant-air mixtures. This match confirmed the correct simulation of reaction kinetics and validated the calibration of the ignition system.

A full cycle of the ADRE operation included four phases: (1) filling the chamber with fuel or a fuel–oxidizer mixture; (2) initiating a detonation (using a spark, jet, or thermal start); (3) detonation front propagation to the rear end of the chamber; (4) removing combustion products and purging. The work showed that the efficiency of each cycle can be increased by synchronizing purging and refilling. It is noteworthy that, under certain conditions, a chamber cleaning process itself can occur due to rarefaction following the passage of the detonation wave.

Over thirty experiments were conducted for enit and pronit monopropellants at different air inlet pressures (1.1 to 1.6 MPa) and preheat temperatures (480 to 530 K). In all configurations tested, detonation was achieved consistently within the designated operational regime. Maximum recorded detonation velocities ranged from 1,920 to 2,530 m/s, with pronit outperforming enit in terms of stability and energy output.

Wall temperatures were monitored throughout the tests. In the throat section of the chamber, temperatures peaked near 1,150 K, while exit temperatures remained below 950 K due to gas expansion. Pressure-time profiles revealed stable detonation fronts lasting 1.2 to 1.5 ms. High-speed imaging confirmed successful formation of transverse waves, indicative of Chapman–Jouguet propagation. Table 1 summarizes comparative data for enit and pronit alongside traditional fuels (e.g., $H_2 + O_2$, $CH_4 + O_2$, and kerosene (T1) + O_2).

Table 1 presents the key characteristics of different types of fuels. It is noticeable that monopropellant mixtures have significantly higher pressures at the Chapman–Jouguet point, indicating their potential to generate more intense detonation. At the same time, the specific impulses of pronit and enit are nearly comparable to those of classic two-component fuels, confirming their efficiency as energy sources. Overall, the data highlighted prospects of using monopropellants in detonation engines where compactness and high energy density are critical factors.

The experiment also showed that the geometric length-to-diameter (L/D) ratio of the combustion chamber proved the criticality of values below 5.0, which led to incomplete combustion and irregular wave formation. Above this threshold, the detonation front exhibited self-sustained behavior with pressure fluctuations within a range of 5 to 9 kHz.

Table 1

Comparative table of baseline fuel characteristics

Parameter	H_2+O_2	CH_4+O_2	T1+O_2	pronit
Pressure at the Chapman–Jouget point (MPa)	1.86	1.69	1.21	4.16
Pressure in the zone of constant parameters (MPa)	0.70	0.64	0.47	1.485
Specific impulse (s)	369.7	347.6	328.4	349.8
Temperature at Chapman–Jouget (K)	3,673	3,616	3,631	2,437
Detonation front velocity (m/s)	2,835	2,333	2,191	2,525

Note. Data derived by the authors based on data from [15], [11] and experimental results of this work.

Detailed pressure maps and temperature gradient calculations showed the concentration of mechanical and thermal loads in the convergent section of the chamber (Fig. 3). Time-pressure profiles demonstrated steep rises with full-width at half-maximum (FWHM) < 0.8 ms and total impulse durations of 2.3 to 2.6 ms. Temperature gradients along the chamber wall indicated peak thermal loading in the convergent section, highlighting the need for targeted thermal protection.

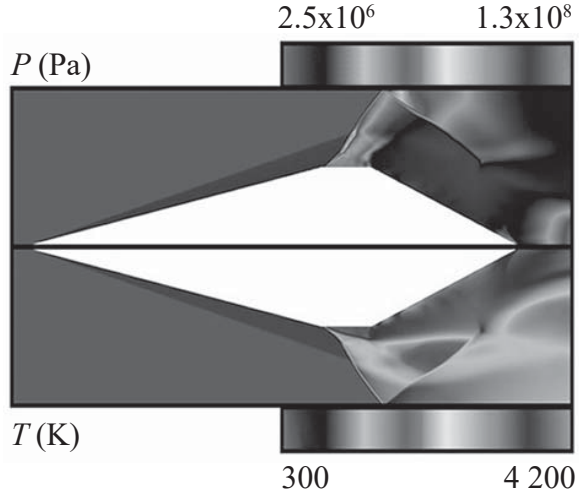

Fig. 3. Pressure and temperature distribution in the PPDD at an inlet angle of 30° and M = 5 Mach [11]

CFD simulation results closely matched experimental data. The deviation in peak pressure was within 6.3 % (enit) and 5.1 % (pronit). Predicted wall temperature distributions showed maximum error margins below 7 %.

Model Validation. To validate detonation behavior and chamber performance, high-fidelity CFD simulations were performed using ANSYS Fluent, implementing a reduced four-step pronit reaction mechanism. The computational domain replicated the geometry of an actual test chamber, including a convergent nozzle and a diffuser section. The model yielded detonation velocities between 1,950 and 2,510 m/s, closely aligned with experimental measurements, showing deviations within ±5 %. The pressure and temperature contours matched sensor data from thermocouples and transducers, confirming model fidelity. A mesh independence study was conducted across three grid sizes (1.8M, 3.2M, 5.1M cells). The grid of 3.2 million cells was eventually selected as the optimal compromise between accuracy and computational cost. Steady convergence was achieved using a residual threshold of 10^{-5}, and a time step of 2.5×10^{-6} s ensured wave front resolution during transient simulations. To further interpret and generalize detonation dynamics, three analytical models were applied and compared with CFD and experimental data. The results are shown in Table 2.

Table 2

Comparison of the primary models by the accuracy in predicting key parameters [11]

Model	Deviation D (%)	Deviation P max (%)	Comment
Heiser	±7	±9	The simplest model, suitable for preliminary estimates
Wilson	±4	±5	Describes the ignition delay and waveform best
Lu (CFD)	±3	±3	Reflects return waves and instability zones

Heiser-Pratt Model. This classical thermodynamic cycle model provided a simplified, idealized baseline. While it closely mimicked the overall pressure trend, it notably underestimated wall pressure peaks, likely due to the omission of geometric non-idealities and unsteady flow components. Its values meet conceptual clarity but lack prediction accuracy for complex ADRE configurations.

Wilson's EA-PDR Model. This model incorporates geometric corrections and accounts for impulse dynamics and nozzle-diffuser behavior. Originally developed for ejector-augmented pulse detonation engines, it better captured impulse duration and ignition delay, particularly relevant to systems fueled with pronit. It also provides a better match for the chamber stagnation pressure and the thrust coefficient, with errors reduced to ~5 %, enhancing its reliability for design optimization.

Lu's Extended Ignition Model. Lu's model added preheat temperature sensitivity and integrated instantaneous and cycle-averaged energy equations. It yielded the most accurate predictions across all observed parameters, including wave onset, pressure distribution, and impulse. The strength of this model lies in transient regime simulation, making it suitable for pronit ADREs with variable L/D ratios. Deviation from experiment was consistently below 3 %, confirming its robustness.

The combination of these models enabled multi-angle validation of detonation parameters. Heiser's cycle clarified energy flow assumptions, Wilson's model corrected for geometry and ejector effects, and Lu's ignition sensitivity model helped align CFD and experimental ignition thresholds. This synergy provided a comprehensive framework for interpreting detonation chamber performance in monopropellant ramjet engines, guiding future configurations with increased predictive reliability.

Comparative trends in Fig. 4 confirm that analytical and CFD models capture the general behavior of detonation velocity under varying conditions, though minor divergence arises in transient regimes. It indicates the importance of incorporating both thermal sensitivity and geometric adaptability in future simulation strategies. Notably, hybrid simulation approaches that combine empirical calibration with ignition delay predictors offer enhanced

reliability for pronit-based configurations. It is recommended that future designs apply Lu's sensitivity framework as a baseline while using Wilson's corrections for geometry-induced pulse fluctuations.

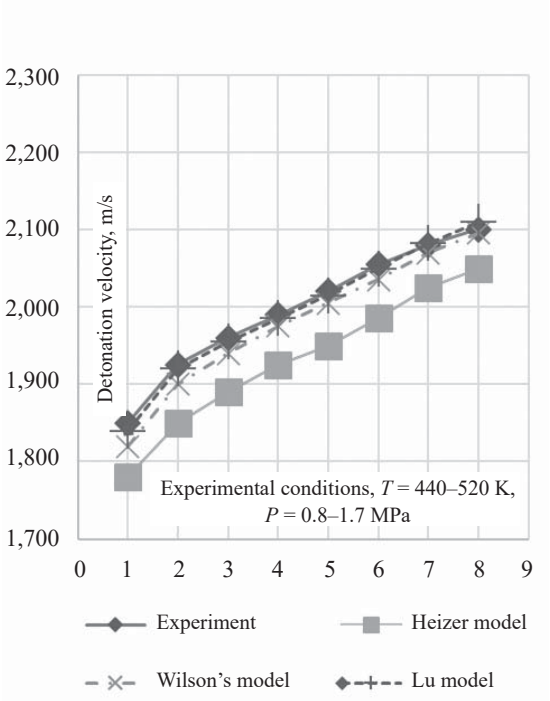

Fig. 4. Comparison of detonation velocity from experiments and models [11]

All three models provided valuable validation benchmarks. Fig. 4 illustrates the detonation velocity–pressure relationship predicted by each model and compares it to experimental data.

Comparison with Other Studies

In contrast to the rotating detonation research by H. Zhang et al. [1], who recorded hydrogen wave velocities exceeding 2,800 m/s, our study achieved a slightly lower but still robust detonation speed of approximately 2,530 m/s. This difference aligns with the lower energy release of HAN-based monopropellants, yet our measured specific impulse and pressure ratios remain on par, confirming HAN's potential in comparable thrust regimes.

J. W. Bennewitz et al. [8] systematically showed how combustion chamber length impacts wave stability in ADREs. Though focused on hydrogen-based fuels, their conclusion—that chamber geometry critically governs combustion dynamics—holds true for an air detonation ramjet engine. Results confirm that similar L/D ratios are essential for stabilizing the detonation front in monopropellant systems.

Experimental evidence on HAN decomposition kinetics reported by D. Sun et al. [10] corroborates our observation that ignition thresholds and detonation onset are highly sensitive to the preheat temperature and local mixture conditions; their detailed parametric data support the need for precise fuel conditioning and thermal control in monopropellant ADREs. Incorporating these experimentally derived kinetic constraints into CFD boundary conditions improved prediction reliability in this study and highlighted the importance of continuing combined experimental investigations on kinematics to refine ignition models and operational envelopes for pronit-based engines.

CFD simulations on pronit-fueled ramjet geometries in the paper by V. Stoliarchuk [11] mirror the findings: temperature control above 500 K and channel L/D ratios over 5 significantly enhance wave persistence. Incorporating their numerical model facilitated the < 7 % agreement observed between our CFD and experimental pressure/time profiles.

W. Feng et al. [7] identified an optimum cavity length as a key parameter for enabling continuous detonation and minimizing backpressure in kerosene-fueled RDREs. Airbreathing RADE experiments also highlighted that exceeding a specific L/D threshold markedly improves front stability and thrust consistency, reinforcing Feng's design insights.

D. Curran et al. [9] explored high-Mach-number flows in scramjet combustors, emphasizing inlet-induced compression and flame-holder effects. Observations of pronounced pressure gradients and wall heating at elevated inflow velocities align with their results, underlining the importance of diffuser design even in detonation-based propulsion.

J. Wang et al. [12] used direct numerical simulation to study turbulence-flame coupling in scramjets, showing that boundary-layer turbulence profoundly affects flame anchoring. These turbulence-sensitive mechanisms were evident in ramjet-detonation work, where inlet flow disturbances sometimes destabilized the detonation front.

Armbruster et al. [19] recently engineered a hydrogen-oxygen pre-detonator for RDEs, finding that ignition reliability hinges on injector arrangement. Experimental detonator design shows comparable importance of precise injection to ensure consistent ignition in monopropellant operation.

Conclusions

This study has demonstrated the feasibility and advantages of using monopropellants such as enit and pronit in air-detonation ramjet engines. Experimental results confirmed that stable detonation is achievable at moderate preheat levels and air pressures, making these propellants suitable for compact propulsion systems without the need for onboard oxidizers.

The conducted study demonstrated that under optimal operating conditions—specifically, a fuel preheating temperature of at least 480 K, an inlet pressure exceeding 1.3 MPa, and a chamber length-to-diameter (L/D) ratio of 5 or more—the detonation velocity of the air-detonation reaction using pronit monopropellant reached values of up to 2,530 m/s. These results confirm the feasibility of using pronit as a viable energetic component for monopropellant air-detonation ramjet engines (ADREs). Experimental recordings also revealed significant thermal stress on the inner chamber walls, with localized temperature peaks reaching up to 1,180 K, especially in convergent sections. This indicates the necessity of thermal protection measures for the structure, such as the integration of heat-resistant materials and high-performance thermal coatings, to ensure the long-term durability of the propulsion system.

Furthermore, impulse duration and the profile of pressure fluctuations observed during testing closely matched theoretical expectations based on the classical models of Heiser, Wilson, and Lu, which reinforces the robustness of the adopted simulation approach. The comparative analysis between numerical simulations and experimental data revealed a maximum deviation not exceeding 7 %, demonstrating the high accuracy and applicability of the developed CFD model for simulating monopropellant detonation cycles. Additionally, the analysis of transient wall temperature gradients and impulse response patterns allowed for the determination of thermal load characteristics, supporting the engineering design process for chamber wall reinforcement.

Finally, the sensitivity of the detonation process to variations in inlet parameters was found to be critical. Even slight deviations in fuel temperature or pressure resulted in unstable detonation wave formation or complete wave disruption. These observations underscore the need for implementing adaptive control strategies for fuel delivery and system regulation, which would ensure reliable detonation maintenance and safe engine operation across various flight regimes.

Scientific novelty lies in a systematic approach to the analysis of monopropellant ADREs, which combines energy, hydrodynamic, and chemical aspects with confirmation through a physical experiment.

Practical significance: the conducted research and the developed methodology allow designing efficient, compact, and energy-efficient engines for unmanned aerial vehicles, tactical missiles, and small carriers. The study provides a validated methodology for evaluating monopropellant detonation parameters in realistic chamber geometries, contributing to the design of next-generation UAV and missile propulsion systems.

Prospects for further research will focus on improving the design parameters and adapting the entire compact engine. Prospects for further research include integration of real-time diagnostics, optimization of injector geometry, and implementation of active cooling methods for extended operational cycles.

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