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Analytical Assessment of Blended Fuels for Pulse Detonation Engine Performance

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ABSTRACT

A pulse detonation engine (PDE) is possible to be a next-generation high-performance propulsion system in aerospace-related applications. To generate power or thrust, PDE uses repeated detonations. The current study evaluates the PDE performance with alternative and blended fuels in the Zeldovich–von Neumann–Doring (ZND) model. Parameters such as temperature ratio, pressure ratio, detonation velocity, and specific impulse were determined analytically for the fuels. The computed detonation parameters and specific impulse were compared with those available in NASA's open-source program, Chemical Equilibrium with Applications (CEA), to ensure the results' sufficient validity. It was found that the highest specific impulse was achieved with hydrogen at an equivalence ratio of 1. Analytical values of all the parameters were in an acceptable range as defined by NASA CEA. As compared to pure butane and propane, their blends yielded higher values (1 to 10 percent) of specific impulse. Propane and butane are safe, non-toxic, clean-burning fuels, great energy sources, and can be used as alternative fuels in PDE.

1. Introduction

Nowadays, major environmental issues include pollution from the automobile and aerospace industries, waste disposal, global warming, and deforestation [1]. The world's fuel demand and consumption have been drastically increased due to rapid technological and industrial developments [2]. Alternative and renewable energy sources are unquestionably needed as soon as possible. Commercial airliner jets have shifted their goals to using fuels that are either entirely different from traditional fossil fuels or are mixed with efficiency enhancing substances [3,4].

Such alternative fuels offer a future eco-friendly cleaner utilization with much less dependency on crude oil. Using biofuels reduces emissions significantly [5]. Turbofan, ramjet, and turbine engines used in aircraft are built on deflagration and are employed in quite optimized forms today. The

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defence and industrial sectors are likely to see the biggest growth in demand for unmanned surface vehicles [6]. Further improvement in efficiency is difficult to achieve in deflagration-based engines [7]. A combustion system is one in which fuels are burnt in a chamber [8]. Pressure-gain combustion (PGC) is an alternative approach to traditional combustion in a gas turbine [9]. PGC can be used in detonation engines to eliminate problems associated with deflagration-based engines. In detonation, combustion occurs at supersonic speed. The pressure rises across a detonation front as the specific volume declines [10].

In Europe, a wave rotor is also called a dynamic pressure exchanger [11]. Four-port gas turbine cycle wave rotors are shown in Figure 1. According to the flow path shown in Figure 1, two dissimilar fluids can interchange energy through direct contact and axial displacement. This is because when two gases with different pressures and temperatures come into contact for a brief period, their pressures are equal until they are combined by unstable wave mechanisms [12].

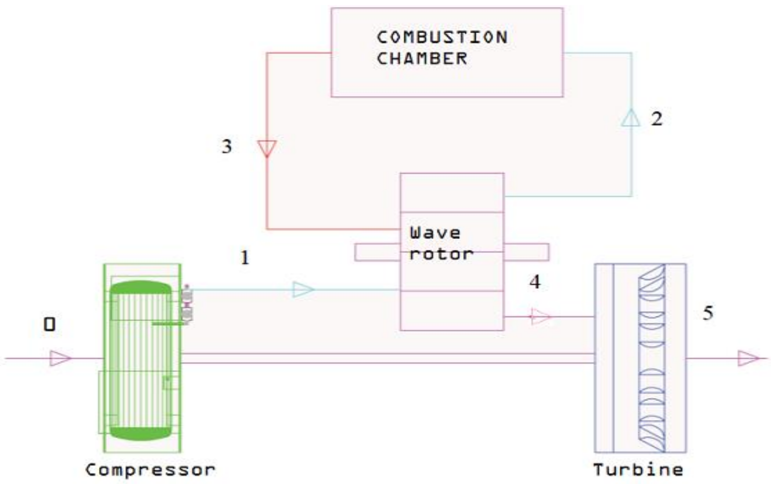

Fig. 1. Gas turbine cycle schematics using a four-port wave rotor

Thermodynamic pressure gain can be obtained practically in RDE [12]. Figure 2 shows that a typical, continuously rotating detonation wave (CRDW) is maintained around a cylindrical core in the annulus. CRDW runs circumferentially close to the head-end with a frequency that varies for a few to dozens of kHz, detonating the blends of fuel supplied through many micro-nozzles from the bottom of the combustion chamber. At high speed, the combusted gas will then be exhausted [13]. The gases that are produced are extended and leave the combustion chamber. The feed pressure is more than sufficient for new reactants to re-establish and flow into the combustion compartment, and subsequently, the detonation wave has passed. As soon as the detonation finishes a whole revolution, there essentially is adequate fresh fuel mixture to sustain the detonation wave.

The phenomenon of the pulse detonation engine is shown in Figure 3. During the filling process, the detonation chamber occupies a uniform mixture of fuel and air. The initiation of detonation starts, possibly at the chamber's closed-end. Behind the detonation wave, a high-pressure region is shaped. Blow down happens when the gases leave the detonation chamber, and work is done [14]. Pulsed detonation engines are an exciting novel propulsion technology that can be applied across subsonic, supersonic, and hypersonic flights [15]. Experiments and computational researchers have demonstrated using a simple PDE cycle to obtain competitive specific impulse values. As a result of these encouraging results, several PDE applications have been proposed. Several civil and military applications were investigated [16]. A pulsed detonation engine's first flight took place in January 2008 [17]. It was suggested that PDE could be used as cost-effective replacements for small gas turbine engines, as potential combustion replacements on existing large-scale gas turbines [18].

Among the engines that work in agreement with the Humphrey cycle is a pulse jet engine that was used during World War 2 for German flying bomb v-1 [19].

Hydrogen, ethylene, kerosene, or JET-A were the most common fuels for PDE until recently. The literature on selected fuels for PDE is limited. The novelty of our study is that this research focused on both pure and blended fuels. The blended fuel equation is first time tested analytically for the PDE, according to the author's literature review. So, this study aims to assess the thermodynamic properties of pulse detonation engines like pressure ratio, temperature ratio, and detonation velocity. Moreover, efforts have been made to determine the specific impulse for three pure fuels, namely hydrogen, propane, butane, and the blended fuels composed of butane, propane, and hydrogen, with a 50 percent contribution of each.

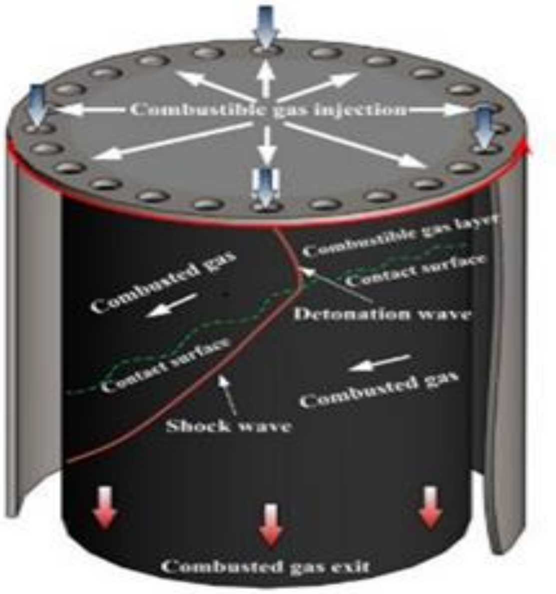

Fig. 2. A typical continuously rotating detonation wave [13]

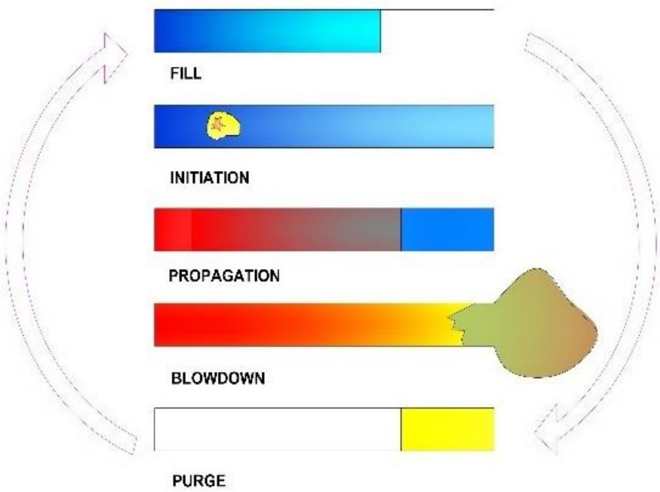

Fig. 3. The working process of the pulse detonation engine

Various studies have already been conducted to understand the pulse detonation engine. Kailasanath and Patnaik [20] idealized the solution to PDE's performance using one-dimensional, unstable numerical simulation. They discovered that lowering the pressure at the tube's exit to ambient levels is a crucial issue that affects the impulse. A higher specific impulse can be accomplished with a more gradual reduction. Mukesh and Rajan [21] found a need for a higher fuel-air blend supply in the detonation tube to sustain the PDE operation at a higher frequency. Thus, PDE is successfully operated at an equivalence ratio of 1, 1.39 for 1 and 2 Hz, respectively. The PDE has, therefore, proven to be better than other air respiratory engines. Azami *et al.,* [22] revealed that specific volume and Mach number ratios are significantly affected by the initial temperature effects. Meanwhile, differences in initial mass flux mainly impact the ratios of temperature & pressure. The observed difference in mass flux may result in considerable limitations on fluctuations in the initial pressure.

Hitch [23] observed that the PDE obtained specific impulses beyond those typically associated with ramjets operating in the same flight condition. Significant performance improvements can be achieved by adding a divergent exhaust nozzle to prevent severe losses from expansion. Wintenberger, Austin, Cooper, Jackson, and Shepherd [24] found that the particular impulse of a fixed composition is approximately independent of the initial pressure and temperature. Alam, Sharma, and Pandey [25] used two varieties of fuels to analyze the difference in shock propagation, flame temperature, and velocity. They concluded that deflagration to detonation (DDT) depends on the length of the flame. Also, in the ethylene-air mixture, the static pressure and flame velocity are higher than in the ethane-air blend.

Srikrishnan & Dash [26] inspected the reaction of blockage on deflagration transition to detonate at different input pressures. The stoichiometric kerosene-air mixture is used during the analysis. The computational fluid dynamics (CFD) analysis of 2D blockage flow transition to detonation concluded that blockage shape and position significantly impact output velocity. Detonation depends on input pressure and substantial turbulence. Furthermore, the chemical enthalpy and burning rate also further affected the formation of detonation waves. Researchers like Khan *et al.,* conducted several test on rocket and jets flow [27]. Peace and Lu [28] conducted a numerical assessment of the PDE. The addition of diverging conical nozzles was analyzed to increase the thrust and impulse. Moreover, the specific impulse increased and appeared to increase the nozzle expansion area ratio to the range of 2.25-2.5. It was also found that the propulsive efficiency improved by up to 21% by introducing diverging conical nozzles.

Kasahara, Hasegawa, Nemoto, and Yamaguchi [29] made a pulse detonation rocket called Todoroki and used a horizontal sliding check to validate the thrust measurement model. They reported that the stability of the PDE's operation relies on the ratio of the purge gas's thickness and the diameter of the tube. The model's expected thrust was within 4% of variation when compared to the experimental results. Harris *et al.,* [30] compared specific impulse (Isp) with ramjet over different flight Mach numbers. The results of all patterns were identical, demonstrating that the Isp from a PDE is greater than that of a ramjet for beneficial thrust levels over a broad range of Mach numbers.

Ma, Fuhua, Choi, and Yang [31] researched thrust chamber dynamics in a single-tube air-breathing PDE. On PDE, the repeated operation was analyzed analytically as well as numerically. They concluded that as compared to the conventional steady systems, For PDEs, the intrinsic inconsistency of the flow conditions at the nozzle exits and the internal flow deficit related to chamber shock dynamics are special. In most cases, performance surges with declining close-up valve time for an assumed cycle period and purge time. A larger purge time decreases the specific thrust but raises the specific impulse for a specified cycle time. Wintenberger *et al.,* [24] developed the analytical model and validated it against experimental results. By varying the initial pressure, equivalence ratio, and nitrogen dilution. Endo and Fujiwara [32] investigated the efficiency of pulse detonation engines. Simple formulas for the impulse density per one cycle operation and the time-averaged thrusts have been derived based on the simplified theoretical analysis. Numerically the efficiency estimates for an idealized PDE investigated by Cheatham and Kailasanath [33] used JP-10 used as fuel. Results show that liquid-fueled PDEs are comparably efficient to gas-fueled PDE devices with small enough droplets and sufficient fuel pre-vaporization. A quasi 1-D finite-rate CFD chemical model was created and implemented by C. I. Morris to research pulse detonation rocket engine (PDRE) gas dynamics and performance [34]. He selected four different PDRE geometries, which were then checked for single-shot performance and analyzed for blowdown time characteristics. The results show that the performance of a baseline detonation tube can be improved with both direct extensions and converging divergent nozzles. However, optimized C-D nozzles typically increase their performance more effectively than straight extensions, particularly with higher pressure ratios.

Baklanov *et al.,* [35]; less feed is used to fill the combustion chamber valve with fuel and oxidant. They discovered that using a pre-combustion chamber with annular obstacles reduces the duration of DDT. Recently carlos Xisto *et al.,* [36] developed a model for anticipation of NOx production in pulsed detonation combustors. The model is built using CFD data for various combustor inlet pressure, equivalence ratio, and temperatures. They discovered that detonation in lean mixes considerably reduced NOx emissions. Another method for reducing NOx production is to use stratified charges, which divide the tube into sections. The pulse detonation engine was studied by V. B. Nguyen *et al.,* [37]. Jet-A liquid fuel is considered as a fuel, while air as an oxidizer. The data suggest that the mass fraction of pre-vaporized fuel is critical to the success of the DDT process. The effect of thermodynamic detonation parameters on the performance of the pulse detonation engine is determined through analytical and computational study by warimani *et al.,* [38]. They concluded that methane, kerosene, and a 50 percent blend of hydrogen + methane, hydrogen + kerosene, and methane + kerosene might be utilized as alternate fuels for PDE to avoid the issues caused by hydrogen fuel. Table 1 shows the chemical and physical properties of fuels. Hydrogen having the lowest molecular weight, and gasoline having the highest value. Heavy hydrocarbons are less sensitive to detonation. The flame velocity of propane, butane, Liquefied petroleum gas (LPG), and gasoline are almost the same but hydrogen having a comparatively higher flame velocity. It's also worth noting that the gas density of hydrogen is the lowest of any gas, necessitating further safety measures to prevent fuel leakage.

Table 1
Chemical and physical properties of fuels [39–42]

Fuel	Hydrogen	Propane	Butane	Liquefied petroleum gas (LPG)	Gasoline
Chemical formula	H_2	C_3H_8	C_4H_{10}	C_4H_{10} (60%) &C_3H_8 (40%)	C_8H_{18}
Molecular weight(g/mol)	2.016	44.097	58.12	44.09	114.23
Gas density (kg/m^3) @ STP	0.090	1.901	2.48	1.89	748.9
Flame velocity (m/sec)	3.06	0.45	0.44	0.4	0.35
Ignition temperature (K)	845	766	560.9	510	275
Ignition energy (10-5 J)	2.0	30.5	10	10	24

2. Numerical Methodology

2.1 One-Dimensional Analysis

It is necessary to build an empirical prototype to determine the theoretical limit on PDE's efficiency and to identify several performance loss mechanisms. Since PDEs work in an unsteady flow in the combustion chamber, an analytical model is essential. While the structure of actual detonations is exceptionally three-dimensional, a one-dimensional analysis offers substantial insight. The first attempt to describe the detonations based on a one-dimensional approach is still valid today as it provides a framework for creating a more detailed understanding. Pulse detonation engine thermodynamic assessment is analyzed by referring to a one-dimensional (1D) model built on the Chapman–Jouguet (CJ) and the Zeldovich, von Neumann, and Doring (ZND) theories. The detonation waves compress the gas in front of it, resulting in a considerable increase in pressure and temperature after the combustion process. This process is called the one-dimensional Chapman-Jouguet theory and the ZND model.

2.2 Assumptions Considered for One-Dimensional Analysis

This modeling was only for the case of ideal combustion. As shown in Figure 4, the control volume is chosen. The upstream and downstream boundaries are located in the regions where there are not at all temperatures or species concentration changes. We can perform a reasonably rigorous analysis with the following assumptions: (1) the flow is one-dimensional and steady; (2) the area is constant; (3) the combustion and flue gases are modeled to ideal-gas law; (4) specific heats are constant, and Cp and Cv are equal; (5) the body forces are negligible; and (6) adiabatic conditions are prevailing throughout the detonation process (i.e., there are no heat losses to the surroundings).

The fundamental conservation law can be written as the flow under consideration is conserved in one dimension and steady. Figure 4 shows the flow with constant volume.

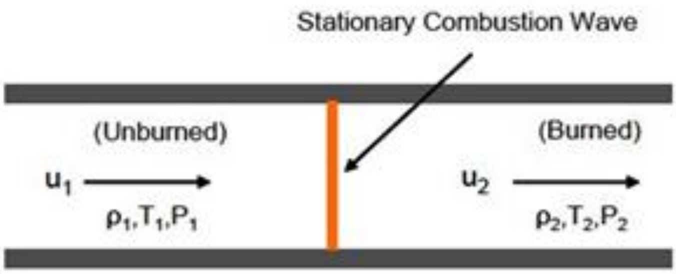

Fig. 4. One-dimensional detonation wave in the constant area duct [43]

The speed at which the unburn mixture enters the detonation wave is approximated as one-dimensional for an observer moving with the one-dimensional detonation wave as depicted in Eq. (1).

$$V_D = v_{x,1} \; and \; velocity \; of \; burned \; gases = \; v_{x,2} \quad (1)$$

The governing equations that define the flow and reaction progress in the pulse detonation engines are with a single step & irreversible reaction in this research.

2.3 Detonation Parameters

The detonation parameters like pressure ratio, temperature ratio, & detonation velocity of the alternative fuels are premeditatedly referred to by Turns [44]. Turns [44] shows that the specific heat of the unreacted mixture can be obtained. Before looking for these properties, we need to determine the unreacted and reacted mixtures' composition by the expression given below.

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \left(\frac{y}{2}\right)H_2O + 3.76aN_2 \quad (2)$$

where $a = x + \left(\frac{y}{4}\right)$

We can denote the exact chemical reaction by balancing the amounts of C, H, O, and N on the left and right sides of the equation. After the equation has been balanced, we can find the thermochemical properties by using the equations mentioned below.

Specific heats at constant pressure at both states 1 and 2 are given in Eq. (3) and (4).

$$C_{p,1} = \frac{\sum_{state1} X_i \hat{c}_{p,i}}{MW_1} \quad (3)$$

$$C_{p,2} = \frac{\sum_{state2} X_i \hat{c}_{p,i}}{MW_2} \quad (4)$$

The gas constant R_2 can be evaluated using Eq. (5)

$$R_2 = \frac{R_u}{MW_2} \quad (5)$$

The specific heat ratio γ_2 can be calculated using Eq. (6)

$$\gamma_2 = \frac{C_{p,2}}{C_{v,2}} = \frac{C_{p,2}}{C_{p,2} - R_2} \quad (6)$$

By referring to Turns [1], enthalpies-of-formation can be obtained to calculate the heat of formation, q, as mentioned in Eq. (7). Enthalpies-of-formation is converted into a mass balance.

$$q \equiv \sum_{state1} Y_i h^0_{f,i} - \sum_{state2} Y_i h^0_{f,i} \quad (7)$$

With the heat of formation known, the detonation velocity and temperature at state 2 can be calculated by using Eq. (8) and (9), as shown below

$$v_D = \left[2\gamma_2 R_2(\gamma_2 + 1)\left(\frac{\hat{c}_{p,1}}{\hat{c}_{p,2}} T_1 + \frac{q}{\hat{c}_{p,2}}\right)\right]^{\frac{1}{2}} \quad (8)$$

$$T_2 = \frac{2\gamma_2^2}{\gamma_2 + 1}\left(\frac{\hat{c}_{p,1}}{\hat{c}_{p,2}} T_1 + \frac{q}{\hat{c}_{p,2}}\right) \quad (9)$$

The properties at state 2′ can be determined by employing the ideal-gas normal-shock equation. These properties are used to compare states 1 and 2. The specific heat ratio of the mixture and the Mach number at state 1 are required to determine all the properties at state 2' using Eq. (10). We assume $\gamma = 1.3$ and Mach number at state 1

$$M_{a1} = \frac{V_{x1}}{C_1} = \frac{V_{x1}}{\sqrt{\gamma R_1 T_1}} \quad (10)$$

After obtaining the Mach number at state 1 and the specific heat ratio, all the properties at state 2' can be evaluated using Eq. (11), (12), and (13).

$$\frac{P_{2'}}{P_1} = \frac{1}{\gamma+1}\left(2\gamma Ma_1^2 - (\gamma - 1)\right) \tag{11}$$

$$\frac{T_{2'}}{T_1} = (2 + (\gamma - 1)Ma_1^2)\frac{2\gamma Ma_1^2 - (\gamma-1)}{(\gamma+1)^2 Ma_1^2} \tag{12}$$

$$\frac{\rho_{2'}}{\rho_1} = \frac{(\gamma+1)Ma_1^2}{(\gamma+1)Ma_1^2+2} \tag{13}$$

The Mach number at states 2 and 2' can be determined using Eq. (16) to determine the aircraft's motion—whether it is in subsonic or supersonic regime.

$$n = 2\ and 2' \tag{14}$$

$$V_{x,n} = \frac{\rho_1}{\rho_n}V_{x,1} \tag{15}$$

$$M_{a,n} = \frac{V_{x,n}}{\sqrt{\gamma_n R_n T_n}} \tag{16}$$

2.4 Equations Used for the Blended Fuels

The blended fuel equation set is taken from the mathematical model presented in Yildiz and Çeper [45]. The chemical equation used to describe the combustion reaction is expressed by Eq. (17).

$$frcC_nH_m + (1 - frc)C_\propto H_\beta O_\gamma + \left(\frac{\delta}{\Phi}\right)(O_2 + 3.773N_2) \xrightarrow{yields} X_1CO_2 + X_2CO + X_3H_20 + X_4H_2 + X_5O_2 + X_6N_2 + X_7H + X_8O + X_9NO + X_{10}OH \tag{17}$$

where frc is the fraction of the selected fuel; $C_nH_m \& C_\alpha H_\beta O_\gamma$ Is the selected hydrocarbon-based fuels, n, m, α, **δ**; and Φ represent the number of atoms of carbon, hydrogen, and oxygen in the fuels, respectively. Furthermore, x_1-x_{10} denotes the number of moles for each product. In this research, CO2, CO, H2O, H2, and O2 are considered combustion products.

$$\delta = frc\left(n + \frac{m}{4}\right) + (1 - frc)\left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right) \tag{18}$$

2.5 Specific Thrust and Specific Impulse

$$F_{sp} = (1 + f)V_e - V_\infty \tag{19}$$

F_{sp} is the specific thrust, f is the overall fuel to air ratio of the blend of the reactants different for fuel, which was calculated using the formula, V_e is exit velocity of the engine, and V∞ is the axial velocity (636 m /s). The V_e value is determined using Eq. (8), as explained in section 3.3. The same detonation velocity is considered here. The specific impulse I_{sp} can be determined by Eq. (20).

$$I_{sp} = \frac{F_{sp}}{fg} \tag{20}$$

where I_{sp} is the specific impulse, f is the overall fuel to air ratio of the blend of the reactants and purge air, g is the gravitational constant.

3. Results and Discussion

3.1 Validation of the Model

In comparison to the current investigation's findings, experimental evidence for the detonation of hydrocarbons is very small. Only restricted evaluations are made due to the lack of sufficient data. Furthermore, no information was existing for the blended fuels used in this analytical model. According to the author's literature survey, before, no one has conducted an analytical investigation of the detonation using blended fuels, which is used here (Table 2). The equations used are unique to PDE. However, the above model was tested first against the Turns [44] case study before employing it in the current research. The blended fuels equation was obtained from Yildiz and Çeper [45]. Specific impulse for hydrogen-air validated by Wintenberger *et al.,* and Fuhua Ma's article [24,46]. Wintenberger *et al.,* [24] found that fuel-based specific impulse for hydrogen-air is in between 3000 sec to 5000 sec. F.Schauer *et al.,* [47] results for fuel-based specific impulse were in between 4200 to 7100 sec using hydrogen-air. And specific impulse for propane-air validated with Wintenberger *et al.,* [24].

Table 2
Validation of hydrogen fuel with available literature

Fuel	Parameter	Analytical Model	S. Yungster & K. Radhakrishnan [48]	K. Kailasanath [49]	B. D. Taylor *et al.,* [50]	E. C. Maciel *et al.,* [51]
Hydrogen	Pressure ratio (P_2/P_1)	24.10	23	20	31.47	14
	Temperature ratio (T_2/T_1)	15.60	10	-----	10	12.16
	Velocity(m/s)	2524.36	2400	2380	2020	1996

3.2 Validation of the Model Analysis of Fuel Blends and its Comparison with NASA CEA Data

In this analysis, NASA's open-source software (CEA) was used to estimate the detonation parameters of various alternative and blended fuels. CEA is a program that computes chemical equilibrium product concentrations from any variety of reactants and finds the transport and thermodynamic properties for the product mixture. As shown in Figure 10, 11, and 12, the pressure ratio, temperature ratio, and velocity have been plotted for hydrogen, butane, propane, and blends with a combination of 50% of each. The corresponding values taken from NASA CEA are also shown to compare with the current study's analytical results. Butane and propane are compared with hydrogen to generate a new kind of alternative fuel. Butane, or C_4H_{10}, is a natural gas alkane derivative that can be used either as two distinct structural isomers, n-butane or isobutane or as a combination of the two.

Meanwhile, propane possesses a molecular formula of C_3H_8 and a melting temperature of 85.45 K, the lowermost of all recognized organic compounds. Figure 5, 6, and 7 show the ZND structure for selected fuels. ZND considered that the fuel mixture's compression takes place immediately at the front of the shock wave. In the induction field, an increase in temperature results in mixture ignition.

The mixture then burns until it ultimately converts into a combustion product. This leads to the generation of a shock wave and a thin chemical reaction area, which is called a detonation wave.

Figure 5, 6, and 7 demonstrate the pressure ratio, temperature ratio, and density ratio for hydrogen, butane, and propane fuels. The pressure ratio, temperature ratio, and density ratio of the hydrogen are 24.09, 15.60, and 1.811. Hydrogen has the highest values in comparison to the other pure and blended fuels. All the values of fuels are within the required range of properties of detonation.

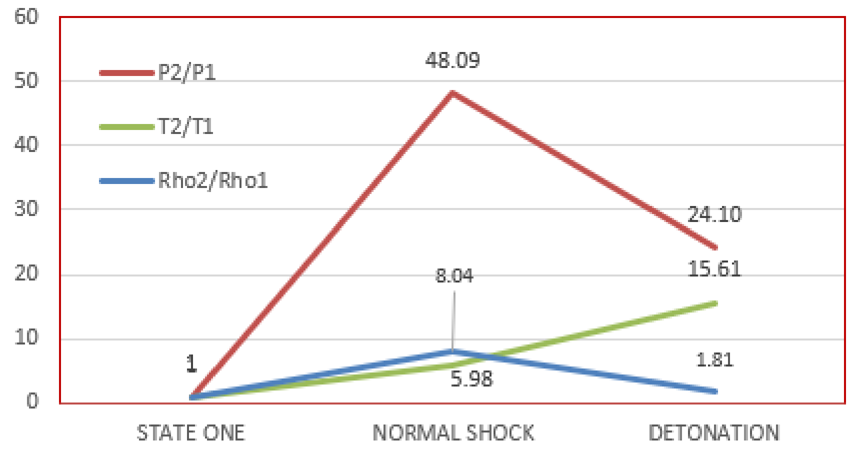

Fig. 5. ZND structure of hydrogen

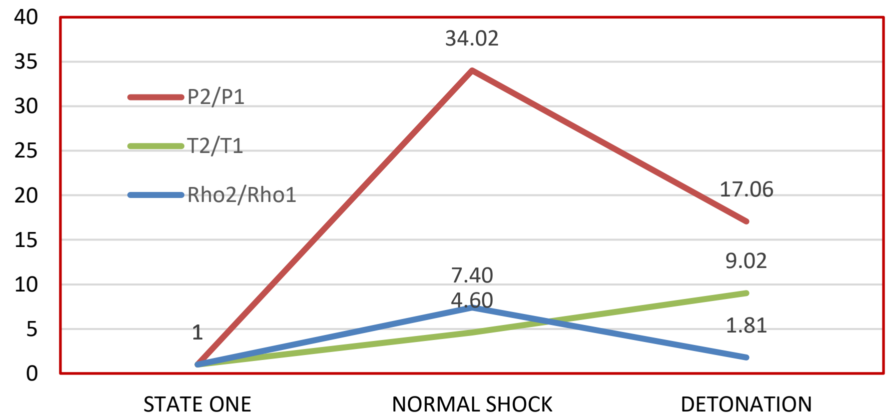

Fig. 1. ZND structure of butane

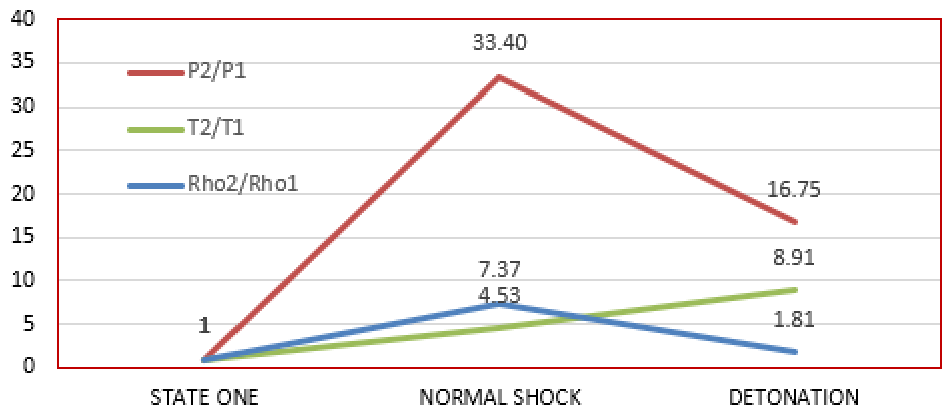

Fig. 2. ZND structure of propane

As shown in Figure 8 and 9, it is worth noting that heat release rate and air to fuel ratio play a vital role. As illustrated in Figure 8, the specific impulse of fuel depends on the heat release rate. As heat release increases, specific impulse also increases. Other than hydrogen, all other fuels have similar specific impulses and heat release rates. Figure 9 reveals that the air-fuel ratio of fuel is critical to the engine's efficacy. If the air-to-fuel ratio is the lowest possible, the fuel-specific impulse would be the maximum. Since hydrogen has the smallest air-to-fuel ratio (0.029), the specific impulse is the maximum. Since all other fuels have nearly identical air-to-fuel ratios, their specific impulses are nearly identical.

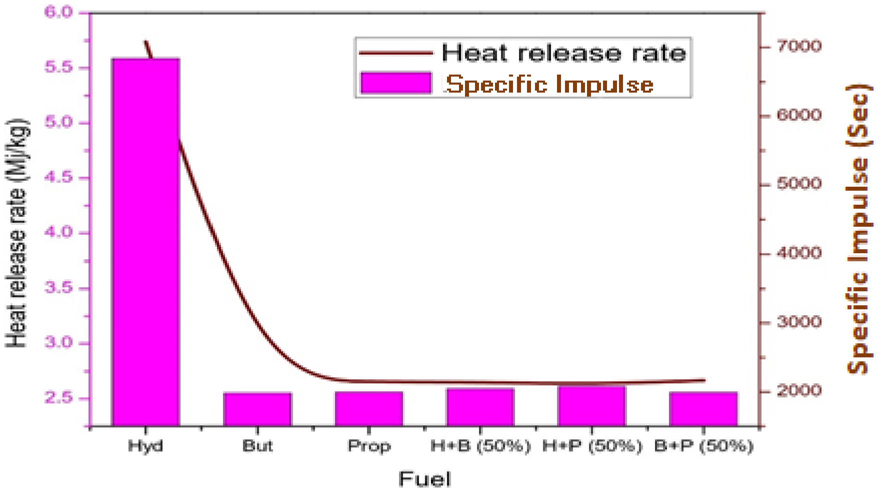

Fig. 8. Effect of heat release rate on detonation velocity

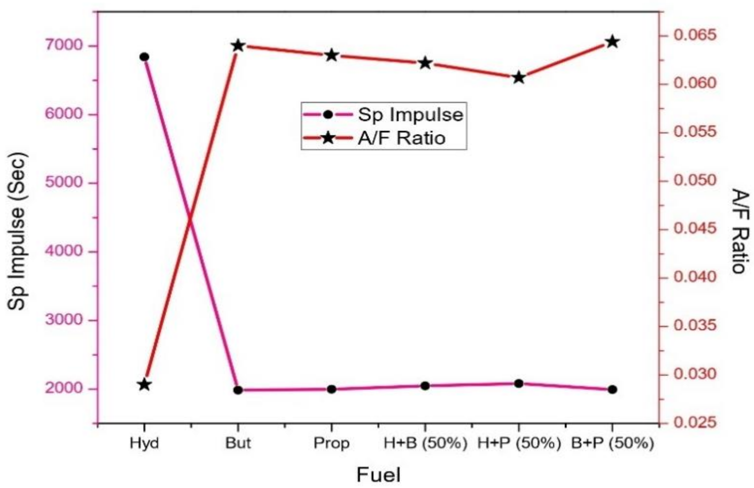

Fig. 9. Effect of air to fuel ratio on specific impulse

As shown in Figure 10, the percentage difference or percentage error between the analytical results and the NASA CEA results are significantly less, which indicates that the results from the recent study are within the acceptable range. Still, only hydrogen values are higher due to higher heat release (5.7 Mj/Kg) and lower air to fuel ratio (0.029) than other fuels. In the analytical results, the highest pressure ratio (24.09) was recorded for hydrogen. Whereas the lowest value of pressure ratio (16.07) obtained was for the blend of 50% hydrogen and propane. Regarding the accuracy of the results, the hydrogen-propane and hydrogen-butane combination showed the slightest error than the corresponding NASA CEA values. The standard detonation pressure ratio value is 13-55, and it can be noticed that all the values were within this range.

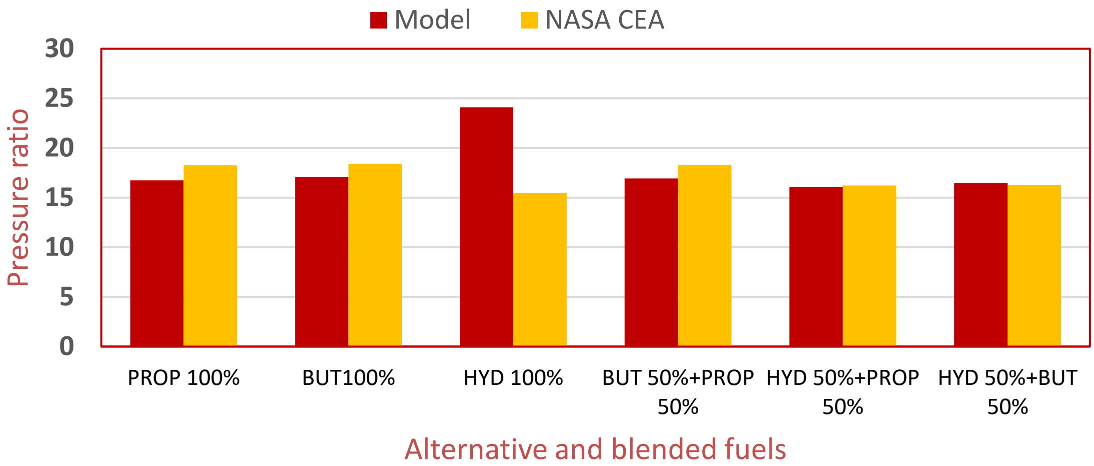

Fig. 10. The pressure ratio of alternative and blended fuels

Figure 11 shows the trend of temperature ratio for different fuel blends. Compared with NASA CEA values, the numerical results experienced a 10.46 % variation within the acceptable range accept hydrogen. The standard detonation value for temperature is 8 to 21. All fuel blends achieved a temperature ratio of more than 8. Numerically, the highest temperature ratio was 15.61, which was observed with pure hydrogen. On the other hand, the lowest value of the temperature ratio was 8.73, which was achieved with a blend of 50% hydrogen and 50% propane.

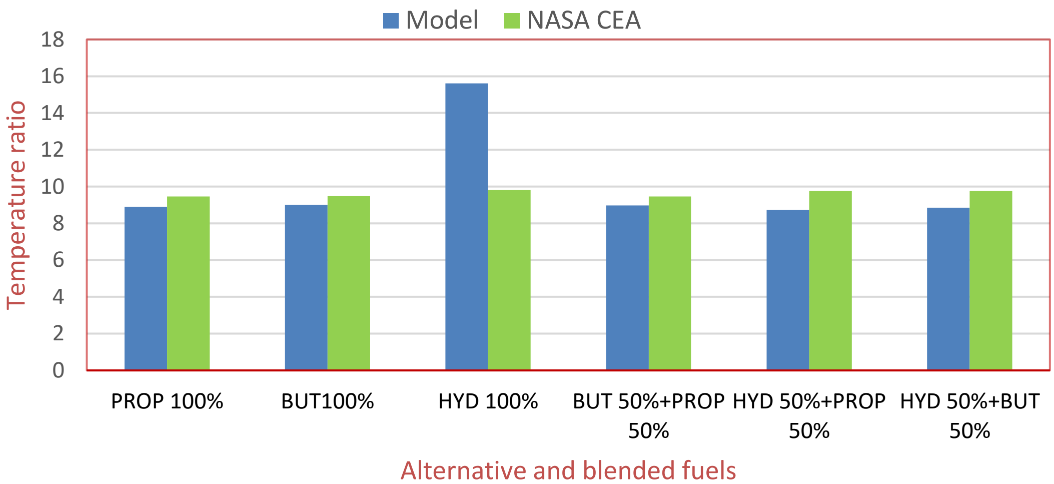

Fig. 11. Temperature ratio of alternative and blended fuels

Figure 12 shows that the detonation velocity is plotted for fuel blends and the corresponding NASA CEA values. It is seen that the highest detonation velocity was 2524.37 m/s, which was numerically obtained with hydrogen. The higher velocity of hydrogen fuel or hydrogen was designated as the best fuel since there is no carbon dioxide (CO_2), carbon monoxide (CO), or soot in it. Still, only water was generated in the burning of hydrogen fuel. On the contrary, the lowest value of 1769.58 m/s was achieved with a blend of 50% hydrogen and 50% propane. The maximum percentage difference or error between the analytically obtained values and NASA CEA values was 7.40 %, within the acceptable range.

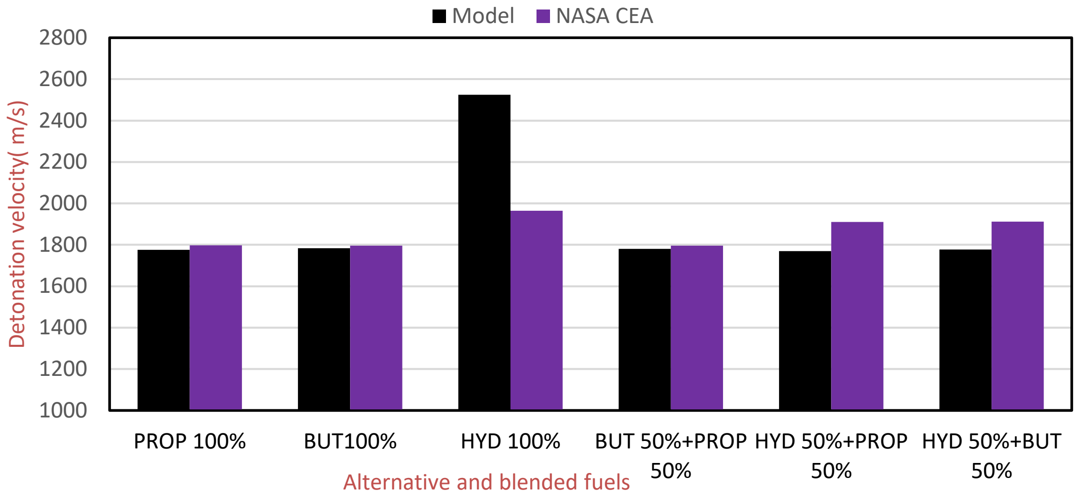

Fig. 12. The velocity ratio of alternative and blended fuels

3.3 Performance Analysis of Alternative and Blended Fuels

Figure 13 represents the trend of specific impulses for all the fuel samples. It is found that the maximum specific impulse of 6842.17 seconds was experienced with pure hydrogen fuel because, as said before, there is no formation of carbon dioxide (CO_2) in it. It thus justifies why hydrogen is considered the best fuel for PDE, as mentioned in many earlier studies. Compared with pure butane and propane, relatively higher values of specific impulse are found with their blends. Hydrogen has a much higher energy release than other hydrocarbon fuels. That is the reason behind hydrogen's best performance for aerospace applications. Also, it has wide flammability limits and a short ignition time. Furthermore, it has excellent diffusivity and gives a higher specific impulse due to its low molecular weight.

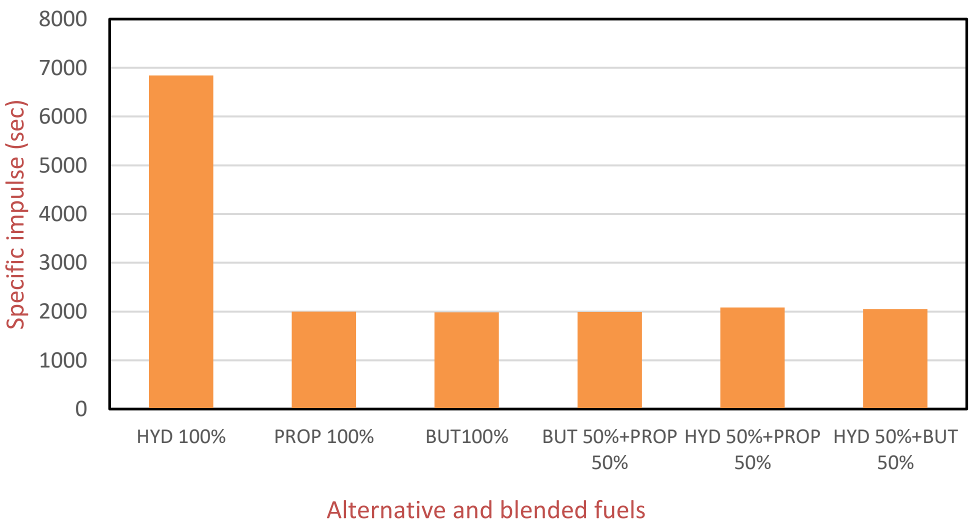

Fig. 13. The specific impulse of pure and blended fuels

4. Conclusions

Analytical pure fuel like hydrogen, butane, propane and its blend of 50 % of each fuel were selected to study the thermodynamic performance in a simple PDE combustor. PDE thermodynamic assessment is analysed by referring to a one-dimensional (1D) model built on the Chapman–Jouguet (CJ) and the Zeldovich, von Neumann, and Doring (ZND) theories. Parameters such as temperature ratio, pressure ratio, detonation velocity, and specific impulse were determined. The implemented analytical model is benchmarked via available numerical, experimental, and NASA CEA results. The following conclusions can be drawn:

i. A one-dimensional analysis has been used to study the detonative parameter and the propulsive output of a pulse detonation engine. PDE fueled by pure fuels like hydrogen, propane, butane, and the blended fuels butane 50%-propane 50%, hydrogen 50%-butane 50%, and hydrogen 50% and propane 50% were tested. The model predictions have been compared with the conclusions of NASA CEA and several pieces of literature available. These indicate a good correlation that is within 15% error.
ii. This research's novelty lies in the equations used for blended fuels for PDE—that is, they are used for the first time for PDE. Among all the three pure fuels, the highest specific impulse was achieved with the hydrogen of 6842.17 sec.
iii. Pure butane predicted excellent pressure ratio values, temperature ratio, and detonation velocity with 17.06, 9.02, and 1782.86 m/s, respectively. These butane fuel values are near to the detonation values of hydrogen fuel. No considerable changes in pressure ratio, temperature ratio, and detonation velocity were observed with butane and propane when compared with each other.
iv. Propane and butane are both safe, non-toxic, clean-burning fuels and are excellent sources of energy. Thus, there are no long-term adverse environmental effects with butane and propane. They can be used as alternative fuels in PDE. This initial approach has produced good results for the further development of a realistic pulse detonation engine.

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