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Analytical Evaluation of Loss Mechanism Effects on PDE Performance with Variation of Refilling Beta Parameters

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ABSTRACT

The present research work is to investigate, how the pulse detonation engine's (PDE) performance is affected by thermodynamic detonation factors. This analysis deals with the evaluation of PDE by using pure fuels like hydrogen, propane, and butane and a blend of hydrogen (50%) + propane (50%), butane (50%) + hydrogen (50%) and propane (50%) + butane (50%). The performance prediction model method is based on flow paths. Performance loss mechanisms, like the refilling process are recognized and enumerated. Inside flow damage, which mostly results from shock waves inside the PDE combustion tube, is a major factor in the PDE's performance degradation. The novelty of the present analysis is to observe that the Hydrogen fuel displays the maximum specific impulse of 7280 s with a detonation velocity of 2321 m/s at the value of beta 0.17. whereas, the lowest specific impulse is produced by butane with the same beta value.

1. Introduction

Detonation waves have a significant effect due to their inherent speculative advantage over deflagrative waves for impetus applications. Detonation can be initiated by igniting a combustible mixture at the closed end of a long tube open at the opposite end [1]. In this situation, the flame initiated at the closed end is accelerated as it propagates through the mixture because of the burning gas that is contained between the flame and the closed end expanding. This acceleration leads to the formation of a shock wave preceding the combustion zone and propagation at supersonic velocities [2]. However, the engine based on detonation can attain greater thermodynamic efficiency for aerospace systems. It is well known that the application of analytical techniques to assess the performance of PDE using alternative fuels, and high Mach number has been regarded as one of the important influencing factors in the detonation [3].

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Table 1 shows literature reviews to date on pulse detonation engines focusing on parameters like thermodynamics properties investigated, and fuels used for analysis. From this survey, most researchers used hydrogen as fuel research. Most of the study is focused on a single cycle only. So, the research gap is visible, and it is necessary to investigate PDE for alternative fuels. While hydrogen fuel is widely used in aerospace applications for its numerous benefits, still it has drawbacks like high flammability limit, storage problems, and high expenses which have to be addressed [4]. Hence it is necessary to find alternative fuels for PDE; with pure and blended fuels, the purpose of this study is to conduct an analytical analysis of the effect of the filling factor on straight tube PDE [3].

Table 1
Survey of various propellants used for pulse detonation engines

Reference	Propellant	Parameters	CFD/EXP/ANA
Xisto *et al.,* [6]	Jet A-Air	Pressure& velocity parameter	CFD
Yungster *et al.,* [7]	H_2- Air	Thermodynamic properties & performance	CFD & Experiment
Hanraths *et al.,* [8]	H_2- Air	Operating frequency, sampling time, fill time, PDC outflow, and probe geometry were changed to analyse Nox	Experiment
Djordjevic *et al.,* [9]	H_2- Air	Thermodynamic properties	CFD
Yungster and Breisacher [10]	Jet A-Air	Thermodynamic properties & performance	CFD & Experiment
Hishida *et al.,* [11]	Ar-diluted oxyhydrogen mixture (2H2+O2+7Ar)	Processes for purging and refilling to achieve a dependable and high-frequency operation	CFD
Ma *et al.,* [12]	Ethylene fuel	Pressure histories and gross specific impulse	CFD
Kawai and Fujiwara [13]	Ar-diluted stoichiometric oxyhydrogen	The performances of four straight model PDEs that have different tube lengths a	CFD
Fan *et al.,* [14]	H_2- oxygen	The impact of the filling period's duty cycle on flow characteristics and propulsion efficiency	CFD
Mohanraj and Merkle [15]	H_2-oxygen	Performance	CFD
Yungster and Perkins [16]	H_2-oxygen	Thrust, impulse, and mass flow rate characteristics	CFD
Xisto *et al.,* [17]	H_2- Air	Adjusting the system purge fraction, the PDC-turbine performance and flow behavior are examined for a range of power input situations.	CFD
Zhang *et al.,* [18]	H_2-air	Thermodynamic performance	CFD
Cambier and Tegner [19]	H_2-air	Design variation and performance	CFD
Li *et al.,* [20]	Ethylene-air	Pressure information on the thrust wall from two-dimensional simulations,	CFD
Wintenberger *et al.,* [21]	Various fuels	Performance of PDE	Analytical
Azami and Savill [22]	Jet-A, Acetylene, Jatropha Bio-synthetic Paraffinic Kerosene, Camelina Bio-synthetic Paraffinic Kerosene, Algal Biofuel, and Microalgae Biofuel	Thermodynamic performance	Analytical

Examining how fuel variety affects PDE is crucial in two ways: using blended fuels adds originality and provides relevant information to the ongoing PDE study. It assists in assessing PDE performance. The effect of hydrogen fuel on the performance of PDE was obtained from the available literature, and on this basis, investigations on other pure and blended fuels were carried out. From the results, information gleaned from the PDE study may be used by other high-speed engines to employ the fuels under investigation. The factors for performance degradation, such as the process of refilling are analyzed by varying beta (β). BETA value is considered lower that is 1/9 (0.11) only for stoichiometric hydrogen fuel as fuel and air as oxidizer and fixed values for cycle time and other parameters related to time [5]. The main objective of this work is to investigate the effect of BETA value variation on PDE performance.

2. Analytical Prediction and Validation

Analytical models can be classified into two categories. The first is based on unsteady gas dynamics theories to determine the impulse by time integration of the instantaneous forces acting on the thrust wall [23]. These models can only be applied to simple straight detonation tubes with single-pulse operations. The second category obtains the engine impulse based on the flow properties at the exit plane. The analytical model presented here closely follows the approach of Heiser and Pratt [24] but takes into account the effects of the refilling velocity and the purging process to provide more accurate results. It is desirable to create a straightforward analytical model that can be used to evaluate PDE performance and compare it to the output of a numerical simulation [25]. In addition, the analytical prediction model is created to determine the PDE's theoretical performance limitation. Many researchers considered filling velocity in analytical prediction up to 1000 m/s. So, this research analysis is done for selected fuels up to 1000 m/s only [5,14,26]. Considering values beyond 1000 m/s is not practically possible. In a practical experiment, only 30 to 35 m/s of filling velocity is considered in a pulse detonation engine [27,28].

The presented analytical model closely follows the approach [24,29,30]. To get more precise findings, however, take into account the impacts of the refilling velocity and the purging procedure. The ratio of the purge to the valve open period is known as beta (β). The β value varied till 0.5, which means varying fill velocity from 200 to 1000 m/s. Thus, three time periods govern the PDE series. They are,

i. The valve is closed during the valve close-up time (T_{close}), which is also when detonation and the blowdown of combustion products occur in the tube.
ii. The time (T_{purge}) when a small volume of cold air is introduced into the tube to stop new reactants from pre-igniting and
iii. The time (Trefill) that the flammable mixture is delivered to the tube during refilling.

These various time durations like T_{fill}, T_{det}, $T_{blowdown}$, and T_{purge} were obtained by using formulas.

$$T_{fill}=\frac{Length\ of\ tube}{fuel\ inlet\ velocity} \tag{1}$$

$$T_{det}=\frac{\text{Length of the tube}}{\text{NASA det velocity}} \tag{2}$$

$$T_{blowdown}=12\%\ \text{of}\ T_{det} \tag{3}$$

$$T_{purge}=\frac{Length\ of\ the\ tube}{Speed\ of\ sound} \tag{4}$$

$$T_{total}= T_{fill} + T_{det} + T_{blowdown} + T_{purge} \tag{5}$$

$$T_{open}= T_{fill} + T_{purge} \tag{6}$$

$$T_{close}= T_{det} + T_{blowdown} \tag{7}$$

Eq. (1) to (7) were used to find various times related to the pulse detonation engine. Based on this, the Beta (β) value is calculated. Beta (β) which is given by,

$$\beta=\frac{T_{purge}}{T_{open}} \tag{8}$$

Air to fuel ratio f heat release rate q (MJ/kg), and detonation velocity V_D were obtained by the method explained [31]. The fuel-to-air mass ratio f should be replaced by its overall quantity $\overline{f}$ and heat release rate q should include the effect of purged gas so replaced as $\overline{q}$ shown below

$$\overline{f} = f\left(1-\beta\right) \tag{9}$$

$$\overline{q} = q\left(1-\beta\right) \tag{10}$$

$$U_e=\left[2\gamma_2 R_2\left(\gamma_2+1\right)\left(\frac{C_{p,1}}{C_{p,2}}T_1+\frac{q}{C_{p,2}}\right)\right]^{\frac{1}{2}} \tag{11}$$

Where the specific heats at states 1 and 2 are given at constant pressure by Eq. (12).

$$C_{p,1}=\frac{\sum_{state1} X_i c_{p,i}}{MW_1}\ ,\ C_{p,2}=\frac{\sum_{state2} X_i c_{p,i}}{MW_2} \tag{12}$$

The specific thrust and impulse are obtained as follows

$$F_{sp}=\left(1+f\right)u_e-u_\infty \tag{13}$$

u_∞ is the velocity at the free stream and its value is 636 m/s.

$$I_{sp}=\frac{F_{sp}}{f_g} \tag{14}$$

Each fuel selected PDE is analyzed by varying beta values (β). All conditions are tested at 298 K temperature and 1 atm pressure.

The equations for mixed fuel are derived from the mathematical model [32]. The chemical Eq. (15) represents chemical composition and describes the combustion reaction.

$$frcC_nH_m + (1-frc)C_\alpha H_\beta O_\gamma + \left(\frac{\gamma}{\phi}\right)(O_2 + 3.773N_2) \xrightarrow{Yields} X_1CO_2 + X_2CO + X_3H_2O$$
$$+X_4H_2 + X_5O_2 + X_6N_2 + X_7H + X_8O + X_9NO + X_{10}OH \tag{15}$$

where frc is the selected fuel fraction; C_nH_m & $C_\alpha H_\beta O_\gamma$ is the hydrocarbon-based fuel. The symbols n, m, α, δ, and φ stand for the proportion of carbon, hydrogen, and oxygen atoms in the fuels, respectively. The number of moles for each product is also indicated by the letters X1–X10. In this study, the combustion products CO_2, CO, H_2O, H_2, and O_2 are taken into account.

$$\delta = frc\left(n + \frac{m}{4}\right) + (1-frc)\left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right) \tag{16}$$

Using Eq. (15) and Eq. (16) fuels are blended such as 50% of each fuel of Hydrogen + Butane, Hydrogen + Propane, Butane + Propane, Hydrogen + Kerosene, Hydrogen + Methane, and Kerosene + Methane shown in Table 2.

Table 2
Illustration of the balanced equation for the selected fuel

Fuel	Balanced equation
Hydrogen	$H_2+0.5O_2+1.88N_2 \rightarrow H_2O+1.88N_2$
Butane	$C_4H_{10}+6.5O_2+24.44N_2 \rightarrow 4CO_2+5H_20+24.44N_2$
Propane	$C_3H_8+5O_2+18.8N2 \rightarrow 3CO2+4H_2O+18.8N_2$
Hyd + But (50%)	$0.5H_2+0.5C_4H_{10}+3.5O_2+13.20N_2 \rightarrow 2CO_2+3H_20+13.20N_2$
Hyd + Prop (50%)	$0.5H_2+0.5C_3H_8+2.75O_2+10.375N_2 \rightarrow 1.5CO_2+2.5H_2O+10.375N_2$
But + Prop (50%)	$0.5C_4H_{10}+0.5C_3H_8+5.75O_2+21.694N_2 \rightarrow 3.5CO_2+4.5H_2O+21.694N_2$

Analytical assessment of PDE by varying filling factors and performance loss mechanisms due to the purging and refilling process. The analysis is done on pure (hydrogen, propane, and butane) fuels and blended fuels composed of hydrogen, propane, and butane with a 50 percent contribution of each by varying Beta (β) values. A valve located at the thrust wall controls how the PDE detonation tube operates. There are typically two ways that a valve can operate. Upon the end of the blowdown process, the valve opens to allow the fresh reactants to be charged into the tube for the second cycle. The valve timing is controlled so that no fresh reactants escape from the open end to the ambient. This stage requires that the leading fresh reactants be caught by the detonation wave of the next cycle somewhere within the detonation tube, or, ideally, at the exit plane of the detonation tube. After the refilling process finishes, the valve closes, and the next cycle begins by repeating the same process [23].

So, the third area of focus for the dissertation research is to predict the loss mechanism on PDE performance by varying refill BETA parameters considering various fuels and their blends of 50% analytically. This study is beneficial because varying BETA parameters can understand the performance of PDE. The literature survey mentions that blowdown and refilling processes are considered in the multi-cycle analysis. So, multi-cycle performance is different from single-cycle performance. Therefore, it is necessary to study the multicycle performance of PDE using computational modeling and detailed flow visualizations. This study is beneficial because multicycle performance can be identified. It was believed that these results would give direction toward optimizing a practical PDE system.

3. Results and Discussions

Heavy hydrocarbons require higher values of pressure and temperature to initiate detonation. After initiation, a detonation wave propagating in a closed-end tube is followed by an isentropic expansion wave (Taylor wave) [33]. Figure 1 shows that the flow is brought to rest at some distance behind the detonation wave. The time taken to reach the tube end varies for different fuels. Hydrogen fuel takes a shorter time to reach the tube end than other fuels. The pressure decreases to a value of ambient pressure at the end of the tube; the detonation propagates for a short time afterward. The detonation products flow out of the tube, creating a shockwave in the outer region, and a series of expansion waves are reflected into the tube [34]. Eventually, the chamber pressure decays to the ambient level, and the blowdown process is finished. At this stage, the first cycle is completed.

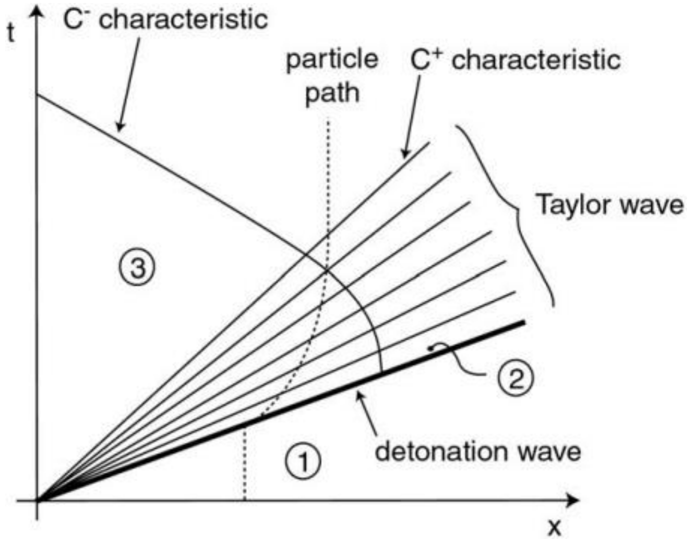

Fig. 1. Taylors Wave Reflection Space-Time Diagram [33]

The filling factor is vital in determining how much of an impact it has on engine dynamics and propulsive performance. It can be defined as a variation of the BETA (β) value due to changes in filling velocity. The detonation velocity and specific thrust of propane and butane reduce in the same pattern as the increase of beta angle shown in Figure 1 and Figure 2 respectively. As given in Table 3, Table 4 and Table 5, the highest performance is shown by hydrogen fuel because, as aforementioned in my previous research, hydrogen fuel performance is considered excellent because of its lower air-to-fuel ratio (0.029) and higher heat release (5.7 MJ/Kg) compared to other fuels. Additionally, it has a quick ignition time and broad flammability limits which results in high detonation velocity as well as high specific thrust compared to propane and butane fuel shown in Figure 2 and Figure 3 [35]. Due to its low molecular weight, it also possesses great diffusivity and provides a larger specific impulse shown in Figure 4. Therefore, hydrogen has the best performance for aerospace applications. As explained by Ma *et al.,* [23], the present research also has the same trend for the performance parameters of selected fuel. That is thrust (F_{sp}) decreases and specific impulse (I_{sp}) increases with increasing β in all selected fuels, as shown in Table 3 to Table 5.

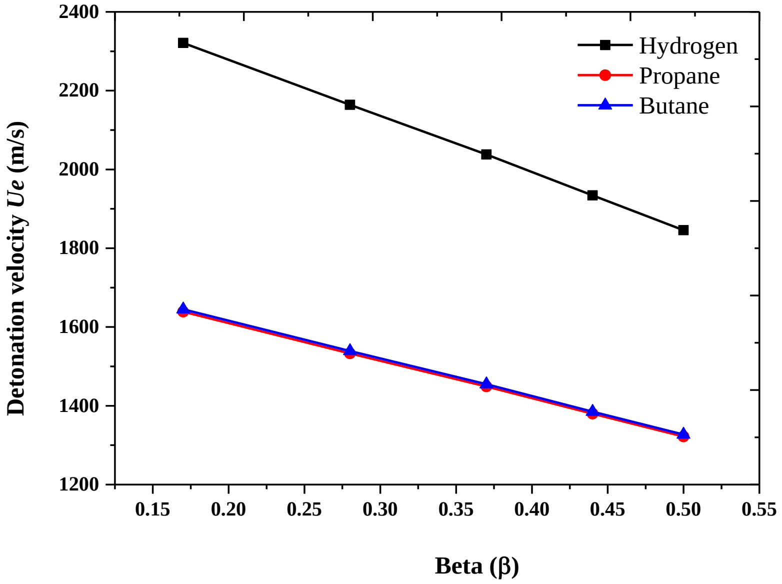

Fig. 2. Variation detonation velocity w.r.t. beta angle for pure hydrocarbon fuel

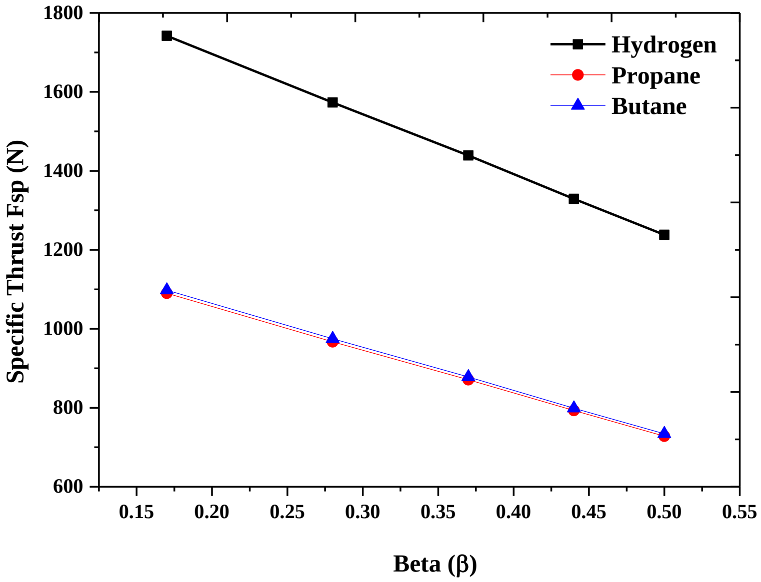

Fig. 3. Variation of Specific thrust w.r.t. beta angle for pure hydrocarbon fuel

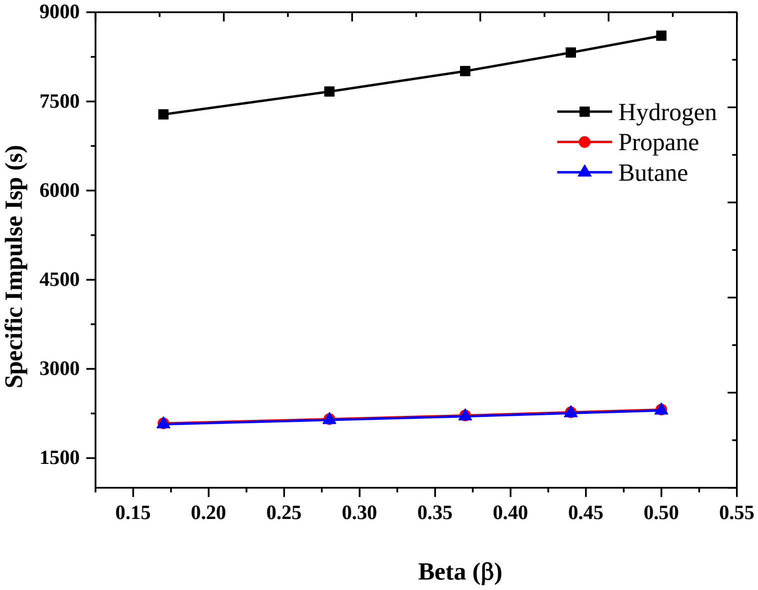

Fig. 4. Variation specific impulse w.r.t. beta angle for pure hydrocarbon fuel

Table 3

Variation of performance for different BETA values considering hydrogen fuel

Fuel	Filling velocity (m/s)	BETA (β)	U_e (m/s)	F sp (N)	Isp (Sec)
Hydrogen	200.00	0.17	2321	1742	7280
	400.00	0.28	2164	1573	7666
	600.00	0.37	2038	1439	8010
	800.00	0.44	1934	1329	8321
	1000.00	0.50	1846	1238	8605

Table 4

Variation of performance for different BETA values considering Propane fuel

Fuel	Filling velocity (m/s)	BETA(β)	U_e (m/s)	F sp (N)	Isp (Sec)
Propane	200.00	0.17	1639	1090	2083
	400.00	0.28	1533	967	2155
	600.00	0.37	1449	871	2216
	800.00	0.44	1380	793	2269
	1000.00	0.50	1322	728	2314

Table 5

Variation of performance for different BETA values considering butane fuel

Fuel	Filling velocity (m/s)	BETA (β)	U_e (m/s)	F sp (N)	Isp (Sec)
Butane	200.00	0.17	1645	1098	2070
	400.00	0.28	1539	975	2142
	600.00	0.37	1455	878	2203
	800.00	0.44	1385	799	2256
	1000.00	0.50	1327	734	2301

Figure 5, 6 and 7 show the effect of 50% blended fuels on the formation of detonation velocity, specific thrust, and specific impulse. It depicts, that a larger β value translates to a decrease in the air-to-fuel mass ratio of the reactants [36]. As heat released from the combustion process decreases the kinetic energy of the additional air, leads to an increase in the specific impulse [37]. The butane fuel blended with hydrogen and propane has a maximum detonation velocity of about 1643 m/s.

However, hydrogen blended with propane produces a maximum detonation velocity of 1739 m/s at β= 0.17 shown in Figure 5.

In pure fuels, the highest specific impulse is achieved by hydrogen fuel with the value of 8605 s and at a filling velocity of 1000 m/sat β value of 0.5. The specific impulse of 2314 s, 2301 s, 2172 s, 2194 s, and 2150 s was achieved by Propane, Butane, the blend of Hydrogen and Propane, Hydrogen and Butane, and the blend of Propane and Butane respectively at β value of 0.5.

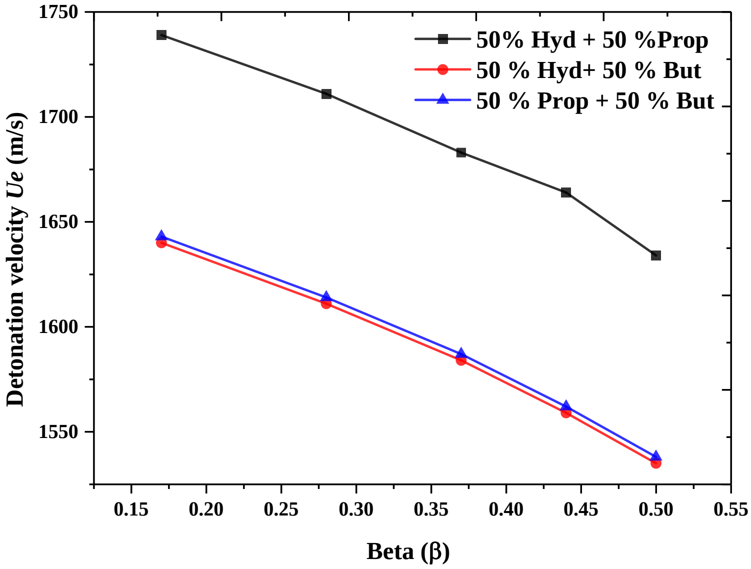

Fig. 5. Variation detonation velocity w.r.t. beta angle for blended hydrocarbon fuel

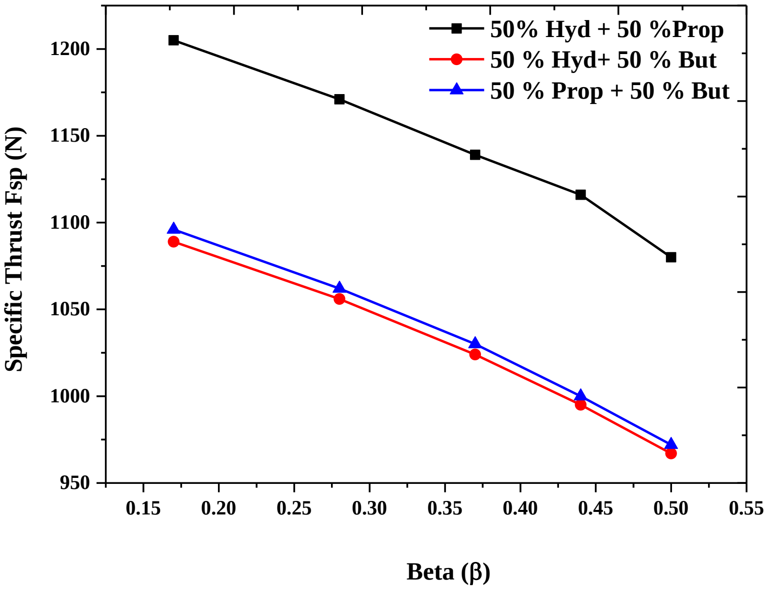

Fig. 6. Variation of Specific thrust w.r.t. beta angle for blended hydrocarbon fuel

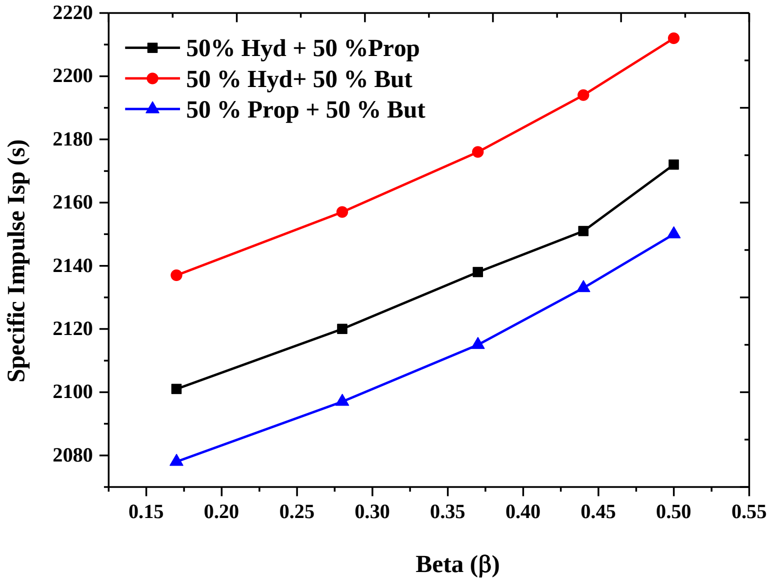

Fig. 7. Variation specific impulse w.r.t. beta angle for blended hydrocarbon fuel

Analytically calculated the performance of various blended fuels with the variation of β angle (purge-to-valve-open time ratio) shown in Table 6, 7 and 8. The result of hydrogen and propane blended fuel at different β angles varies from 0.17 to 0.50. In the first case, corresponding to the pure hydrogen fuel at the same β angle as well as the same refilling velocity, the blended hydrogen-propane fuel generates specific thrust and impulse lowering about 30% and 70% respectively. Therefore, all the blended fuels generate much lower performance compared to the pure fuels. However, in blended fuels, hydrogen-butane has a maximum specific impulse of 2212 s at β =0.5 compared to the other blended fuels.

Table 6
Variation of performance for different BETA (β) values considering the blend of Hydrogen and propane fuel

Fuel	Filling velocity (m/s)	BETA (β)	U_e (m/s)	F sp (N)	Isp (Sec)
50% Hyd + 50% Prop	200.00	0.17	1739	1205	2101
	400.00	0.28	1711	1171	2120
	600.00	0.37	1683	1139	2138
	800.00	0.44	1664	1116	2151
	1000.00	0.50	1634	1080	2172

Table 7
Variation of performance for different BETA (β) values considering the blend of Hydrogen and Butane fuel

Fuel	Filling velocity (m/s)	BETA (β)	U_e (m/s)	F sp (N)	Isp (Sec)
50% Hyd + 50% But	200.00	0.17	1640	1089	2137
	400.00	0.28	1611	1056	2157
	600.00	0.37	1584	1024	2176
	800.00	0.44	1559	995	2194
	1000.00	0.50	1535	967	2212

Table 8
Variation of performance for different BETA (β) values considering the blend of Propane and butane fuel

Fuel	Filling velocity (m/s)	BETA (β)	U_e (m/s)	Fsp (N)	Isp (Sec)
50% Prop + 50% But	200.00	0.17	1643	1096	2078
	400.00	0.28	1614	1062	2097
	600.00	0.37	1587	1030	2115
	800.00	0.44	1562	1000	2133
	1000.00	0.50	1538	972	2150

4. Conclusion

Pure fuel & its blend of 50% study were accomplished on detonation wave propagation using hydrogen, propane, and butane fuels in a PDE. Formulas were employed for analytical calculations and implemented as a benchmark for computational analysis. The results are validated using available experimental work literature, and they match previous work. The analytical results are as follows:

i. Hydrogen fuel forecasts the maximum value of 2321 m/s at 0.17 beta value and having a specific impulse of 7280 s. The lowest value of 1846 m/s at 0.5 beta value and having a specific impulse of 8605 s. The fuel with hydrogen had the highest impulse out of the three fuels.
ii. Simple light-molecule-containing combustion products tend to produce greater detonation velocity values and detonate more easily. Butane achieves the lowest particular impulse with a value of 2070 s because heavier hydrocarbons are less susceptible to detonation.
iii. It is shown that; propane, butane, and a 50 % blend of hydrogen + propane, hydrogen +butane, and propane+ butane can also be utilized as fuel for PDE as substitute fuels so that difficulties formed in PDE by using hydrogen fuel can be eradicated.

This method works well for forecasting PDE parameters, but the analytical findings can also be used to direct future work on creating a workable pulse detonation engine.

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References

[1] Harish, H. V., Birlie Fekadu, and Manjunath K. "Numerical Studies on Thermo-Hydraulic Characteristics of Turbulent Flow in a Tube with a Regularly Spaced Dimple on Twisted Tape." *CFD Letters* 13, no. 8 (2021): 20-31. https://doi.org/10.37934/cfdl.13.8.2031
[2] Stephen, R. "Turns. An introduction to combustion: concepts and applications." *Mechanical Engineering Series*. McGraw Hill (2000).
[3] Maciel, E. C., and C. S. T. Marques. "2-D simulation with OH* kinetics of a single-cycle pulse detonation engine." *Journal of Applied Fluid Mechanics* 12, no. 4 (2019): 1249-1263. https://doi.org/10.29252/jafm.12.04.29593
[4] Al Rizeiqi, Nasser Mohammed, Nasser Al Rizeiqi, and Ali Nabavi. "Potential of Underground Hydrogen Storage in Oman." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 27, no. 1 (2022): 9-31. https ://doi.org/10.37934/araset.27.1.931
[5] Ebrahimi, Houshang B., and Charles L. Merkle. "Numerical simulation of a pulse detonation engine with hydrogen fuels." *Journal of Propulsion and Power* 18, no. 5 (2002): 1042-1048. https://doi.org/10.2514/2.6053
[6] Xisto, Carlos, Olivier Petit, Tomas Grönstedt, and Anders Lundbladh. "Assessment of CO_2 and NO_x emissions in intercooled pulsed detonation turbofan engines." *Journal of Engineering for Gas Turbines and Power* 141, no. 1 (2019): 011016. https://doi.org/10.1115/1.4040741

[7] Yungster, Shaye, K. Radhakrishnan, and K. Breisacher. "Computational and experimental study of NO_x formation in hydrogen-fueled pulse detonation engines." In *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, p. 3307. 2004. https://doi.org/10.2514/6.2004-3307

[8] Hanraths, Niclas, Myles D. Bohon, Christian Oliver Paschereit, and Neda Djordjevic. "Unsteady Effects on NO_x Measurements in Pulse Detonation Combustion." *Flow, Turbulence and Combustion* 107 (2021): 781-809. https://doi.org/10.1007/s10494-021-00252-3

[9] Djordjevic, Neda, Niclas Hanraths, Joshua Gray, Phillip Berndt, and Jonas Moeck. "Numerical study on the reduction of NOx emissions from pulse detonation combustion." *Journal of Engineering for Gas Turbines and Power* 140, no. 4 (2018): 041504. https://doi.org/10.1115/1.4038041

[10] Yungster, Shaye, and Kevin Breisacher. "Study of NOx formation in hydrocarbon-fueled pulse detonation engines." In *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, p. 4210. 2005. https://doi.org/10.2514/6.2005-4210

[11] Hishida, Manabu, Toshi Fujiwara, and Sho-ichi Ito. "A Multi-Cycle CFD Analysis of Oxyhydrogen Pulse Detonation Engine." In *44th AIAA Aerospace Sciences Meeting and Exhibit*, p. 557. 2006. https://doi.org/10.2514/6.2006-557

[12] Ma, Fuhua, Jeong-Yeol Choi, and Vigor Yang. "Internal flow dynamics in a valveless airbreathing pulse detonation engine." *Journal of Propulsion and Power* 24, no. 3 (2008): 479-490. https://doi.org/10.2514/1.29957

[13] Kawai, Soshi, and Toshi Fujiwara. "Numerical analysis of first and second cycles of oxyhydrogen pulse detonation engine." *AIAA Journal* 41, no. 10 (2003): 2013-2019. https://doi.org/10.2514/2.1891

[14] Fan, Wei, Jianling Li, Qiang Li, and Chuanjun Yan. "Numerical investigation on multi-cycle operation of pulse detonation rocket engine." *International Journal of Turbo and Jet Engines* 25, no. 3 (2008): 189-196. https://doi.org/10.1515/TJJ.2008.25.3.189

[15] Mohanraj, Rajendran, and Charles Merkle. "A numerical study of pulse detonation engine performance." In *38th Aerospace Sciences Meeting and Exhibit*, p. 315. 2000. https://doi.org/10.2514/6.2000-315

[16] Yungster, Shaye, and Hugh Perkins. "Multiple-cycle simulation of a pulse detonation engine ejector." In *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, p. 3630. 2002. https://doi.org/10.2514/6.2002-3630

[17] Xisto, Carlos, Olivier Petit, Tomas Grönstedt, Andrew Rolt, Anders Lundbladh, and Guillermo Paniagua. "The efficiency of a pulsed detonation combustor-axial turbine integration." *Aerospace Science and Technology* 82 (2018): 80-91. https://doi.org/10.1016/j.ast.2018.08.038

[18] Zhang, Zhihong, Zhiqiang Li, Yunke Wu, and Xingdong Bao. "Numerical studies of multi-cycle detonation induced by shock focusing." In *Turbo Expo: Power for Land, Sea, and Air*, vol. 49750, p. V04AT04A041. American Society of Mechanical Engineers, 2016. https://doi.org/10.1115/GT2016-56713

[19] Cambier, J-L., and J. K. Tegner. "Strategies for pulsed detonation engine performance optimization." *Journal of Propulsion and Power* 14, no. 4 (1998): 489-498. https://doi.org/10.2514/2.5305

[20] Li, Chiping, K. Kailasanath, and Gopal Patnaik. "A numerical study of flow field evolution in a pulsed detonation engine." In *38th Aerospace Sciences Meeting and Exhibit*, p. 314. 2000. https://doi.org/10.2514/6.2000-314

[21] Wintenberger, E., J. M. Austin, M. Cooper, S. Jackson, and J. E. Shepherd. "Analytical model for the impulse of single-cycle pulse detonation tube." *Journal of Propulsion and Power* 19, no. 1 (2003): 22-38. https://doi.org/10.2514/2.6099

[22] Azami, Muhammad Hanafi, and Mark Savill. "Pulse detonation assessment for alternative fuels." *Energies* 10, no. 3 (2017): 369. https://doi.org/10.3390/en10030369

[23] Ma, Fuhua, Jeong-Yeol Choi, and Vigor Yang. "Thrust chamber dynamics and propulsive performance of single-tube pulse detonation engines." *Journal of Propulsion and Power* 21, no. 3 (2005): 512-526. https://doi.org/10.2514/1.7393

[24] Heiser, William H., and David T. Pratt. "Thermodynamic cycle analysis of pulse detonation engines." *Journal of Propulsion and Power* 18, no. 1 (2002): 68-76. https://doi.org/10.2514/2.5899

[25] Sonachalam, M., P. PaulPandian, and V. Manieniyan. "Emission reduction in diesel engine with acetylene gas and biodiesel using inlet manifold injection." *Clean Technologies and Environmental Policy* 22 (2020): 2177-2191. https://doi.org/10.1007/s10098-020-01968-y

[26] Ma, Fuhua, Jeong-Yeol Choi, and Vigor Yang. "Propulsive performance of airbreathing pulse detonation engines." *Journal of Propulsion and Power* 22, no. 6 (2006): 1188-1203. https://doi.org/10.2514/1.21755

[27] Gong, Jishuang, and Hu Ma. "Experimental study on pulse detonation engine with two-phase inhomogeneous mixture." *International Journal of Aerospace Engineering* 2020 (2020): 1-11. https://doi.org/10.1155/2020/8816807

[28] Ma, Lin, Jay Jeffries, Ronald Hanson, Kevin Hinckley, Pierre Pinard, and Anthony Dean. "Characterization of the fuel fill process in a multi-cycle pulse detonation engine using a diode-laser sensor." In *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, p. 3834. 2005. https://doi.org/10.2514/6.2005-3834

[29] Ma, Fuhua, Jeong-Yeol Choi, and Vigor Yang. "Thrust chamber dynamics and propulsive performance of multitube pulse detonation engines." *Journal of Propulsion and Power* 21, no. 4 (2005): 681-691. https://doi.org/10.2514/1.8182

[30] Kailasanath, K., G. Patnaik, and C. Li. "The flowfield and performance of pulse detonation engines." *Proceedings of the Combustion Institute* 29, no. 2 (2002): 2855-2862. https://doi.org/10.1016/S1540-7489(02)80349-2

[31] Turns, Stephen R. *Introduction to combustion*. Vol. 287. New York, NY, USA: McGraw-Hill Companies, 1996.

[32] Yildiz, Melih, and Bilge Albayrak Çeper. "Estimation of equilibrium combustion products of diesel-biodiesel fuel blends using the developed solving process for CnHm and CαHβOg fuel blends." *International Journal of Automotive and Mechanical Engineering* 14, no. 2 (2017): 4332-4347. https://doi.org/10.15282/ijame.14.2.2017.16.0345

[33] Taylor, Brian, David Kessler, Vadim Gamezo, and Elaine Oran. "The influence of chemical kinetics on the structure of hydrogen-air detonations." In *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, p. 979. 2012. https://doi.org/10.2514/6.2012-979

[34] Valli, D. Mahaboob, and D. R. T. K. Jindal. "Pulse detonation engine: parameters affecting performance." *International Journal of Innovative Research in Science, Engineering and Technology* 3, no. 4 (2014).

[35] Muthuswamy, Sonachalam, and Manieniyan Veerasigamani. "Comparative experimental analysis on dual fuel with biodiesel-acetylene in reactivity controlled compression ignition engine." *International Journal of Ambient Energy* 43, no. 1 (2022): 6317-6328. https://doi.org/10.1080/01430750.2021.2014958

[36] Bakar, Shahirah Abu, Norihan Md Arifin, and Ioan Pop. "Stability Analysis on Mixed Convection Nanofluid Flow in a Permeable Porous Medium with Radiation and Internal Heat Generation." *Journal of Advanced Research in Micro and Nano Engineering* 13, no. 1 (2023): 1-17. https://doi.org/10.37934/armne.13.1.117

[37] Rusdi, Nadia Diana Mohd, Siti Suzilliana Putri Mohamed Isa, Norihan Md Arifin, and Norfifah Bachok. "Thermal Radiation in Nanofluid Penetrable Flow Bounded with Partial Slip Condition." *CFD Letters* 13, no. 8 (2021): 32-44. https://doi.org/10.37934/cfdl.13.8.3244