Study Of Feasibility Of Pulse Detonation Engine Powered By Alternative Fuels

Mahammadsalman Warimani, Muhammad Hanafi Azami, S. A. Khan, Ahmad Faris Ismail

***Abstract:** World energy demand will continue to increase because of the development of the economy of the world and an increase in population. Non-renewable crude oil- derived liquid fuels are used in the world for more than two hundred years. 90 % of liquid fuels are estimated to be consumed for energy generation and transportation. Liquid fuels cause environmental pollution like carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOx) and sulfur-containing residues which results in global warming. As we know energy is required but it is short supply, on other side waste is unwanted but it also unavoidable. Agricultural, industrial & domestic waste can be converted into biodiesel, biogas utilizing various techniques. Biogas, biodiesel, biomass, biofuel, alcohol, vegetable oils and so on can solve environmental problems. A pulse detonation engine is anticipated to be a high- performance, next-generation aerospace propulsion engine. This new concept propulsion systems that use repetitive detonations to generate power or thrust. This review is, therefore, a parallel comparison with the hope of analyzing comparatively various biofuels that have been used and documented for PDE. Biofuel combustion characteristics are also investigated in detonation mode. The strategy for exploring the possibility of using biofuels for PDE operation is presented here.*

Key words -Pulse detonation engine, Biofuels, and combustion

I. INTRODUCTION

A number of research publications in the globe specially in Europe and the USA showing more interest in sustainable and economical sources of biofuels [1].The two most critical environmental problems that cause climate change are greenhouse gases and clean development mechanism. In the meantime, petroleum fuels are decreasing [2]. Non-renewable crude oil- derived liquid fuels are used in the world for more than two hundred years; 90 % of liquid fuels are estimated to be consumed for energy generation and transportation. Liquid fuels cause environmental pollution like carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x) and Sulphur-containing residues which results in global warming. With populaces expanding quickly and many developing nations extending their manufacturing base and output, overall vitality request will undoubtedly increment. Then again, realized raw petroleum stores could be exhausted in under 50 years at the present rate of utilization [3]. Due to the rising price, non - renewability and environmental disadvantages of fossil fuels, researchers have sought the appropriate alternative renewable fuels [4][2]. Depending on the PDE type, they can range from simple single tube systems to multi-tube systems, valve-free or mechanical valves, they can be used as combustion chambers for gas turbine and turbofan engines, and they can also be used for rocket propulsion. The PDE can range in size from micro - engines to huge gas turbine or turbojet engine systems [5]. PDE physical parameters are dependent on the fuel being used in them significantly [6]. This paper aims to investigate various alternative fuel-based research and make a comparative analysis of all fuels using conventional fuels used in PDE.

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II. PULSE DETONATION ENGINE

A pulse detonation engine is anticipated to be a high-performance next-generation aerospace propulsion engine [7]. The attention of researchers from all over the world in the propulsion field has now turned to PDE as their main topic. These involve researches from the United States, Russia, Japan and China, Germany, and Malaysia. From the past few decades, the number of research publications increased considerably [8]. PDE is a novel idea thrust systems that use monotonous ignitions to generate power or thrust [9]. It is a quasi-constant volume combustion process that is not stable in a flow. Detonations are supersonic waves of combustion as opposed to deflagrations. The pressure increases across a detonation front as the specific volume decreases. Detonation occurs in a tube that is closed at one end and leaves behind hot, pressurized gas [10]. In PDE, fuel is burned as a self-governing detonation wave that propagates through a tube [7]. It was Berthelot in 1881 and Vieille in 1883 who systematically measured the velocity of detonation in a variety of gaseous fuels (e.g., H_2, C_2H_4, C_2H_2) mixed with different oxidizers (e.g., O_2, NO, N_2O_4) and diluted with different amounts of inert nitrogen, thus confirming the existence of detonations in gaseous explosive mixtures [11].A wide range of applications for pulse detonation engines has been proposed [10]. It is having more efficiency than an air-breathing rocket engine [12]. The Constant Volume Combustion Cycle Engine (CVCCE) program at the Glenn Research Center of National Aeronautics and Space Administration (NASA) seeks to replace the constant combustion pressure in a conventional gas turbine engine with constant combustion volume.

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The leader in achieving constant combustion volume in a gas turbine is a pulse detonator [13]. PDE would have better performance than turbojets above 3.5 Mach numbers [10].

PDE PROCESS

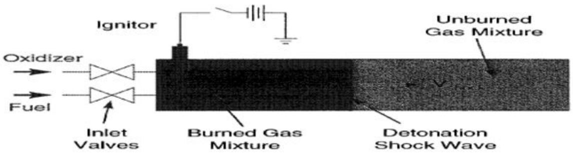

Figure 1. Working of pulse detonation engine [14].

The pulse detonation engine consists of a tube in which the mixture of fuel and oxidizer is detonated, the combustion gasses coming out of detonation chamber having high velocity. Finally, detonation chamber blowdown and refill occur — figure 1. Shows schematic spark-ignited PDE, the fuel-oxidizer (usual oxygen) is admitted into the combustion chamber through the inlet valves, which are then closed, through inlet valve fuel and oxidizer enters the combustion chamber. And the combustion chamber is closed, and when ignitor is fired, the detonation wave from the combustion tube spreads. Thrust pulse is produced when the combustion chamber is left by burnt gases. Hot gasses in the combustion chamber must be removed, and the detonation chamber must be replenished with fuel and oxidizer to achieve a high thrust level, this cycle must be repeated very fast [14].

III. WHY PULSE DETONATION ENGINE PREFERRED

Very rapid conversion of material and energy is the critical detonation future. This quick burning, about 10,000 times, is faster than in a flame. Due to the speed of a process, the overall process is almost constant volume ; there is no time for pressure equilibrium [15]. PDE based air breathing propulsion systems promise significant performance advantages over turbojet ramjets by lower complexity, lower weight unit thrust, lower unit cost [19]. The PDE cycle will be an attractive propulsion system due to the reliability benefits of very few moving parts, engine scalability ,and geometry flexibility [13].

IV. COMMON FUELS USED IN PDE

- **Propane**

Propane has a molecular formula C3H8. It is having a melting temperature of 85.45 K which is the lowest of all known organic compounds. Propane is an ideal model for exploring the structure melting relationships due to its lowest melting point out of the largest class of compounds known in nature. Propane is the most abundant organic natural reservoir on Earth and one of the most common fuels [16]. Propane may be a useful surrogate fuel for preliminary studies of the pulse detonation engine [17].

- **JP-10**

The air force report laboratory (AFRL) Fuels Branch (Wright Patterson Air Force Base) required the measurement and modeling of physical properties on an aviation turbine fuel. JP -10 fluid has a significant density (0.94 g / cm^3) and a specific impulse of 297.4 sec. These characteristics, together with the lowest freezing point of the fluid (−79 ° C), have made this fluid the only air - breathing missile fuel currently used by the United States [18]. The tetrahydro dicyclopentadiene exo-isomer (THDCPD) is the main component of a synthetic liquid aircraft and missile fuel called JP-10 which is also attractive for rocket applications due to its desirable physical properties and high energy density compared to more conventional blended fuels [19].

- **Kerosene**

Kerosene, an industrial petroleum product that has a large number of petroleum hydrocarbons (C9-C15) [20]. Russian - built kerosene fueled rocket engines such as the RD-170 or its proposed U.S. counterparts such as the RD-704, the Fastrack engine and the combined - cycle hydrocarbon rocket engine were identified as potential candidates for reusable single - stage launch vehicles to orbit [21]. Aviation kerosene will continue to play a significant role on a global scale for a long time [22].

WORK WAS DONE ON COMMON FUELS USED IN PDE

Fuel used	Conclusion
JP10-air.	Detonation speed is lower than the theoretical CJ values &its value is above 1600 m/sec. Deflagration to detonation (DDT) with JP10-air can be obtained for a tested equivalence range of 0.9 - 1.3 [23].
Propane-air	Wave velocities in stoichiometric conditions are above 1500 m / sec. Poor mixture control and fuel chemistry are factors that may have contributed to the detonation problem [23].
Liquid kerosene Oxygen	The wave velocity even reached 111.14 % of the CJ detonation wave velocity, and the pressure spike reached 74.25 % and 73.98 % of the CJ pressure level, the result was that the pressure profile and the wave velocity both met the criteria for stable detonation waves for the Shchelkin spiral length 30 cm (6D) [24].
JP-10 vapor	The velocity in the stoichiometric JP-10/air mixture is nearly equal to, but still slightly lower than, the CJ velocity presented. Simulated detonation pressures are reasonably consistent with simulation detonation pressure on monodispersed droplets of different diameters, and initial concentrations indicated the need for small droplets and near - equivalent initial concentrations to achieve CJ speed and pressure [25].
Vapor-phase JP-10 Combinations	Here the self - supporting detonation wave's average velocity was five hundred and ten m/s, which is as small as twenty six percent of the C J value. The deflagration wave catches up with the shock which is in front, and the ignition trend begins at the location of the compression instrument p7. The optimum DDT absorption is 164.54 g / m3, and the analogous speed of ignition is 560 m/s [26].

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Vapor-phase JP-10 Combinations	The velocity of the wave obtained from the pressure transducers is checked against the calculated value and typically below 1%. In Detonations, a tiny fraction of C6 H14 (0.07% of the total mixture) could be initiated in mixtures [27].

V. WHY BIO FUELS?

Biofuel is considered an alternative oil fuel worldwide due to the problem of Earth's environment and energy dry out [28]. Biofuels depend on the use of biological materials such as plants to produce hydrocarbon-based fuels, creating a further carbon cycle loop. The biomass used to produce fuel would absorb CO_2 from the atmosphere as it grows before it is harvested. The use of biofuels as a replacement for kerosene has therefore been discussed many times over the past few years [10]. A large amount of waste is generated because of everyday human being activities. World energy demand will continue to increase because of the development of the economy of the world and an increase in population. For decreasing the dangerous effects of the waste product on health & environment, various disposal techniques are necessary. Agricultural, industrial & domestic waste can be converted into biodiesel, biogas utilizing various techniques [29]. Gas to liquids, coal to liquids, biofuels, and oil sand bitumen, were identified as non-conventional methods to produce liquid fuel. Their combined contribution is projected to rise from the current 3% to about 9% over the next two decades. Therefore, the use of alternative, non-petroleum derived hydrocarbon fuels is likely to be emphasized in a rational future energy use scenario [30].

Following the Iraq / Mideast crisis, dependence on foreign sources of petroleum has again been dramatized, and a renewed interest in alternative fuels has sparked [31] as we know due to the non-renewable nature of fossil fuels, shortage of fuel about to happen [1]. This situation gave rise to an interest in the identification and channeling of renewable fuels [3]. Biogas, biodiesel, biomass, biofuel, alcohol, vegetable oils and so on can solve environmental problems [2]. It is much easier to focus on what is termed “drop-in” fuels. These are alternative fuels that have been tested and certified without modification for use in existing hardware [32]. Because of limited farmland availability, biofuels can only supply a small percentage of the energy needs of most countries [33]. Biofuels are becoming competitive with crude oil prices. Bio-jet fuels will require additional processing beyond biodiesel or ethanol fuels. It is therefore expected that a bio -jet fuel will cost more than bio diesel fuel. Coal or natural gas synthetic fuels are likely to remain more competitive than biofuels [33]. Preheating or acceleration to high velocity is required to detonate heavy hydrocarbon fuels like Jet-A & Biofuels [34]. Currently approved fuels are in relatively short supply and costly [35]. As the supply of fossil fuels decreases, the price of fuel will rise, and higher fuel prices will most likely lead to higher supplies of alternative renewable energy. Renewable sources of energy currently cost more than conventional fossil fuels but can become economically viable in the near future [10].

- **Micro algae**

Microalgae required due to several significant benefits, including higher photosynthetic efficiency, more energy yields per hectare. More biomass production, more growth rates, and farming land not needed to be related to other alternative fuels. This alternative fuel is having similar properties of Petro diesel. Microalgae used as a replacement to biodiesel and none of the other alternative fuel as capable as microalgae [36]. Oil content in microalgae by weight of dry biomass can exceed 80% [37]. Microalgae have a significant interest in the production of biofuels of the next generation that cannot be treated as different from petroleum fuels based on their properties. This is because the use of microalgae for the production of biofuels would have less adverse effects on food supply and other agriculture as they can be grown on non - arable land using fresh, waste or saline water sources and enable more efficient recycling of nutrients and higher productivity [38].

- **Biogas**

Combustion systems capable of operating using biogas as a fuel would contribute to help combat continuous global warming by burning methane gas from organic waste instead of allowing it to escape into the atmosphere where it adds to the greenhouse effect [39]. In addition, a few percentages of reactive material such as hydrogen sulphide (H_2S up to 1 - 5 %) and hydrogen (H_2 up to 0 - 1 %) can be found in biogas. These reactive materials may increase the possibility of igniting and propagating the biogas to produce high - speed deflagrative waves of combustion. The deflagration wave could transit under certain circumstances into the faster transmission of combustion accompanied by a shock wave called detonation [39]. Biogas composition varies depending on its source and preparation method. Methane (CH_4) at a volumetric percentage of 50-60% and carbon dioxide (CO_2) at 25-50% are the significant components of biogas. Some minor constituents, like H_2S, N_2, and O_2, sometimes exist [29]. K. M. Saqr et al. [40], scrutinize that, When the percentage of methane in the biogas was not less than 65 %, detonation was found if the dilution of nitrogen is not higher than 8 %. In some cases, where biogas is produced by in-plant generators, the percentage of methane is about 50 to 60 %. Consequently, consistent detonation for energy generation applications using such fuel is somewhat challenging to achieve. One possible solution is to enrich biogas with some highly detonating gasses to improve its detonation properties. They used Chemical equilibrium calculations to calculate the ideal biogas detonation characteristics with two different secondary fuels, hydrogen, and hydrogen peroxide fuels. Several mixture ratios were formulated to represent a combustible biogas mixture with each of the 0.0 - 0.5 mixing ratios of the secondary fuels. Oxidizer used was air which having ambient pressure and 343K and equivalence ratio between 0.7 to 1.0. It was found that hydrogen peroxide - containing mixtures provide higher pressure and Mach number than hydrogen - containing mixtures.

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Hydrogen mixtures, on the other hand, provided higher detonation speed and temperature than hydrogen peroxide. The trends in hydrogen peroxide mixtures were in all cases much more favorable than the hydrogen mixtures. The molecular composition of hydrogen peroxide justified this. The addition of oxygen in the hydrogen peroxide molecular structure provides increased combustion for biogas, particularly close to stoichiometry and rich limits [40].

VI. NATURAL GAS

The significant components of dry natural gas are methane (CH_4) with a volumetric percentage of 96% and ethane (C_2H_6) with 2% Some minor components, sometimes such as propane, isobutane, n-butane, isopentane, hexanes, heptane also exist [41]. Natural gas is colorless, shapeless and odorless in its pure state. It is a flammable gas, and when burned, it provides a significant amount of energy. Compared to other fossil fuels, it is an environmentally friendly clean fuel. During the combustion of natural gas, sulfur dioxide emissions are negligible. Hence, the Nitrous oxide and carbon dioxide emissions are lower, thereby reducing the problems associated with the acid rain, ozone layer or the greenhouse gases [41]. But the sizes of tubes required to realize DDT in mixtures of feasble fuels, such as natural gas, with air, are in fact unacceptable in PDE according to available data [42]. S. M. Frolov et al. [42], In 2010, at the Semenov Institute of Chemical Physics ' Center for Pulse - Detonation Combustion, they applied the concept of fast DDT to develop and test an experimental model of the natural gas fueled pulse - detonation combustor (PDC). The most important result of this is the proof of the feasibility of cyclic deflagration to detonation with a detonation run up distance of 2.5–3 m in the near limited diameter tube (94 mm) with an open end at a separate feed for natural gas and air with a relatively low ignition energy of about 1 J. The problem of rapid DDT has been solved by careful selection of the shape and placement of obstacles, providing optimal adaptation of the acceleration rate of flames and the amplification of shock waves. Experimentally demonstrated the feasibility of controlled repeatable (with a frequency of up to 2 Hz) deflagration to detonation transition over a length of 3.5 m and further detonation propagation at an average speed above 1600–1700 m in a tube with an open end and separate supply of natural gas and air as fuel components [42].

VII. BIOGAS PDE EXPERIMENT RESULT IN MALAYSIA

Universiti Teknologi Malaysia (UTM) has been testing Biogas PDE at the High-Speed Reaction Flow Laboratory (HIREF), Universiti Teknologi Malaysia (UTM), Malaysia since 2005. This facility is utilized for research and learning of the features of biogas shock waves compared to numerous other gasiform oils and investigational learning of restricted biogas pulse ignition. Biogas consisted of sixty five percent methane with a carbon dioxide content of thirty five percent. At different percentages of dilution, the oxygen concentration in the oxidizer combination was adulterated with nitrogen gas. HIREF also conducted computational and investigational training of biogas fuel characteristics (High Speed Reacting Flow Laboratory) [43].

VIII. CURRENT WORKS ON VARIOUS BIOFUELS

M. H. Azami et al. [34], Focused on one - dimensional detonation mode of combustion analysis of alternative fuels. Originally, least circumstances for detonating each petroleum are established. Pressure, temperature and density ratios for different types of fuel are then methodically investigated at every step of the combustion tube. For the comparision of these fuels, the effect of different early circumstances is examined mathematically [34]. They concluded that biofuels from microalgae are the greatest profound to the early circumstances, Mass flux dissimilarity might levy drastic constraints on initial pressure changes at elevated mass flux, we can rise the initial pressure above a widespread choice, and also the paraphernalia of the preliminary heat affect Mach number ratios and specific volume significantly, Although differences in preliminary mass flux affect most temperature and pressure ratios [34]. PDE has been investigated by bio fuels by M. H. Azami et al. [36]. Various biofuels are tested for feasibility and effectiveness to be used in PDE. The key findings of their efforts are, in Mach number, compression, hotness, and precise bulk was identified by changing the initial bulk mutability, hotness and stress. Meanwhile, light fuels are detonated with no trouble, further increasing initial conditions caused in an abundant more chemical reaction rate as there were more free atoms available for reaction [36]. Single - pulse combustion wave speeds investigated for propane, natural gas and biogas in an uninterrupted channel by M A Wahid et al. [39]. Pulse combustion of Biogas and hydrocarbon - oxygen mixtures were investigated using a single pulse combustion tube experimentally and calculations based on 1-D inviscid flow theories. In the experiments, propane and natural gas containing 92.7%, methane and synthetic biogas containing 65% methane and 35% carbon dioxide, these three types of hydrocarbon fuels were used. At different percentages of dilution, mixtures were diluted using nitrogen. The composition of the mixture was determined and prepared by partial pressure technique. Experiments were done at the atmospheric condition, 1 atm, and 300 K. Fast response pressure transducers were used to determine the propagation velocity and pressure [39]. The following findings have been found,

1. The velocity data from the experiments show that propane is more sensitive to the propagation of detonation compared to natural gas and biogas. However, the likelihood of detonation in both hydrocarbon fuels decreases with an increase in nitrogen dilution [39].
2. Biogas combustion wave can be accelerated to propagate detonation by using an obstacle of 500 mm length with a nitrogen percentage of up to 35 %. By increasing the length of the obstacle, detonation may occur within a higher percentage of the dilution of nitrogen. The presence of obstacles in the biogas or natural gas pipelines, such as excessive gas, valve, and short-range junction, could speed up accidentally ignited mixture to detonate.

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If the number of obstacles in the gas pipeline is high, precaution or any means of ventilation should be applied [39]. T. Shimada et al. [28], presented a two-dimensional mathematical investigation of ignition using bioethanol. The two-phase detonation of ethanol/air authentication existed first and replicated in comparison with the ignition of JP10/air. They concluded that Detonation of ethanol/air has a minor cell size to relate for PDE superior to the ignition of JP10/air. The current prototypical ethanol response is rationally virtuous compared to the experimental speed. [28]. The significant components of dry natural gas are methane (CH_4) with a volumetric percentage of 96% and ethane (C_2H_6) with 2% Some minor components, sometimes such as propane, isobutane, n-butane, isopentane, hexanes, heptane's [41].

IX. CHALLENGES FOR APPLICATION OF BIOGAS IN PDE

Biogas / oxygen mixtures are less sensitive to detonation compared to hydrocarbons such as butane and propane. The main component of biogas is methane that can be used as fuel. Limiting the use of biogas as PDE fuel includes a lower calorific value, a comparatively large cell width and a lower critical point [2].

X. MITIGATION IN USING BIOGAS FOR PDE

Spark timing & fuel - to - air ratio needed to be maintained due to the poor quality of biogas combustion. It is possible to increase the efficiency of combustion by removing CO_2. Additives are added in small quantities to improve the combustion characteristics [2]. The fuel's ignition properties are critical to the detonation process. The fuel can be stored in several different forms, but must be delivered as a gas, liquid and/or solid of sufficiently small droplet size to allow a stable detonation to occur [44] [45]. For example, solid particles or liquid droplets must be no larger than several tens of microns to ensure that the particle breakup time is compatible with the detonation time scale [44].

XI. CONCLUSION

Raw petroleum stores could be exhausted in under 50 years at the present rate of utilization. Due to the rising price, non - renewability and environmental disadvantages of fossil fuels, researchers have sought the appropriate alternative renewable fuels. As the supply of fossil fuels decreases, the price of fuel will rise, and higher fuel prices will most likely lead to higher supplies of alternative renewable energy. Biofuel is considered an alternative oil fuel worldwide due to the problem of Earth's environment and energy dry – out. First, to achieve the above benefits of biofuels, it is necessary to increase the use of biofuels in order to increase the demand for biofuels and to boost the production of biofuels. By adding additives biofuels can be used in PDE as fuel.

REFERENCES

1 K. Dutta, A. Daverey, and J. Lin, “Evolution retrospective for alternative fuels : First to the fourth generation,” *Renew. Energy*, vol. 69, pp. 114–122, 2014.

2 A. G. Dairobi, M. A. Wahid, and I. M. Inuwa, “Feasibility Study of Pulse Detonation Engine Fueled by Biogas,” *Appl. Mech. Mater.*, vol. 388, pp. 257–261, 2013.

3 E. Crabbe, C. Nolasco-hipolito, G. Kobayashi, K. Sonomoto, and A. Ishizaki, “Biodiesel production from crude palm oil and evaluation of butanol extraction and fuel properties,” *Process Biochem.*, vol. 37, no. 2, pp. 65–71, 2001.

4 M. H. Gargari and S. M. Sadrameli, “Investigating continuous biodiesel production from linseed oil in the presence of a Co-solvent and a heterogeneous based catalyst in a packed bed reactor,” *Energy*, vol. 148, pp. 888–895, 2018.

5 P. Wolan´ski, “Detonative propulsion,” in *Available online at www.sciencedirect.com Proceedings of the Combustion Institute 34*, 2013, vol. 34, pp. 125–158.

6 A. S. Jayoria, B. A. Dogra, and T. Jindal, “Various fuels used in pulse detonation engine-A review,” in *5th National Symposium on Shock Waves*, 2018, no. February, pp. 1–9.

7 B. T. E. Ndo and T. F. Ujiwara, “A Simplified Analysis on a Pulse Detonation Engine Model,” *japan Soc. Aeronaut. Sp. Sci.*, vol. 44, no. 146, pp. 217–222, 2002.

8 D. M. Valli and T. K. Jindal, “Thrust Measurement of Single Tube Valve less Pulse Detonation Engine,” *Int. J. Sci. Eng. Res.*, vol. 4, no. Issue 3, pp. 1–8, 2013.

9 D. M. Valli and T. K. Jindal, “Pulse Detonation Engine : Parameters Affecting Performance,” *Int. J. Innov. Res. Sci. Eng. Technol.*, vol. 3, no. 4, pp. 11229–11237, 2014.

10 R. Singh, G. Ameyugo, and F. Noppel, *Jet engine design drivers: past, present, and future*. Woodhead Publishing Limited, 2012.

11 J. H. S.LEE, *The detonation phenomenon*. Cambridge University Press, 2008.

12 S. Tripathi and K. M. Pandey, “Review on factors affecting the performance of pulse detonation engine,” in *AIP Conference Proceedings*, 2018, vol. 1952, pp. 1–7.

13 E. Gutmark, J. Hoke, F. Schauer, D. Allgood, and R. Bradley, “Performance Measurements of Multicycle Pulse-Detonation-Engine Exhaust Nozzles,” *J. Propuls. Power*, vol. 22, no. 1, pp. 70–779, 2008.

14 B. Hitch, “An Analytical Model of the Pulse Detonation Engine Cycle,” in *40th AIAA Aerospace science meeting &exhibit*, 2002, no. c, pp. 1–14.

15 K. Kailasanath, “Review of Propulsion Applications of Detonation Waves,” *AIAA J.*, vol. 38, no. 9, pp. 1698–1708, 2000.

16 M. Podsiadło, A. Olejniczak, and A. Katrusiak, “Why propane?,” *J. Phys. Chem. C*, vol. 117, no. 9, pp. 4759–4763, 2013.

17 J. M. Austin and J. E. Shepherd, “Detonations in hydrocarbon fuel blends,” vol. 132, no. February 2002, pp. 73–90, 2003.

18 T. J. Bruno, M. L. Huber, A. Laesecke, E. W. Lemmon, and R. A. Perkins, *Thermochemical and thermophysical properties of JP-10*. 2006.

19 M. J. Zehe and R. L. Jaffe, “Theoretical calculation of jet fuel thermochemistry. 1. Tetrahydrodicylopentadiene (JP10) thermochemistry using the cbs-qb3 and G3(MP2)//B3LYP methods,” *J. Org. Chem.*, vol. 75, no. 13, pp. 4387–4391, 2010.

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20 T. GALIN, C. McDOWELL, and B. YARON, "The effect of volatilization on the mass flow of a non-aqueous pollutant liquid mixture in an inert porous medium: experiments with kerosene," *J. Soil Sci.*, vol. 41, no. 4, pp. 631–641, 1990.

21 T. Wang, "Thermophysics Characterization of Kerosene Combustion," *J. Thermophys. Heat Transf.*, vol. 15, no. 2, pp. 140–147, 2001.

22 V. P. Zhukov, V. A. Sechenov, and A. Y. Starikovskiy, "Autoignition of kerosene (Jet-A)/air mixtures behind reflected shock waves," *Fuel*, vol. 126, pp. 169–176, 2014.

23 F. R. Schauer, C. L. Miser, and K. C. Tucker, "Detonation Initiation of Hydrocarbon-Air Mixtures in a Pulsed Detonation Engine," no. January, pp. 1–11, 2005.

24 J. Li, W. Fan, C. Yan, and Q. Li, "Experimental investigations on detonation initiation in a kerosene-oxygen pulse detonation rocket engine," *Combust. Sci. Technol.*, vol. 181, no. 3, pp. 417–432, 2009.

25 L. Liu and Q. Zhang, "Numerical Simulations of the Effects of Droplet Size and Concentration on Vapour-Droplet JP-10 / Air Detonations," vol. 15, no. 1, pp. 175–190, 2018.

26 J. Huang, S. Li, Q. Liu, J. Li, and X. Chen, "Deflagration to detonation transition in JP-10 mist/air mixtures in a large-scale tube," *J. Hazard. Mater.*, vol. 339, pp. 100–113, 2017.

27 J. M. Austin and J. E. Shepherd, "Detonations in hydrocarbon fuel blends," *Combust. Flame*, vol. 132, no. 1–2, pp. 73–90, 2003.

28 T. Shimada, A. K. Hayashi, E. Yamada, and N. Tsuboi, "Numerical Study on Detonation Characteristics Using a Bio-Fuel," in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2012, no. January, pp. 1–11.

29 X. Meng, W. De Jong, and T. Kudra, "A state-of-the-art review of pulse combustion: Principles, modeling, applications, and R&D issues," *Renew. Sustain. Energy Rev.*, vol. 55, pp. 73–114, 2016.

30 K. Kumar and C. Sung, "A comparative experimental study of the autoignition characteristics of alternative and conventional jet fuel / oxidizer mixtures C," *Fuel*, vol. 89, no. 10, pp. 2853–2863, 2010.

31 R. O. Price, "Liquid hydrogen-an alternative aviation fuel?," *Int. J. Hydrogen Energy*, vol. 16, no. 8, pp. 557–562, 1991.

32 H. Pfaender, A. P. Payan, and D. N. Mavris, "Long-term Alternative Fuels Scenarios," in *AIAA/3AF Aircraft Noise and Emissions Reduction Symposium AIAA*, 2014, no. June, pp. 1–18.

33 D. Daggett, O. Hadaller, R. Hendricks, and R. Walther, "Alternative Fuels and Their Potential Impact on Aviation," *Icas-2006-5.8.2*, no. October 2006.

34 M. H. Azami *et al.*, "Comparative Analysis of Alternative Fuels in Detonation Combustion," in *52nd AIAA/SAE/ASEE Joint Propulsion Conference AIAA*, 2016, pp. 1–17.

35 A. H. Epstein and E. Hartford, "Aeropropulsion for Commercial Aviation in the Twenty-First Century and Research Directions Needed," *AIAA J.*, vol. 52, no. 5, pp. 7–10, 2014.

36 M. H. Azami and M. Savill, "Pulse Detonation Assessment for Alternative Fuels," *energies*, vol. 10, no. 367, pp. 1–19, 2017.

37 A. Karmakar, S. Karmakar, and S. Mukherjee, "Properties of various plants and animals feedstocks for biodiesel production," *Bioresour. Technol.*, vol. 101, no. 19, pp. 7201–7210, 2010.

38 Z. Ristovski *et al.*, "Experimental Investigations of Physical and Chemical Properties for Microalgae HTL Bio-Crude Using a Large Batch Reactor," *Energies*, vol. 10, no. 4, p. 467, 2017.

39 M. A. Wahid and H. Ujir, "Reacting Shock Waves Characteristics for Biogas Compared to Other Gaseous Fuel," in *The 4 th International Meeting of Advances in Thermofluids*, 2012, vol. 99, no. Imat 2011, pp. 90–99.

40 K. M. Saqr and H. I. Kassem, "Ideal detonation characteristics of biogas- hydrogen and -hydrogen peroxide mixtures," *Latest Trends Theor. Appl. Mech. Fluid Mech. Heat Mass Transf.*, vol. 69–72, no. September 2014, 2010.

41 S. Faramawy, T. Zaki, and A. A. E. Sakr, "Natural gas origin, composition, and processing: A review," *J. Nat. Gas Sci. Eng.*, vol. 34, pp. 34–54, 2016.

42 S. M. Frolov, "Natural-Gas-Fueled Pulse-Detonation Combustor," *J. Propuls. POWER*, pp. 1–6, 2010.

43 M. A. Wahid *et al.*, "Pulse Detonation Engine Research Development at High Speed Reacting Flow Laboratory - HiREF , Universiti Teknologi Malaysia," *Appl. Mech. Mater.*, vol. 388, pp. 285–291, 2013.

44 Thomas Bussing, *Pulse Detonation Engine Theory And Concepts Thomas*. 2019.

45 A. H. L. And and D. R. Ballal, *Gas Turbine Combustion - Alternative Fuels and Emissions*. 2010.

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