Chapter

A State of Art Review on Thermodynamics Performance Analysis in Pulse Detonation Combustor

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Abstract

Pulse detonation engines (PDEs) are most exciting for future propulsion generation. Detonation combustion in pulse detonation combustor is an energetic combustion process which is differs from other combustion process. The detonation wave propagation in detonation tube is a pulse setting combustion phenomena. Detonation combustion process is thousands times faster than deflagration combustion process. PDE utilizes several pulse of detonation wave to produce propulsive force. The potential applications of PDEs are drastically reduces the cost of orbit transfer vehicle system and flying mode applications. Of course it can be used as ground level applications also. Draw back are DDT in shortest possible time in the combustor. In this regards, worldwide researchers are focusing on scientific and technical issues related to improvement of PDC. The present chapter deals with review study on detonation combustion process, historical overview on chemical kinetics, calorimetric and entropy transport, energy and exergy analysis and factor effecting on deflagration to detonation transition with recommendable future research.

Keywords: pulse detonation combustor, CFD, detonation, deflagration, ejector

1. Introduction

The high speed engine concept was born in the early 1900s, which produced shaft work and designed to drive a variety of vehicles, including ships and locomotives, until further introduction of jet engine on 1930s. The history of pulse detonation engines concept can be traced back to German engineer Hoffmann, H. [1]. In 1941, they tested a prototype engine using acetylene-oxygen and benzene-oxygen mixtures. Earlier in between 1952 and 1956, Nicholls et al. [2] at the University of Michigan have independently come up with the idea of using intermittent detonation for propulsion system and built the first PDE, which utilized detonation of hydrogen-air mixture to produce thrust. When crude oil prices increased significantly in the mid-1980s Eidelman et al. reinitiated research on PDE to overcome these scarcities. Krzycki [3] experimentally studied the propane-air pulse detonation engine which is operating at 25–50 Hz at naval ordnance test station at China Lake, California on 1962. From this analysis it was observed that minimum thrust is produce at minimum operating frequency. Lynch et al. [4] performed CFD studies on PDREs and air breathing PDEs on 1990. Their analyses forecasted that PDEs would be incorporated with space transport vehicles by the early 2000s. Earlier starting in 1990s, experimental study of single and multi-pulse detonation engine combustor were conducted by Bussing et al. [5] at Adroit systems Inc., a company that was bought up by Pratt and Whitney on 2001. They tested pulse detonation engine using different fuels including hydrogen and ethylene. Most of the PDE research centers are found in Canada, US, Russia, China. There are very less number of PDE research centre in India, so researcher are focusing on pulse detonation research area as it is excited for future propulsion technology [6].

Propulsion applications of detonation can be classified into three categories: standing detonation, pulse detonation and rotating detonation [7–9]. The basic pulse detonation engine has a very simple structure. It consists of a constant area tube. The deflagration to detonation transition is controlled by supplying fuel and oxidizer in detonation tube. The ignition system and nozzle are used for accelerating the flow, which is to be used for propulsion. A practical pulse detonation engine may also have one or more devices to bring about deflagration to detonation transition such device are Shchelkin spiral and blockage [10]. The PDE consists of two or more combustion chamber, which is joined to common plenum chamber. The conditions are applied for accelerating the flow before entering the detonation tube with different nozzle. The can-annular four chambered PDE is can illustrated for propulsion system. In multi-chambered design, each chamber can be at different stage in the cycle, thus creating a smoother flow through the nozzle [11]. The ejector enhances the deflagration to detonation transition in detonation tube with an array setting in exit section of pulse detonation rocket engine. Another feature of the ejector design is that the detonation waves from the combustors can be used to enhance the propulsive performance, which provides additional thrust enhancement [12].

Detonation is a supersonic mode of combustion process. In combustion process detonation waves are much more energetic process than conventional deflagration combustion and it produces a very strong wave coupled with a chemical reaction zone, propagating at supersonic speed. A detonation wave compresses combustion mixture, increasing the combustion product pressure, density of species mass fraction. It is a subsonic combustion process and fuel air reaction propagates at relatively low speed and reasonably low pressure from a trailing reaction zone. The propagation of deflagration mode of combustion consists of diffusion of unburned gases ahead of flame front and burnt gases behind the combustion flame. Deflagration produces small decrease in pressure and can be modeled as a constant pressure process [13]. One of the primary attributes deflagration flame travels at a speed, which is significantly lower than that the speed of sound ($Ma < 1$). So it can be identify by subsonic combustion process. Detonation combustion is a constant volume combustion process. The strength of leading shock depends on the detonation wave propagation velocity. A simple planar model for the supersonic detonation shock wave is used for Chapman-Jouguet detonation model analysis [14]. This is a rapid exothermic reaction and instantaneously changes the local pressure and temperature. The ignition of fuel-air mixture can produce deflagration flame and later on transition to detonation wave. The different combustor geometry can accelerate the deflagration flame and transition to detonation wave. Several researchers have been studied on PDE with research gape and scope of future research work [15–17]. The applications of RDE chamber are jet engines, such as turbojet or gas turbine, ramjet or rocket. Continuous detonation wave engine is used for supersonic and hypersonic propulsion applications. The framework of French Research and Development and scientific research also consider these for space applications. However incoming reacting air-mixture is greater than the C-J velocity of fuel-air mixture. Such engine is scramjet engine with an oblique detonation wave at inlet to combustor called the oblique detonation wave engine [18]. Chapman [19] explained on 1889 that the minimum speed of burnt gas is equal to speed of sound in gas mixture. Later on Jouguet on 1905 [20] applied Hugoniot's method to explain the detonation velocity. The explosive mixture can get supported with two modes of combustion. When the flame propagates at slow velocity relative to unburnt gases, it is define as deflagration mode. In detonation mode wave propagates at about 2000 m/s accompanied by an overpressure rise is near about 20 bars [21–23]. They independently developed the basic thermodynamic model behind detonation. Principle operation of standing detonation engine is relatively simple. Fuel is injected into supersonic flow and detonation wave is stabilized inside the engine by wedge or other means and products are expanding inside nozzle. The combustion wave velocity can be propagates at higher the C-J detonation velocity within the Mach number of 5. The principle of rotating detonation engine (RDE) is based on the formation of detonation in a disk type combustion chamber. The shape of combustion chamber is toroidal or ring-like shape [24, 25]. The detonation wave parameters are depending on critical detonation tube diameter and minimum detonation tube diameter. The minimum and critical diameters are important parameters for evaluation of performance of PDE. The detonation will successfully propagate in a tube when the diameter must be larger than λ/3, where λ is the cell size. For square and rectangular ducts, the width and height of the duct must be larger than λ [26]. A review of the gas dynamics and chemistry of real detonation is discovered by Fickett and Davis [27]. They found out initiation of detonation wave, which follows by a series of percentage of fuel-oxidizer mixture in combustion chamber. The detonation wave in a confined tube causes the reaction of fuel-air mixtures, which creates turbulence; as a result "an explosion in an explosion" is takes placed. The two strong shock waves are created in the opposite direction, the forward shock waves are known as retonation. A self-propagating C-J detonation wave is formed at steady state retonation process. The pre-detonation wave velocity is 1000 m/s while the characteristic C-J detonation speed is over 2000 m/s. A large explosion occurs at onset of detonation, resulting in an over-driven detonation wave that decays to the C-J velocity. The wall roughness controls the wave propagation by inducing large-amplitude unsteady and turbulent flow, complex wave interaction processes and high temperature behind shock reflections. These effects represent ways that the flow can generate large-scale turbulence for flame folding and large temperature fluctuations causing detonation initiation [28].

2. Review on thermodynamics cycle analysis

A pulse detonation engine uses repetitive cycle of detonation waves to combust fuel-oxidizer mixture for producing thrust. PDE operates by propagating detonation wave through a tube filled with a combustible mixture and generates propulsive thrust. This process results are near about constant volume combustion process, which produces high pressures from the leading shock wave. Pulse detonation engine consists of valve less combustor with straight tube, which is closed at one end and open at other end. The pulse detonation engine combustion cycle consist of four basic thermodynamics process. The first process is filling time (t_{fill}) of fuel-air mixture for detonation combustion, which is estimated as length of the tube over filling velocity. The second one is detonation combustion. This process takes place within fraction of millisecond. As soon as the detonation wave reaches to the closed end region the pressure and velocity decrease from initial position to exit end region. Fully developed detonation wave travels with the magnitude of Chapman-Jouguet speed. This C-J speed of reacting fuel-air mixture varies between 1400 m/s and 1800 m/s. The detonation time of the wave (t_c) is therefore similarly estimated by the length of the tube over the C-J wave velocity. The time required for blow down (t_b) stage can be estimated by the length of the tube to the rarefaction velocity. At last in the purging process the tube is scavenged off hot detonation products by using fresh air. Purging process is necessary to prevent auto ignition of the fresh fuel-oxidizer mixture. The time taken for purging the tube with the fresh air (t_{purge}) is the length of the tube over the purging velocity [29]. So total sum of the time for all the four stages are as follows:

$$\mathrm{T} = t_{fill} + t_c + t_b + t_{purge} \tag{1}$$

The PDE can run by any fuel, liquid or gaseous, like natural gas, propane, bio-gas, hydrogen, kerosene, jet fuels and octane etc. From an engineering stand point fuel can be selected for based on heating value, detonability, ignition time, energy release, adiabatic flame temperature and sensivity with air [30]. Povinelli and Yungster [31] studied the thermodynamic cycle of hydrogen-air mixture at static conditions in pulse detonation combustor. The specific thrust, fuel consumptions and impulse of detonation combustion are analyzed by using CFD analysis with finite rate chemistry. Alam et al. [32] studied on Brayton, Humphery and ideal thermodynamics cycle analysis in pulse detonation combustor. They found Humphery cycle efficiency can be increases with higher value of compression ratio. The thermodynamics cycle efficiency of air breathing pulse detonation engine is studied by Wu et al. [33]. They found that chocked convergent-divergent nozzle is required to improve the efficiency. Vutthivithayarak et al. [34] discussed the Humphrey and F. J. (Fickett-Jacobs) cycles in PDE. These cycles are illustrated with hydrogen-air combustion for generic heat release.

3. Review on chemical kinetics and entropy transport

The two-step chemical kinetics model of detonation combustion has been studied by Fomin [35]. This kinetics model has been used for stoichiometric, lean and rich mixture for combustion. This model is also followed by Le Chatelier's principle and 2nd law of thermodynamics. The pulse detonation combustor has lower entropy change and self-pressure gain compared to isobaric combustion process for same operating conditions [36]. Mehdi Safari et al. [37] studied on entropy generation with species transport equation for detonation combustion by large eddy simulation. Detonation initiation in hydrogen-air depends on mixture sensivity and geometrical parameters. Qi et al. [38] investigated the thermodynamics characteristics of methane-air detonation in pressure gain combustor. They compared the entropy change in detonation combustion process with gas turbine cycle. They found that cycle efficiency enhance rate up to 11.89%. Lu et al. [39] studied on DDT in a channels with obstacles using chemical diffusive model (CDM) integrated with reactive

Navier stokes equation. They found that CDM reduces the ignition time of detonation wave. Wu et al. [40] studied on atomization of liquid fuel detonation combustion. They found that nozzle can effectively atomize fuel-air mixtures under high pressure condition. Maciel and Marques [41] studied on hydrogen fuelled single cycle pulse detonation engine in Ansys Fluent. When OH^* kinetics added to the reaction set, they found cellular structure of detonation wave front in reaction zone. Ivanov et al. [42] studied on hydrogen-oxygen flame acceleration and transition from DDT in a channel using reactive Navier-Stokes equations. They found that steady detonation wave front is form in wider detonation channels of 10 mm and closed to C-J detonation propagation speed. Srihari et al. [43] studied on stoichiometric ethylene-air mixture of detonation combustion with one-step overall reaction model. They found that chemical reaction models have capable to predict the detonation wave velocity with reasonable accuracy.

4. Review on energy and exergy analysis

Ma et al. [44] studied on temporal variation of activation energy release rate of iso-octane vapor-air mixture in an obstacle-filled detonation tube. Their result shows that the activation energy influences the flame propagation parameters and deflagration-to-detonation transition process. Hutchins and Metghalchi [45] studied on exergy analysis of pulse detonation engine. They found that during deflagration to detonation transition period exergy loss is more. Bellini and Lu [46] studied on exergy analysis of fuel-air mixture at high frequency source within the detonation chamber. They found that combustion product accelerates inside the combustor in presence of Shchelkin spiral. The exergy analysis of pulse detonation power device designed for power production using gaseous fuel methane (CH_4) and propane (C_3H_8) is analysis by Bellini and Lu [47]. The exergetic efficiency was analyzed for different cycle frequency corresponding to detonation tube length. Rouboa et al. [48] studied on exergy loss of hydrogen-air detonation during shock. They also observed exergy destruction increase with augmentation of hydrogen concentration in reacting mixture. Petela [49] studied on exergy analysis of gaseous fuel-air detonation. They observed that exergy gives a quantitative theoretical useful work that is obtained from different energy form combustion process and it is a function of system and environment. Som and Datta [50] and Som and Sharma [51] studied on theoretical model of energy and exergy balance in a spray combustion process. They found that exergy destruction in this combustion process can be reduced through proper control of chemical reactions.

5. Results from CFD simulation and calorimetric analysis

The numerical investigations have been done in Ansys fluent platform. The **Figure 1** shows that the ejector effects on unsteady detonation combustion wave phenomena in pulse detonation combustor. The time dependent detonation wave contour plots clearly shows that 0.033 seconds is required to reach the fully developed detonation wave [52]. They also found that ejector plays the vital role for vortex formation of reacting mixture in PDE combustor. They also observed that leading vortex rings are found in shrouded ejector taper angle of $+4^{\circ}$. The **Figure 2** shows the mass fraction contour analysis of NO_x pollutant number of hydrogen-air and

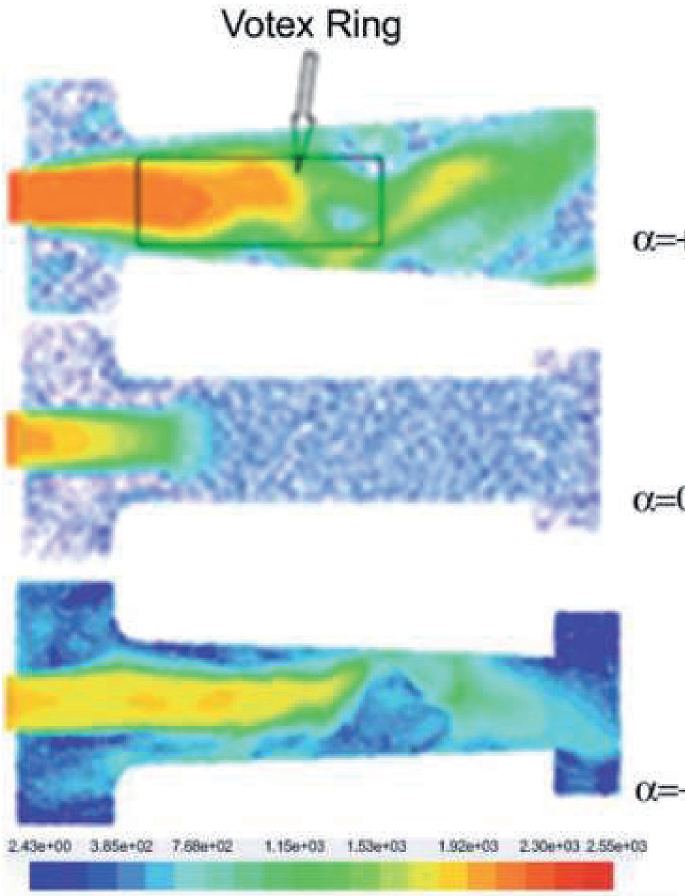

Figure 1.
Effect of shrouded ejectors on vortex ring formation of detonation wave [53].

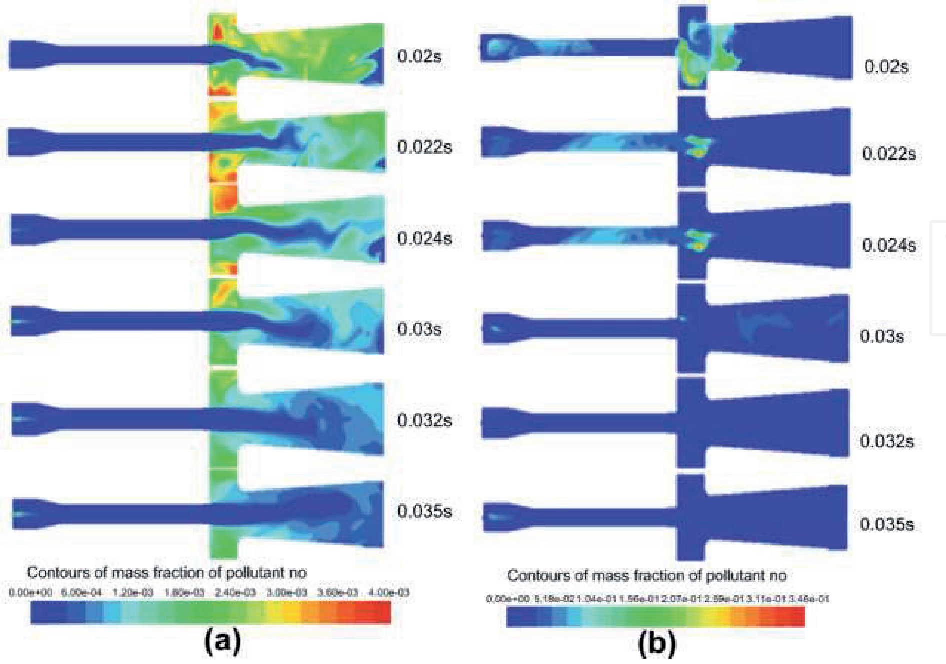

Figure 2.
The mass fraction contour analysis of NO_x *pollutant number of (a) hydrogen-air and (b) kerosene-air combustion [53].*

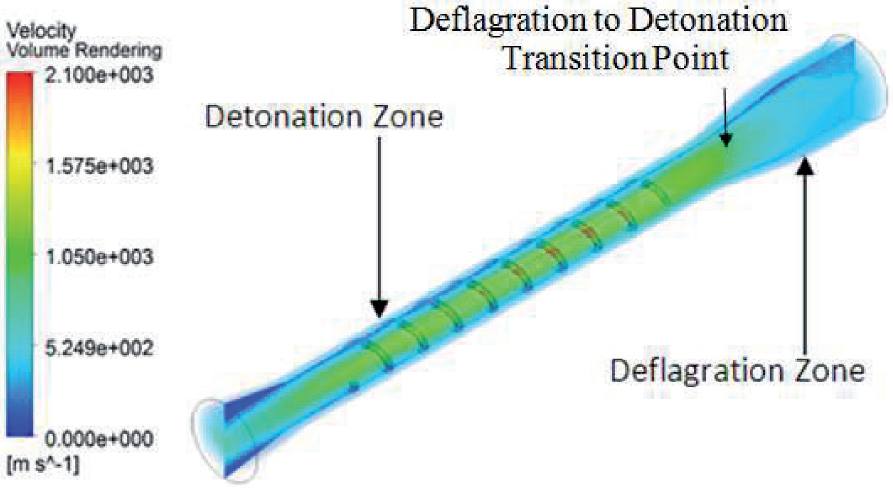

Figure 3.
Deflagration and detonation zone define by C-J velocity for exergy analysis [54].

kerosene-air detonation [53]. Lesser the fuel mass fraction higher the exergetic efficiency was found in pulse detonation combustor. The **Figure 3** shows the deflagration and detonation control volume for exergy analysis [54]. Alam et al. [55, 56] numerically studied on hydrogen-air detonation in pulse detonation combustor. Later on they also studied detonation combustion using alternative fuels, i.e. octane (C_8H_{18}), hexane (C_6H_{14}), pentane (C_5H_{12})-air combustion in PDE combustor. They observed combustion efficiency of pentane-air mixture is higher than that of other fuels. Alam et al. [57] studied the combustion wave propagation in obstructed detonation tube. Their simulation results were carried out for stoichiometric mixture of kerosene-air and butane-air mixture at atmospheric conditions. They found that mixing of butane-air combustion process is better than kerosene-air mixture. Furthermore, the stoichiometric ethane-air (C_2H_6-air) and ethylene-air (C_2H_4-air) fuel mixture at atmospheric pressure conditions has been studied by Alam et al. [58]. The effect of blockage ratio of 0.4, 0.5, 0.6 and 0.7 in channel for detonation wave acceleration are shown in **Figure 4.** The contour plot analysis shows the shock wave initiation and propagation time period in detonation tube is reduced by smaller blockage ratio of 0.5 [59]. Tripathi et al. [60] computationally studied on effect of obstacle on flame propagation velocity. Alam et al. [61] studies on flame acceleration in pulse detonation engine with changing the obstacle clearance. They found that combustor pressure is reduced as increase the obstacle clearance. P. Debnath and Pandey [62] studied on deflagration to detonation transition in PDE combustor with Schelkin spiral effect inside the detonation tube. They found that Schelkin spiral accelerate the flame propagation. Alam et al. [63] numerically studied on flame propagation in obstructed pulse detonation combustor with hydrogen-air mixture. They found that performance is increase up to 4.46% and this value increase for ϕ = 1.3. Debnath and Pandey [64] studied on effect of different nozzle on flame acceleration and they found that divergent nozzle has more effect on flame acceleration. The **Figure 5** shows the comparison of thrust power for PDE combustor with several nozzle. Chourasia et al. [65] studied on progress and motivation of research in pulse detonation combustor. Xudong Zhang et al. [66] studied on critical mode of gaseous methane-air detonation propagation in an annular tube based on reactive

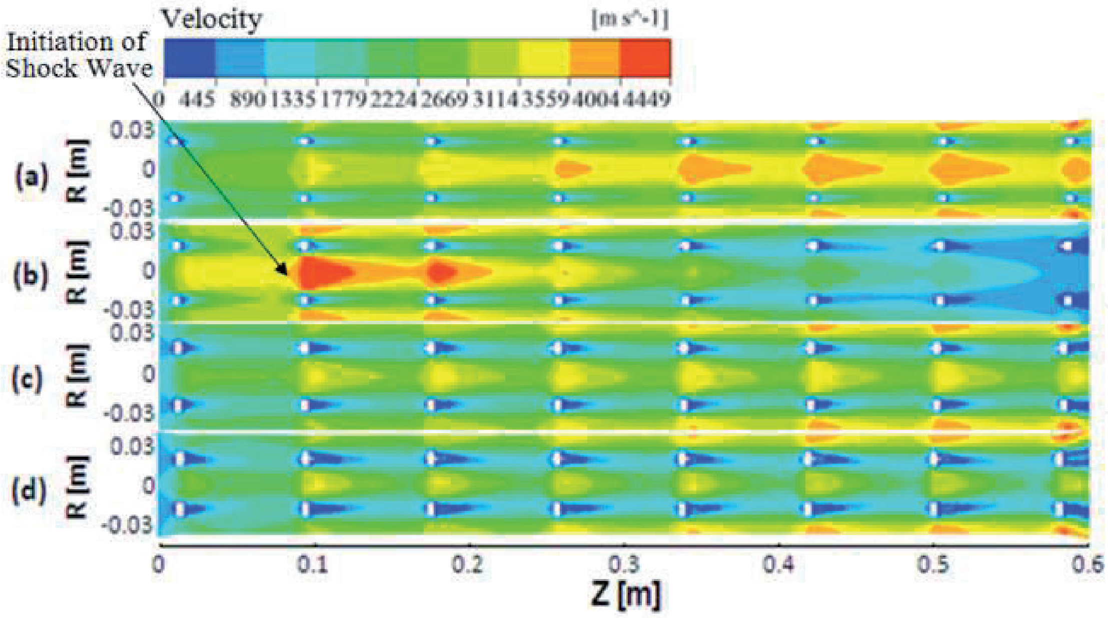

Figure 4.
Effect of blockage ratio on detonation wave propagation [59].

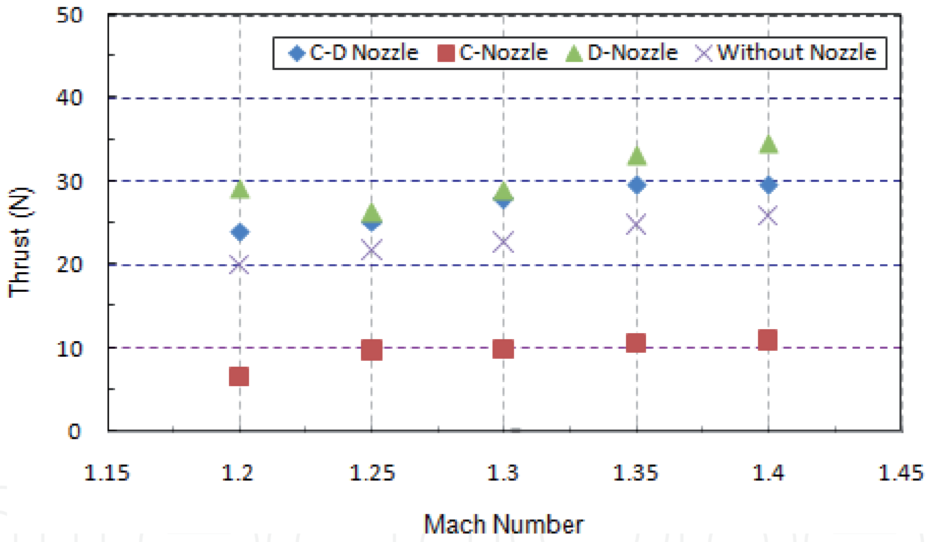

Figure 5.
The propulsive thrust variation for PDE combustor with C-D nozzle, C-nozzle, D-nozzle and without nozzle at different Mach number [64].

Navier Stokes Equations. They found that trajectories of triple point of the shock wave cell structures are petal pattern. Wang et al. [67] studied on effect of oxygen concentration on propane-air detonation in pulse detonation engine with straight nozzle, convergent nozzle, and convergent-divergent (CD) nozzle. Their results indicate that for the PDE with straight nozzle requires the shortest possible time for reacting gas burnt with high-temperature in detonation tube. Jishnu Chandran and Salih [68] studied on development of a benchmark solution in compressible liquid flows for shock tube problems. The compressibility effects in liquid water have been studied using the high-accuracy modified NASG equation of state. Arjun Singh et al. [69] studied on thermodynamic parameters for the formation of activation energy and self-acceleration for thermal explosion from critical temperature. They found that the thermal stability has been significantly reduced in presence of hydroxyl-terminated poly butadiene. Dong et al. [70] studied on correlations among detonation velocity, thermal stability, heat of combustion and decomposition kinetics of nitric esters. They found that oxygen coefficient plays positive role on decomposition of heat release efficiency of detonation combustion.

6. Concluding remarks

The above literature survey represents that there is more research is needed in pulse detonation combustor for shortest possible pulse time of deflagration to detonation transition. The future proposed research can be analyzed by changing the design of PDE combustor and operating conditions. The series of numerical simulations and optimization can be performed desire research objectives of pulse detonation engine. From the CFD and calorimetric analysis the smaller blockage ratio of 0.5 is found better to reduce detonation wave run up distance. The ejector enhance the shortest possible time of 0.033 s, which is required for fully developed detonation wave. More possible pulse time can be reduced by ejector geometry modification. Lesser the hydrogen fuel mass fraction of 0.25 higher the exergetic efficiency of 67.55% is obtained from detonation combustion process. Once the computational model is validated, further simulation can be carried out with accuracy. There are several detonation tube geometry is steal in debate for acoustics atomization and evaporative characteristics of liquid fuel detonation wave.

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