# Computational Investigations on the Effect of Blockage Ratio on Detonation Inside a Pulse Detonation Engine Combustor

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**Abstract:** Pulse Detonation Engine is an intermittent propulsion system where detonation waves are utilized to produce repetitive thrust. These detonation waves are the most efficient means of burning a fuel-air mixture and releasing its chemical energy content. Consequently, detonation mode of combustion leads to nearly constant-volume combustion process and results in higher thermodynamic efficiency as compared to the conventional propulsion system. Hence, a propulsion system based on the detonation can be a revolutionary propulsion system for a variety of aerospace vehicles. The performance and reliability of such propulsion system explicitly depends on the sustainability of detonation wave. As of now, no practical design of pulse detonation engine is available. One of the possible reasons is the difficulty in initiating and sustaining repetitive detonation of the fuel air mixture. The presence of an obstacle such as shchelkin spiral plays a very crucial role for the formation and stabilization of detonation wave in the pulse detonation engine combustor. However, the formation and sustainability of detonation wave requires an appropriate number of obstacles, obstacle geometry and blockage ratio. The present work involves computational analysis on the effect of obstacle and blockage ratio on the detonation wave propagation in a pulse detonation engine combustor. Computational modeling and simulation of the combustor with stoichiometric hydrogen-air mixture has been done by using a commercially available CFD code. Simulation results of different configurations of the combustor have been analyzed and compared. The simulation of interaction of the detonation wave with obstacles revealed formation of reflected waves and giving rise to a complex flow pattern inside the combustor. The simulation results have been compared with those of NASA CEA code. These results provide valuable insight into the interaction of obstacle and detonation wave and the effect of blockage ratio on the propagation of detonation wave.

## 1 Introduction

Recent interest in design and development of pulse detonation engine has resulted in numerous theoretical and experimental studies related to initiation and sustaining repetitive detonation in a PDE combustor. These intensive studies illustrate significance of pulse detonation engine in the field of propulsion system. There are two preliminary characteristics which makes pulse detonation engine

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different from the conventional propulsion system such as gas turbine. First, it produces thrust intermittently and second it produces high pressure rise due to formation of detonation wave in the PDE combustor. Detonation is a supersonic combustion process which is essentially a shock front driven by the energy release from the reaction zone in the flow right behind it. Hence, the high pressure ratio associated with detonation combustion due to reaction driven shock front, reduces the requirement of compression or pumping devices. Some of the promising advantages of a pulse detonation engine include the higher thermodynamic efficiency, higher specific impulse, simplicity of manufacture and reduction in the moving parts. A key hurdle in the realization and development of pulse detonation engine is obtaining reliable and repeatable detonations in the PDE combustor. Two methods are primarily utilized to ignite a mixture for detonation; one being direct initiation by depositing the required amount of energy in the system at a very high rate and in the other, ignition starts with a deflagration and transits to detonation within a finite time and distance. This transition is known as deflagration to detonation transition (DDT).

Detonations have been explored for propulsion applications only for the past fifty years or so because of the difficulties involved in initiating and sustaining a detonation in fuel-air mixtures and have been recently reviewed by kailashnath [1]. Nicholls et al. explored the concept of intermittent (or pulse) detonation waves for propulsion applications [2]. Both single cycle and multi-cycle operations with hydrogen or acetylene as fuel and oxygen or air as oxidizer were demonstrated. The basic set up was a simple detonation tube, open at one end with co-annular fuel and oxidizer injection at the closed end. Chan et al. mentioned about the existence of a critical Mach number of 1.5 that the flame must reach to achieve transition to detonation in hydrogen air mixture [3]. In order to understand the nature and structure of a detonation being used for various propulsion applications further analysis is required. Numerical analysis can help to reduce the cost and time to understand these phenomena. The first numerical simulation of the detonation wave was performed by Taki and Fujiwara for 2D detonation in oxy-hydrogen mixture [4]. Most of these computations have been conducted on structured mesh because the analysis of detonation phenomena requires higher order accuracy for capturing fine details. Bussing and Pappas also reported one-dimensional study of PDE, burning hydrogen-oxygen and hydrogen-air mixtures [5]. The detonation was initiated near the closed end of the engine using a high temperature and high pressure region. Although significant research has been performed in the past to understand DDT phenomena including the use of obstacles to accelerate the transition but little has been done to investigate the effect of obstacle and its blockage ratio on detonation wave. Hence, the present study investigats the effect of obstacle and blockage ratio on the detonation wave in a pulse detonation engine combustor. Computational simulation of PDE combustor with 0% (without obstacle), 20% and 40% blockage ratio has been carried out by using a commercially available CFD code. A comparative study of simulation results has been reported by analyzing pressure contours, hydrogen mass fraction contours and Mach number plots.

# 2 CFD Modeling

A three dimensional viscous reacting flow simulation has been carried out for a typical pulse detonation engine combustor (with and without obstacles) using ANSYS CFX software. ANSYS CFX software uses a finite volume based method. 3D Reynolds Averaged Navier–Stokes (RANS) equations are solved in a fully implicit manner.

The whole computational domain was split into two zones, namely cold zone and hot zone. The hot zone is a small disc portion of the PDE combustor and is located at the extreme left end of the PDE combustor. In the present work, semi-circular obstacles have been used with spacing and width of 4 cm and 0.8 cm respectively. The complete computational domain for all the configurations was discretized into hexahedra cells with interval size of 0. 45mm.

## 2.1 Simulation Strategy

Initial and boundary conditions were set after mesh generation. The complete tube was filled with the premixed stoichiometric mixture of hydrogen and air. The cold zone initial pressure and temperature were kept at 1.0 atm and 300 K, respectively. In literature, many researchers have used high temperature and pressure zone to initiate direct detonation [5,6]. Therefore, in present simulation, detonation was initiated by patching a very small section (Hot zone) with high temperature and pressure. Wall boundary conditions were imposed at left end and on the cylindrical surface of the PDE combustor with no slip as well as adiabatic condition. In addition, outlet boundary condition was defined at open end of the combustor.

To simulate the chemical reaction, Eddy Dissipation (ED) and Finite Rate Chemistry (FRC) model was used with single-step reduced chemical kinetics of hydrogen-air mixture. High Resolution advection and second order Backward Euler transient scheme was used to ensure the global convergence of mass, momentum, energy and species to the residual level of $10^{-5}$. The turbulence model used was standard k-ε model with wall functions.

## 3 Results and discussion

In the present study, the effect of blockage ratio (0%, 20% and 40%) on detonation wave propagation is investigated. Figure 1, illustrates the hydrogen mass fraction and pressure contours with a time interval of 20 µs between each frame.

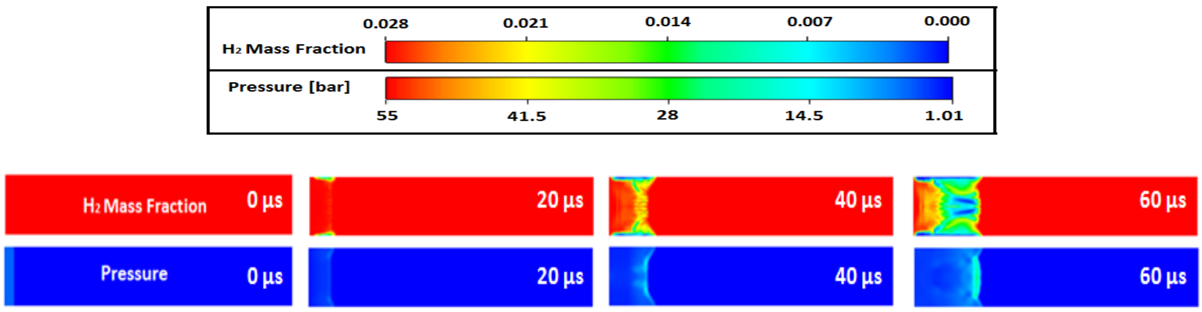


Figure 1. Hydrogen mass fraction and pressure contours plot for 300 mm long part of (0% BR) PDE combustor.

Hydrogen mass fraction and pressure contours were studied and they help in providing an understanding of the flame development as well as the pressure wave formation in the PDE combustor. It can be observed from the hydrogen mass fraction contours plot that disintegration of hydrogen starts near the wall and at the interface of hot zone and cold zone. The possible reason for this could be existence of stationary reacting mixture at the wall due to no slip boundary condition. Later on flame develops due to heat release from the hot zone as well as chemical reactions. Looking at the pressure contours (figure 1), one can notice the development of the pressure wave as chemical reaction begins. It can also be clearly observed from the pressure contours that, pressure wave continuously strengthens with time due to release of energy from the chemical reactions.

Figure 2 shows the variation of Mach number with time and it can be seen from same figure that M = 1 (sonic condition) is achieved in the flow just after a distance of 55 mm from the close end of PDE combustor. This signifies the formation of shock wave. To calculate the detonation velocity, pressure time history was plotted at two locations of the combustor as shown in figure 3. After a simple calculation, the velocity of the wave turns out to be around 2040 m/s. The calculation of Chapman-Jouguet detonation velocity with NASA CEA (Chemical Equilibrium with applications) code for comparison shows a reasonable agreement [7]. The NASA CEA calculation predicts the C-J velocity of 1,966 m/s and C-J pressure 15 bar as per the initial conditions. The comparison between simulation results and NASA CEA code reveals the formation of detonation wave front. Although simulation velocity is comparable with C-J velocity but the simulation pressure value has been observed to be slightly higher, ~ 19 bar ($P_N/P_{CJ}$ ~ 1.8 [8]), which is relatively higher than the C-J pressure value. At the same time, shock wave pressure ($P_N$) at 300 mm has been observed to be 33bar, which is comparable to the peak pressure experimentally obtained by Rudy at el. [9].

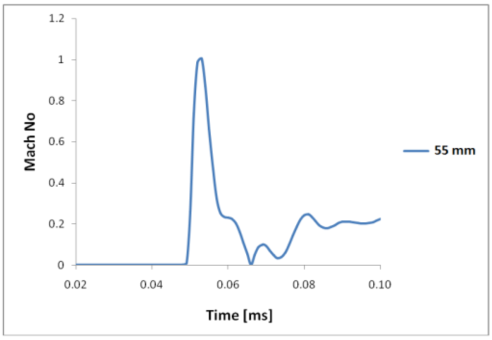


Figure 2. Mach No. plot at 55 mm.

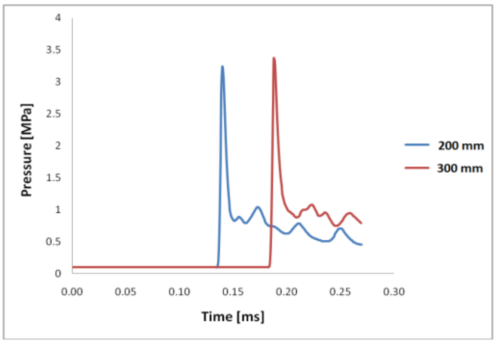


Figure 3. Pressure plot at 300 and 200 mm.

Furthermore, pressure contours for 0% (without obstacle), 20% and 40% blockage ratio laden combustor are plotted and compared (Figure 4). A closer look on the pressure contours shows the formation of reflection waves, as detonation wave interacts with the obstacles. It can also be seen from the Fig. 4 that the presence of obstacle in PDE combustor significantly affects the strength of detonation wave.

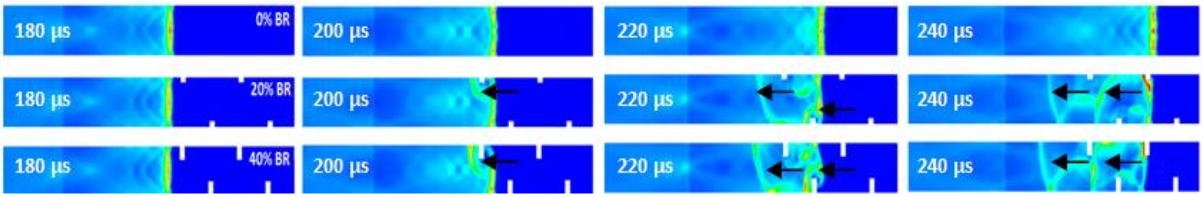


Figure 4. Pressure contours up to 490 mm long part of PDE combustor with all configurations.

To the see overall effect of blockage ratio on detonation wave propagation, results of pressure contour plots for all the configurations of PDE combustor from 0 to 320 μs are presented in figure 5. The time interval between each frame shown in the figure is 20 μs. It can be clearly observed that detonation wave velocity decreases in case of obstacle laden PDE combustor as compared to the simple (0% BR) PDE combustor. Furthermore, the decrease in velocity has been observed to be

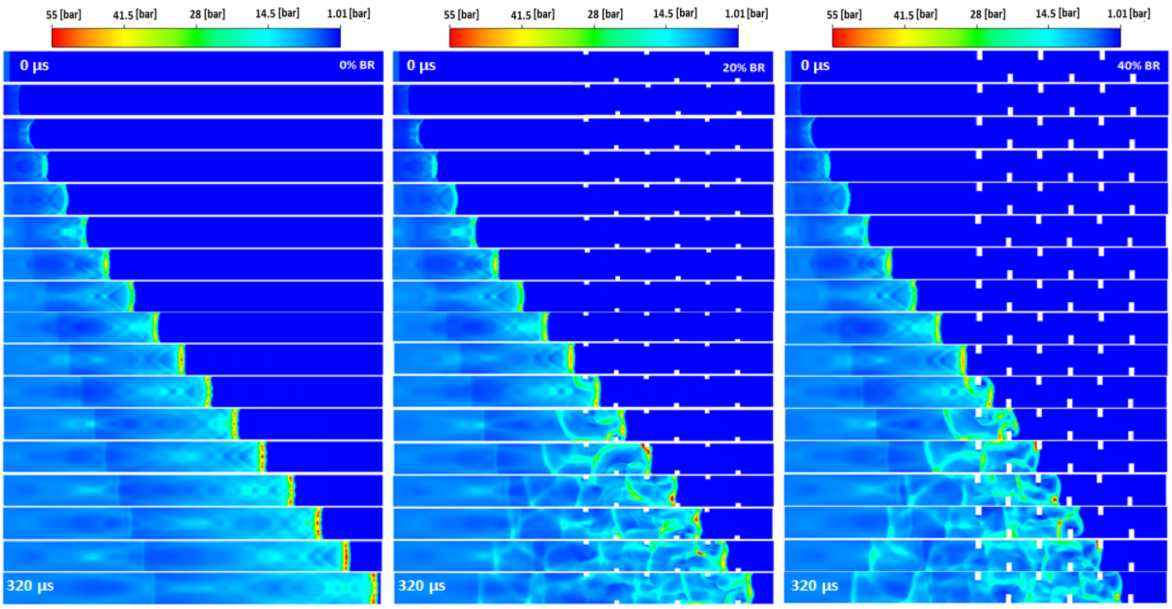


Figure 5. Pressure contours for all configuration of PDE combustor with 600 mm length and 50.8 mm diameter.

more for 40% blockage ratio PDE tube as compared to the 20% blockage ratio PDE tube. In case of simple PDE combustor (0% BR), high temperature and pressure combustible products expand instantaneously just behind the shock wave. This sudden expansion of combustible products pushes the shock wave like a piston and accelerates the detonation wave front. This could be the possible reason for the formation of accelerating detonation wave relative to the obstacle laden PDE combustor. On the other hand, multiple reflection waves are observed during the interaction of detonation wave and obstacles. It can be seen from above figure, that reflection waves are moving towards the closed end of the PDE combustor. The movement of these reflection waves also move the high temperature and pressure combustible products towards the closed end. As a result, shock wave downstream pressure and temperature is reduced. Hence, when detonation wave interacts with the obstacle, it leads to a drop in downstream shock wave pressure and temperature. Consequently, rate of chemical reaction is decreased and leading to a reduction in the detonation wave velocity.

Pressure history at a location 580 mm (near to open end of PDE combustor) has been plotted for all combustor configurations and shown in figure 6. The figure shows that increase in the blockage ratio leads to significant drop in downstream pressure of shock wave. Hence, higher blockage ratio leads to significant drop in pressure and velocity of detonation wave and may result in quasi detonation. Therefore, simulation results suggest that obstacle should be used up to the DDT section only. But, in experiments, it is really difficult to identify the exact location of formation of detonation wave and hence a variable blockage ratio (higher at DDT section while least near the open end) obstacle should be utilized to obtain DDT as well as stable detonation wave.

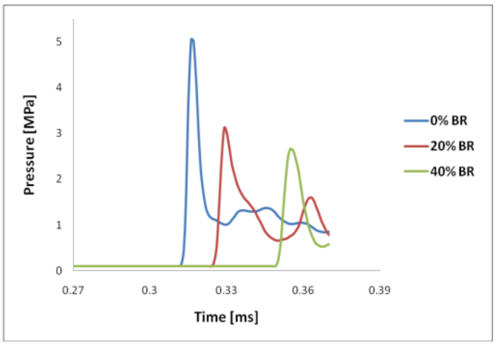


Figure. 6 Pressure history at 580 mm.

## 4 Conclusion

A comparative study on the effect of blockage ratio on detonation wave propagation for stoichiometric hydrogen-air mixtures has been reported in this paper. Following conclusion can be drawn from the analysis of simulation results.

1) Detonation pressure and velocity have been observed to be comparable with NASA CEA code and experimental results. Interaction of detonation wave with obstacles result in the formation of reflection wave.
2) Analysis of simulation results reveal that the interaction of detonation wave with obstacles in the PDE combustor results in a reduction in detonation wave velocity and peak pressure. The decrease in pressure and velocity is more with an increase in the blockage ratio. Simulation result suggests that the length of obstacles used should be extended up to the DDT section or a variable blockage ratio obstacle can be used to obtain a stable detonation wave.
3) Single step chemical kinetics has been used in the present studies. A single diamond pattern was observed. Further work is required to account for multistep chemical kinetics of hydrogen air mixture to capture more details of the propagating detonation wave.

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