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Research Paper

Optimization of a multiple pulse detonation engine-crossover system

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HIGHLIGHTS

- A four PDE-crossover array is operated continuously, in a sequential pattern.
- Combustion is initiated by a shock wave transferred from the previous PDE.
- Increasing skin temperature decreases deflagration-to-detonation run-up length.
- Increasing frequency decreases deflagration-to-detonation run-up length.

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ABSTRACT

A University of Cincinnati experimental study is conducted on a Pulse Detonation Engine (PDE)-Crossover System to investigate the feasibility of repeated, shock-initiated combustion as a means to generate detonation within an annular array of detonation tubes. An optimization study of the system finds that reducing driver PDE length increases auto-ignition failures in the driver PDE due to undesirable feedback of hot products from the driven PDE. Initiation performance in the driven PDE is strongly dependent on initial driven PDE skin temperature in the shock wave reflection region. The optimum initiation performance is achieved within the driven PDE by filling the driver PDE with reactants past the crossover tube entrance. Increasing operating frequency negates the detrimental effect of increased nitrogen dilution. An array of detonation tubes connected with crossover tubes is developed using optimized parameters. Successful operation utilizing shock-initiated combustion through shock wave reflection is achieved and sustained. Results from this array show that if initially driven PDE tubes are operating successfully, all subsequently driven PDE tubes also operate successfully.

1. Introduction

The detonation is a supersonic form of combustion that utilizes a shock wave–combustion wave union to produce pressure-gain across the reaction zone. Modern turbomachinery combustors nominally operate with the subsonic, deflagration mode of combustion that produces a slight overall pressure loss through the chamber. Recent detonation research has aimed to harness this pressure gain as a useful way to generate power [1–3]. Higher work output with lower entropy rise is achieved through near-constant volume combustion [4]. Such pressure gain combustion devices include the pulse detonation engine (PDE), which is a cyclic device that operates with five distinct phases: Fill, Ignition, Deflagration-to-Detonation Transition (DDT), Expansion/Exhaust, and Purge. The impulse produced can be increased by increasing the operating frequency [5]. To be effective within modern turbomachinery engines, an array of detonation tubes would be used within the combustion sections, similar to a cannular combustion chamber design.

A PDE array system generally requires a detonation to be initiated in each combustion tube. A substantial amount of energy is required to directly initiate a detonation for fuel-air mixtures (i.e., 80 kJ for stoichiometric ethylene-air [6]). Rather than depositing a large amount of energy into the reactive mixture, a process called deflagration-to-detonation transition (DDT) can be used to transition a slow moving deflagration wave into a detonation wave. For some air-breathing, fuel mixtures, the length associated with the transition, or DDT run-up length, can be quite large, on the order of several meters [7]. Turbulence-enhancing DDT devices [8–11] decrease this length, but generate a large pressure drop across the system due to the increased blockage.

Methods of initiation within a PDE have been developed that produce an alternative approach to decreasing DDT run-up length without the pressure loss imposed by DDT devices. Such methods include the detonation transfer process, whereby a detonation is transferred from a driving PDE into a secondary, driven PDE through a transfer tube known as a crossover tube. This concept has been studied thoroughly and results indicate that it reduces the overall cycle time and increases overall cycle efficiency [12–16]. However, for the detonation transfer process to work properly, the crossover tube cycle must include a purging and refilling phase to remove

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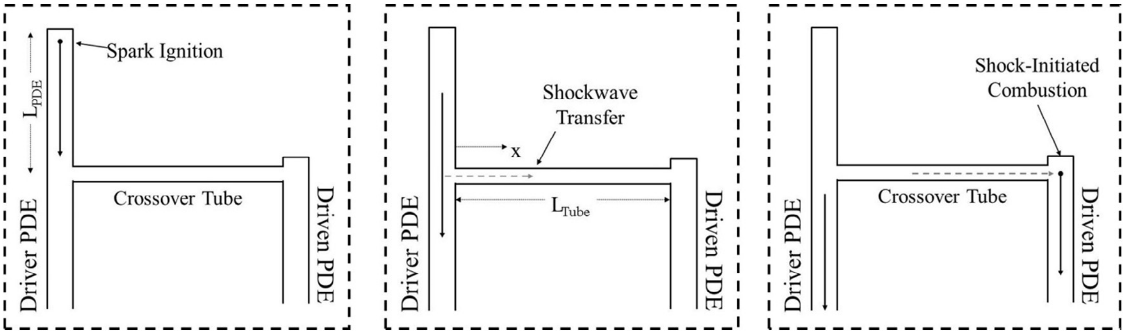

Fig. 1. Dual PDE-crossover system process.

hot combustion products from the crossover tube, preventing auto-ignition and ensuring complete detonation transfer.

Fortunately, a transferred detonation is unnecessary for the crossover system to be effective. While the detonation wave immediately decouples as it enters the crossover tube [16], this decoupling process can be trivial, as DDT run-up length can be decreased through shock-initiated-combustion by shock wave reflection. Fast deflagration and detonation initiation can be achieved for various fuel/oxidizer mixtures by traversing a moderate strength incident shock wave through the reactants into a focusing reflector, a process known as shock focusing [17–19]. Previous work at the University of Cincinnati demonstrates the feasibility of a PDE-crossover system that utilizes shock-initiated-combustion [20–23]. This system reduces the required energy needed to initiate a detonation by exchanging the normal spark ignition source for initiation through shock reflection, and simultaneously reduces the DDT run-up length.

An array of detonation tubes that implement shock-initiated-combustion caused by a transferred shock wave (i.e., Multiple PDE-Crossover System) would be beneficial to future turbomachinery combustor designs. In this system, each detonation tube would be initiated by a previous detonation tube. Furthermore, such a system would utilize pressure-gain combustor to increase system efficiency and reduce energy requirements as each detonation tube would no longer require an individual spark-discharge igniter, but rather a single igniter would initiate the whole apparatus. Use of shock wave transfer through crossover tubes would reduce the DDT run-length within each detonation tube and remove any purge or fill requirements within the crossover tube, as opposed to detonation transfer. Though research has been conducted on multiple PDE-crossover systems that utilize detonation transfer [16], research is required on a system that utilizes shock wave transfer to investigate the feasibility of such an apparatus with added focus to geometric and operational parameters.

The current study develops an optimized Multiple PDE-Crossover System that utilizes shock-initiated combustion caused by shock wave reflection as the primary means of initiation. The array is comprised of four detonation tubes, connected with crossover tubes to transfer shock waves. The system utilizes spark ignition to initiate combustion within the primary driving tube. Shock wave reflection initiates combustion in all subsequent tubes. The purpose of this study is to parametrically investigate shock-initiated combustion within a dual PDE-crossover system and to demonstrate the viability of an optimized, continuously operating, multi-PDE-crossover array.

2. Experimental setup

All experiments in this study are performed in the University of Cincinnati Detonation Engine Test Facility. The facility is a part of the Widen Tabakoff Gas Dynamics and Propulsion Laboratory. The two experimental apparatuses consists of the following components (Fig. 1): (i) a driver PDE, (ii) a crossover tube that transfers a shock wave from the driver PDE to the driven PDE, and (iii) a driven PDE in which shock-initiated combustion is generated by shock wave reflection on the inner wall. The detonation tubes are 25.4 mm in diameter ($D_{PDE} = 25.4$ mm) and both are supplied with a stoichiometric mixture of ethylene, nitrogen, and oxygen. The nominal oxidizer consists of 60% O_2 and 40% N_2 by volume (i.e., $n = N_2{:}O_2 = 0.67$). The detonation cell size associated with this mixture is approximately $\lambda = 3$ mm [6]. The mixture in the driver PDE is ignited using an automotive spark plug that deposits approximately 105 mJ of energy into the reactants. Located 2 D_{PDE} downstream from the spark plug is an orifice plate with a blockage ratio of 0.64 to enhance DDT to approximately 5 D_{PDE} downstream from the spark plug. Further information regarding this driver PDE system is seen in Ref. [23]. A pipe tee located 15.5 D_{PDE} downstream of the spark plug (L_{PDE}) bleeds a shock wave from the driver PDE into the crossover tube. This location is roughly 11 D_{PDE} downstream from the detonation formation point. Crossover tube diameters vary from 10.9 mm to 26.6 mm. Though all crossover tubes used in this study are sufficiently large to sustain a detonation wave (i.e., $D_{Tube} > \lambda/\pi$) [24], research shows difficulty in bleeding a complete detonation (i.e., not decoupled) into a crossover tube [16], preventing detonation transfer in this setup. Fortunately, this investigation relies on shock wave transfer which unimpeded with these crossover tube sizes [22]. The crossover tube transfers the shock wave into the initiation region of the driven PDE. In this region, shock-initiated combustion is achieved as the shock wave reflects off of the inner wall of the driven PDE. The crossover tube enters the driven PDE at the upstream end of the detonation tube, as initiation farther downstream from the closed end of the detonation tube is shown to decrease overall thrust [5]. Within the driven PDE, no spark ignition or DDT devices are present, allowing for full effects from shock-initiated combustion to be characterized.

2.1. Parametric study with dual PDE-crossover system

For array optimization, design parameters are studied using a dual PDE-crossover setup, seen in Fig. 2. The setup is instrumented with ionization probes, flush mounted to both detonation tubes. Three ionization probes are instrumented on the driver PDE. The first ionization probe is located on the driver PDE tee, a varied distance from the spark plug (L_{PDE}), to measure the initial time at which the combustion wave reaches the crossover tube entrance. The second and third ionization probes are located 3 D_{PDE} and 7 D_{PDE}, respectively, downstream of the first. These two ionization probes are used to confirm operation of the driver PDE. The driven PDE is equipped with nine ionization probes to characterize initiation performance and combustion wave speed evolution. Optimum initiation performance is defined as the shortest DDT run-up length within