

# Deflagration to Detonation Transition Processes by Turbulence-Generating Obstacles in Pulse Detonation Engines

Seong-Young Lee,\* Jonathan Watts,† Silvano Saretto,‡ Sibtosh Pal,§ Chris Conrad,† Roger Woodward,\* and Robert Santoro¶  
*The Pennsylvania State University, University Park, Pennsylvania 16802*

The results from a series of detonation experiments conducted to characterize the deflagration-to-detonation transition (DDT) process for ethylene-air mixtures in a 44-mm-square, 1.65-m-long tube are described. Experiments were conducted for both single-shot detonations involving quiescent mixtures as well as multicycle detonations involving dynamic fill. For the experiments, high-frequency pressure and flame emission measurements were made to obtain the compression wave and flame speeds, respectively. In addition, schlieren and hydroxyl-radical/planar-laser-induced-fluorescence (OH-PLIF) imaging were applied to investigate the interactions between the shock-wave and combustion phenomena during both deflagration and detonation. For ethylene-air mixtures, strategically placed obstacles were necessary to achieve DDT. The effect of the presence of obstacles on flame acceleration was systematically investigated by changing the obstacle configuration. The parametric study of obstacle blockage ratio, spacing between obstacles, and length of the obstacle configuration indicated that for successful detonations the obstacle needs to accelerate the flame to a minimum flame speed of roughly half the Chapman–Jouguet detonation velocity. Differences in the flame and compression wave velocities demonstrated the development of a coupled feedback mechanism as the wave propagated along the tube. A series of simultaneous schlieren and OH-PLIF images showed that the obstacle plays a major role in generating small/large-scale turbulence that enhances flame acceleration. Localized explosions of pockets of unburned mixture further enhanced the shock-wave strength to continuously increase the flame speed. The results of this experimental study support the importance of obstacles as a means to enhance DDT and provide a potential solution for practical pulse-detonation-engine applications.

## Introduction

RECENT interest in pulse detonation engines (PDEs) has resulted in several experimental and theoretical studies related to realizing multicycle detonations in tubes that simulate engine operating conditions.<sup>1–5</sup> These studies make a clear case that pulse detonation engines provide the potential for higher specific impulse, reduced complexity, and lower operational costs as compared to current gas turbine technology. For airbreathing applications, hydrocarbon-air propellant combinations are being considered, which are particularly difficult to detonate within a practical length.<sup>6</sup> In addition, a key barrier to the realization of an operational PDE is achieving reliable and repeatable detonations in the shortest distance possible to minimize system weight.

Over the past several decades, researchers have employed a series of repeated obstacles along the flow path to enhance flame acceleration in order to achieve self-sustained detonations.<sup>6–12</sup> Fundamentally, obstacle-induced turbulence increases the flame burning rate by increasing the flame surface area and the transport of local mass and energy. Moreover, turbulence scales play a significant role in flame acceleration associated with burning rate. In the earlier stage of flame evolution upon mild ignition, large scales of turbulence are necessary to increase the surface area or flame folding, whereas excess flame stretching and rapid mixing of the burned gas can have an adverse effect on further flame evolution, which can cause the flame

to completely quench. Once the flame evolves into the distributed reaction zone and thus, transforms into a turbulent flame brush, finer turbulence scales are necessary to increase the flame surface area within the flame brush.<sup>7,10,11</sup> Therefore, optimizing the design of the obstacle configuration is necessary for reducing both deflagration-to-detonation transition (DDT) length and time in a practical PDE as direct detonation initiation in flight vehicles would require an impractical amount of energy.<sup>13,14</sup> In addition, Kiyanda et al.<sup>14</sup> experimentally studied detonation phenomena in a tube without internal obstacles and suggested that as long as the mixture is burned inside the tube the impulse produced by direct detonation ignition and DDT is the same. However, Cooper et al.<sup>15</sup> reported that the measured impulse with internal obstacles is reduced by an average of 25% as compared to the measured impulse for a tube without internal obstacles in their impulse measurements for various obstacle configurations. Thus, minimizing DDT length is a fundamental goal in PDE development, but must also be achieved in such a manner as not to reduce engine thrust. Additionally, if obstacles are employed they must be rugged and lightweight from an engine systems and reliability perspective.

The fast deflagration velocity generated by the turbulent flame acceleration process relies on various parameters, including the sensitivity of the mixture composition, the dimensions of the detonation tube and the size, shape and distribution of the obstacles.<sup>6,7,10,16</sup> Essentially, the flame acceleration process by either obstacle-induced flow or naturally occurring flow instabilities eventually leads to the DDT process throughout the shock-induced combustion ignition region by the positive feedback coupling mechanism between the shock and the flame. The DDT process is often followed by the formation of explosion centers from pockets of reactants, which create blast waves and the process is continuously amplified through multishock interactions with the flame.<sup>17–19</sup> In addition, large-scale experiments performed by Dorofeev et al.<sup>20</sup> have shown that turbulent mixing of fresh and burned gases reduces the sensitivity of the mixture composition for the onset of DDT compared to the laboratory-scale experiment. Experiments and computational investigations of the DDT process demonstrate that the explosion could occur between the leading shock and the flame shock, at the flame front, at the shock front, or at the contact discontinuity formed by the coalescence of shock waves that precede the flame.<sup>17,18</sup> It has been also

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\*Research Associate, Department of Mechanical and Nuclear Engineering.

†Graduate Student, Department of Mechanical and Nuclear Engineering.

‡Postdoctoral Scholar, Department of Mechanical and Nuclear Engineering.

§Senior Research Associate, Department of Mechanical and Nuclear Engineering.

¶Professor, Department of Mechanical and Nuclear Engineering.