



Assessment of flash-boiling for pulse detonation engines

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ABSTRACT

Liquid-fueled pulse detonation engines must complete the process of feeding, mixing, and purging in milliseconds. Such an engine is extremely sensitive to the Sauter mean diameter (SMD – must be less than 10 μm) and particle size distribution of the fuel, requirements which are difficult if impossible for most fuel injectors to achieve. This study selected an injector from a direct injection engine and used the aviation fuel JP-8. Utilizing a wide range of operation pressure and duration time, the injection timing and equivalence ratio could be accurately controlled with good response time. The results of the experiment indicate that an SMD of less than 10 μm can be achieved with a fuel pressure greater than 8 MPa. This condition, however, resulted in an overly long injection penetration. This study further incorporated the concept of flash boiling to derive a smaller SMD. However, this causes carbon deposition to occur due to cracking or thermal reaction. To circumvent this phenomenon, this study established a deoxygenation device to mitigate oxidization, further investigating the influence of heating temperature on the generation of deposition. The results of spray distribution indicated that when the fuel is heated to 100 °C, only 6 MPa is necessary for achieving fuel droplet characteristics favorable for detonation. Regarding deoxygenation, the results were most significant in fuel heated to 500 °C.

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1. Introduction

Pulse detonation engines (PDEs) have been the subject of intense research over the past twenty-odd years [1,2]. When compared to conventional turbojet engines, PDEs are thermodynamically more efficient; they have simpler architectures and possess fewer moving parts. The latter advantages make PDEs potentially inexpensive to manufacture and operate. One of the key challenges in making PDEs a reality is the ability to reliably deliver detonation waves at high frequency. Fundamental studies have shown that direct initiation requires an exorbitantly large amount of energy, of the order of 10^5 J for a stoichiometric, low vapor pressure liquid hydrocarbon/air mixture. Such an energy requirement is far higher than the approximately 100 mJ delivered by a typical automobile spark plug [3]. Thus, the deflagration-to-detonation approach is more practical where a low energy source such as an automotive spark plug is used to accelerate a flame either naturally or with detonation-enhancing devices such as a Shchelkin spiral to lead to a detonation front.

Now, much of the research into detonation physics has utilized gaseous fuels such as hydrogen, acetylene, ethylene and propane. If these fuels were to be used for a PDE, they have to be stored under

high pressure in thick-walled containers which increase weight and which poses safety risks. Consequently, attention has been paid to liquid fuels with their high energy density [4].

While there are many advantages to using liquid fuels, there are also a number of practical challenges revolving from the need to rapidly release the chemical energy. The detonation wave itself can be considered to consist of a shock front followed by an induction and a reaction zone [5–8]. Therefore, if the energy from the chemical reaction is released too slowly, the shock wave can separate from the reaction zone, and the detonation wave fails to form. This is a particular concern when using liquid fuels.

It is generally thought that the liquid fuel should be converted into a vapor state to facilitate detonation. Thus, there is a need to consider atomization and vaporization techniques that can rapidly bring the liquid fuel to a vapor. A large droplet diameter, for example, will take a longer time to evaporate. It may, in fact, not be necessary for all the liquid phase to be converted to the vapor phase but only that a sufficient amount of vapor must be present for the deflagration-to-detonation transition (DDT) process to proceed [9]. Dabora [10] found that droplets with a SMD of less than 10 μm are necessary for successful detonation in a liquid fuel and oxygen mixture. If air is used, the droplet diameter must be less than 3 μm and at least 70% of the fuel must be vaporized [11]. Unfortunately, existing atomizers have difficulty in achieving such performance targets [12].

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Nomenclature

d_i	droplet diameter (μm)	PDE	pulse detonation engine
D_{32}	volume/surface area mean diameter (μm)	SMD	Sauter mean diameter
DDT	deflagration-to-detonation	TTL	transistor–transistor logic
n_i	the relative volume in the class i		

Kawamura et al. [13] compared the characteristics of nozzles in common fuel injection and direct injection systems, including injection penetration, SMD and particle size distribution. The results of their experiment showed that when the fuel pressure within a direct injection nozzle is 10 MPa, the SMD at 60 mm beneath the nozzle can reach approximately 10 μm . Ueda et al. [14] also provided test data on Denso direct injection nozzles, which have a larger adjustment range for injection time and fuel pressure. In addition, Eran and Tali [15] proposed the design of a flash-boiling atomization system, in which the required cone angle, injection penetration, and droplet diameter can be derived by controlling both pressure and temperature. Rajshekhar and James [16] conducted experimental and theoretical analyses of flash boiling. The experimental portion comprised changing the type of fuel, fuel burning, and the pressure and temperature of the test chamber, using three different injectors. The results indicated that increasing the cone angle accelerated mixing with the oxidizer, thereby reducing the atomization and penetration of the injection. In the theoretical portion, Rajshekhar and James [16] proposed a formula for bubble growth at saturation, showing bubble size in relation to time. Schmitz et al. [17] utilized this system to develop an atomizer for direct-injection engines. For applications in diesel fuel engines, Senda et al. [18] discovered that by mixing liquid CO_2 and n -tridecane, the low boiling point and high vapor pressure characteristics of CO_2 aided the atomization.

Summarizing the aforementioned studies, employing liquid fuel to generate detonation waves necessitates an atomization system that meets the requirements of completing atomization within an extremely short time and in achieving an SMD of less than 10 μm . For a flash-boiling atomization system, the fuel must be pressurized to increase the saturation vapor pressure. The fuel must subsequently be heated to raise its temperature to higher than the saturation temperature under normal pressure. Once the needle valve of the atomizer is opened to allow fuel through the orifice, the pressure drops rapidly to within the saturation region. The bubbles generated by the flash boiling push against each other, further promoting atomization. This combined boiling and atomization process yields small droplets and shortens the atomization time.

Tucker [19] utilized fuels with four different vapor pressures to compare DDT characteristics under varying conditions of air temperature and fuel time delay. The fuel was injected into the manifold repeatedly to mix with the oxidizer, and then the fuel/oxidizer mixture entered into the combustion chamber. However, the length of the manifold alters the degree of mixing. A long manifold increases the possibility of droplet deposition after atomization. For atomization by flash boiling, the fuel must be heated beforehand. The temperature and the amount of dissolved oxygen in the fuel affect any potential of fuel cracking or exothermic reactions [20]. The thermal stability of jet fuel can be increased to 755 K by reducing the oxygen content to less than 1 ppm [21]. At this contamination level, reactions with the dissolved oxygen are considered negligible. Further, Tucker et al. [22] designed a deoxygenation device for the liquid PDE system. Prior to heating the fuel, nitrogen gas was used to sparge the fuel tank. Oxygen was decreased to its bare minimum, reducing the possibility of carbon precipitation.

The selection of liquid fuel requires safety and accessibility considerations. Compared to gasoline and fuels with high volatility, kerosene-based fuels such as Jet A-1, JP-5, JP-8, and JP-10 are more widely found in civil and military aviation. With the aforementioned considerations, the present study adopted JP-8 for experimentation. In contrast with the research conducted by Tucker [19], this study installed the atomizer of the flash-boiling atomization system directly in the combustion chamber to reduce the possibility of droplet deposition in the mixed region. Injection duration and fuel pressure controlled the required amount of fuel and droplet size. The oxidizer was simultaneously mixed in during the fuel atomization process to reduce the complexity of the system. During the heating process, deposition of carbon particles altered the composition, further affecting the equivalence ratio. Deposits also lowered the performance of the atomizer or caused blockage. Unfortunately, few studies have examined these issues. Consequently, the present study established a heating system that preheated high-pressure fuel to different temperatures, allowing comparison of deoxygenated or non-deoxygenated fuels at different heating durations. This study employed scanning electron microscopy (SEM) to capture images of precipitate appearance, and an energy dispersive spectrometer (EDS) to analyze the components of the precipitates. Component analysis and relative concentration of the fuel were derived using a gas chromatographer with flame ionization detector (GC-FID). Regarding PDE application, this study defined the operation region to prevent precipitate generation. While testing the performance of fuel atomization under various fuel pressures and spray times, this study also measured the particle size distribution and flow rate of atomization to investigate the influence of fuel temperature on atomization.

2. Experimental setup

2.1. System for fuel thermal stability experiment

GC-FID (Agilent GC-6890N) was employed to analyze the components of JP-8 without heating or deoxygenation, the results of which are displayed in Fig. 1. Compared to the standard sample, the primary components evidently fall between C8 and C14. The equipment used to test the thermal stability of the fuel is shown in Fig. 2, including the deoxygenation device, the high-pressure fuel establishment system, and the heating device. Temperature monitoring and oxygen distribution were captured and controlled using NI-SCXI. The deoxygenation device was purged using high-purity nitrogen (99.999%). During sparging, nitrogen was bubbled through the fuel from a submerged wand. The nitrogen agitated and displaced the dissolved oxygen in both the liquid fuel and in the gaseous ullage region above the fuel. The oxygen content was measured and monitored using a Teledyne oxygen analyzer (Model-3110), a micro-oxygen sensor; with the support of a dissolved oxygen analyzer (Orbisphere 3650/111). The oxygen concentration was reduced to less than 1 ppm. Furthermore, to accelerate oxygen removal, this study applied preheating to increase activation energy. The deoxygenated fuel was introduced into a hydraulic diaphragm accumulator (HYDAC-SBO210). The

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