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TECHNICAL NOTE

Detonation initiation of JP-8–oxygen mixtures at different initial temperatures

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Abstract Liquid fuel with sufficient vapor proportion at micron scale is essentially required to increase specific energy density and reduce volume requirements for application of pulse detonation engine. For JP-8, the fully vaporized temperature ranges from 380 to 410 K. In this study, the fuel vapor with oxygen is not enough to induce the reaction and leads to failure of detonation initiation at the initial temperature of 373 K. Condensed fuel was also observed on the bottom of detonation tube. At 393 K, the detonation wave was successfully generated even though a portion of fuel was in a liquid state. The deflagration-to-detonation run-up distance and the pressure trace at fully vaporized conditions, in which the initial temperatures were at 413, 433, and 453 K, were similar to those of gaseous mixtures, such as propane–oxygen mixture.

Keywords Detonation initiation · Initial temperature · Liquid fuel

List of symbols

DDT	Deflagration-to-detonation
PDE	Pulse detonation engine
SMD	Sauter mean diameter
T	Temperature
t_{ddt}	Time for onset of detonation wave
X_1, X_2	Pressure transducer positions
X_{ddt}	DDT run-up distance

1 Introduction

Pulse detonation engine (PDE) with compact structure could offer better performance in comparison with current propulsion devices. However, one of challenges is how to initiate detonation wave. Most previous researches focused mainly on detonation initiation with gaseous mixtures. Taking the requirement of ignition energy into account, Kaneshige and Shepherd [1] indicated that the critical energy for direct detonation initiation of hydrocarbon/oxygen mixtures is about 10^2–10^5 J, which is sufficiently higher than that from a typical automobile spark plug (≈100 mJ). It is very difficult and impractical to ignite a detonation wave directly. Thus, detonation is usually initiated through deflagration-to-detonation transition (DDT), in which a weak spark initiates a deflagration first and then accelerates to a detonation. Note that the transition distance is known as the DDT run-up distance, X_{ddt}. A model for detonation wave structure was given by Zel'dovich, von Neumann, and Döring independently, namely, the ZND model [2–5]. The detonation is modeled as a shock wave followed by a finite chemical reaction zone. Within the shock wave, no reactions take place. The shock wave adiabatically heats the reactants and proceeds at a finite rate of reaction thereafter. After an induction zone, chemical reactions are triggered and then complete at the Chapman–Jouguet (CJ) detonation state. Furthermore, the effect of initial temperature of a mixture on DDT is of interest. Experimental results showed that the detonation cell size of the two different mixtures, i.e., C_2H_2–O_2 and C_2H_4–O_2, increases with higher initial temperature, which indicates

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decreasing detonability [6,7]. However, the hydrogen and air mixture shows an opposite trend, with detonation cell size decreasing with increasing initial temperature from 300 to 650 K, indicating increasing sensitivity of the mixture to undergo detonations [8]. For the C_2H_4–O_2, H_2–CH_4–O_2 and CH_4–ammonia–O_2 mixtures, the effects of initial pressures and temperatures (0.1–0.7 MPa and 293–540 K) on DDT were investigated by Thomas [9]. The detonation initiation was not clearly correlated with either initial pressures or temperatures, which would affect the fuel lean limit only.

In the practical applications for PDE, liquid fuel should be used to increase specific energy density and reduce volume requirements [10]. Kaneshige and Shepherd [1] indicated that the critical energy for detonation initiation of a typical, stoichiometric, low-vapor-pressure liquid hydrocarbon/air mixture is about the same order as that of hydrocarbon/air mixtures. The induction zone is associated with chemical reaction and droplet evaporation. With lower evaporation volume [11], the chemical reaction releases energy slowly, leading to separation of shock wave and reaction zone, which in turn results in failure of detonation initiation. Furthermore, vapor pressure of fuels with higher molecular weight at room temperature is too low to provide detonable mixtures. As a result, methods such as increasing initial temperature of mixtures and adding fuels of lower molecular weight (hydrogen, acetylene, ethylene, and methane) could be employed to enhance the chemical reaction [12,13]. However, the detonation cell size for the mixture of JP-10 and air [14] showed minor variation with initial temperatures ranging from 373 to 528 K, in which the rich DDT limits and the DDT run-up distance X_{ddt} also show no obvious change. Further, Brophy et al. [15] utilized the mixture of JP-10 and oxygen in a pre-detonator to produce a stable detonation wave that transmitted a main combustor with the mixture of JP-10 and air. The effect of initial temperature on droplet diameter and vapor proportion was significant. When the fuel with equivalence ratio of 1.5 was heated to higher than 375 K, the Sauter mean diameter (SMD, total volume-to-area ratio of the atomized droplets) was less than 3 μm and the vapor content exceeded 70 %. The detonation wave could be initiated.

Safety and accessibility are the major criteria for the selection of liquid fuel for PDE applications. The magnitude of SMD associated with the required time of droplet evaporation is another concern. In aeronautics, kerosene-base fuels are used instead of high-volatility fuels. Therefore, the present study adopted JP-8 for experimentation. The effect of initial temperature of JP-8 on vapor proportion was addressed, and the axial temperature deviation of the detonation tube was taken to be another critical factor influencing detonation initiation. The single-shot experiments were conducted to evaluate X_{ddt}, which could assist the design of a pre-detonator.

2 Experimental setup

The detonation system comprises an atomizer, a detonation tube and heating apparatus. The atomizer is a slit nozzle pressure injector, manufactured by the Denso Corporation (Model 23209-39057-B0), which is used in direct injection gasoline engine. Since the injector is located on the engine itself, it is designed to function in environments of high temperature and pressure. The injector atomizes fuel with a V-shaped fan. The spray dispersion angle is 60° from front view and the injection angle is inclined 20° from the axis of the nozzle tip from side view. A power transistor-based control system that accepts transistor–transistor logic signals was built to operate the injector [16]. This feature provides a flexibility in controlling the dynamic flow rate, i.e., the amount of fuel injected per pulse. Furthermore, injection duration (10 ms) and fuel pressure (5 MPa) were controlled to meet the required droplet size ($<10\mu$m). The injector was installed directly on the closed end of detonation tube. The oxidizer was simultaneously mixed with fuel droplet during the fuel atomization process, which can reduce the complexity of inlet component.

The smooth detonation tube was made of aluminum 6061-T6 with a length of 1,143 mm and inner tube diameter of 101.6 mm with a 9-mm wall thickness, as seen in the schematic drawing shown in Fig. 1. The ignition system is a transformer (Model No. May & Christe z201402e2, 220 VAC-14,000 VDC) at the closed end, and the diaphragm (LUMIRROR polyester film) was employed to separate the detonation tube and the open end. Furthermore, uniform temperature distribution along the axial direction of detonation tube is required. The electric tape heaters were strapped uniformly along the entire length of the detonation tube. Four thermocouples were installed on the tube's inner surface or inserted at the inner tube's center at 76.2, 152.4, 190.5 and 533.4 mm from the closed end. At the designed temperature of 373 K, the temperature distributions and deviation are shown in Fig. 2a. Note that there is no heat isolation cushion to cover the flanges at the closed and open ends. Thus, more energy was required to reach the designed temperature. Therefore, a temperature peak was observed in the initial stage of heating process (before 1,500 s), in which the maximum temperature deviation from the designed temperature is about 70 K. Within 1-h heating duration, the temperature deviation is decreased to about 20 K. Furthermore, it can be seen that the temperature near the flanges was lower than that at the center of detonation tube, indicating significant heat loss of the flanges at the closed and open ends. Thus, the electrically heated rods were inserted into the flanges, as shown in Fig. 1, to reduce the axial temperature variation of the detonation tube. As shown in Fig. 2b, the maximum temperature deviation from the designed temperature could be

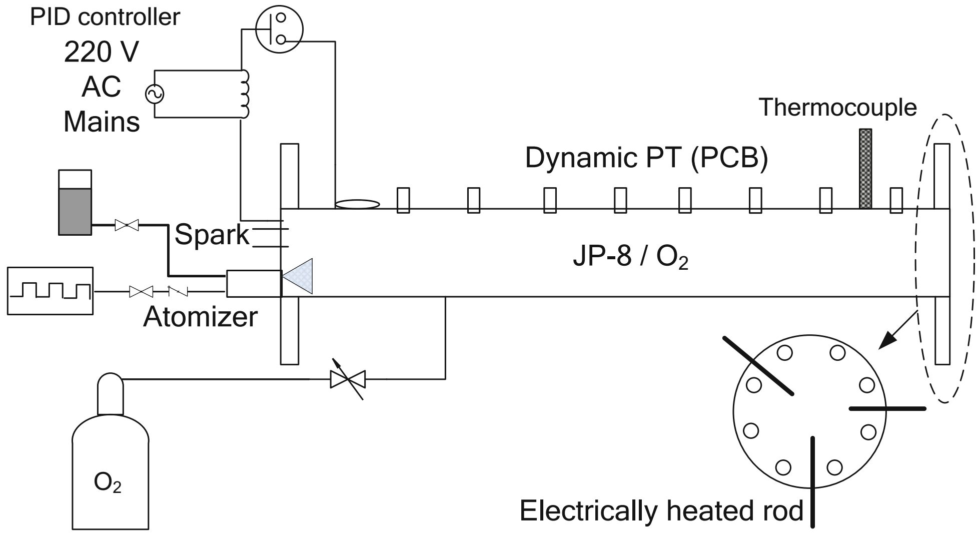

Fig. 1 Experimental facility and instrumentation

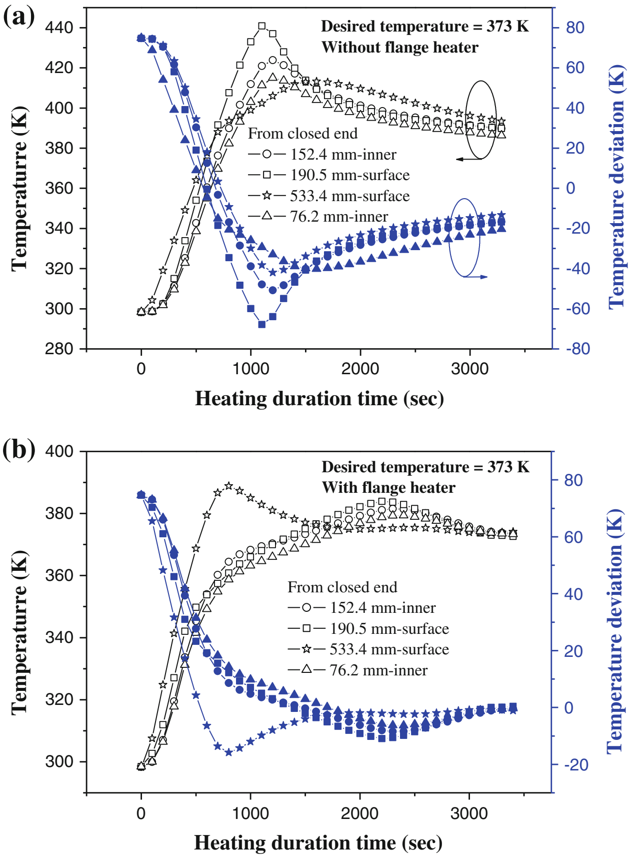

Fig. 2 Temperature deviation of detonation tube. **a** Without flange heater. **b** With flange heater

controlled within 20 K, and the temperature deviation along the axial direction of detonation tube was within 2 K in the 3,000-s heating duration that could insure the experimental stability and repeatability.

The mixture of JP-8 and oxygen was used in the present study. The designed equivalence ratio and initial pressure were 1.2 and 0.1 MPa (1 atm), respectively. The proportion of oxygen was achieved using the method of partial pressure [17]. Prior to each run, the detonation tube was evacuated to 20–30 Pa. The oxygen was subsequently heated to the desired temperature within 2 K using two thermocouples and PID controllers over a period of 1–1.5 h. Then JP-8 was injected into the detonation tube. Furthermore, the pressure transducer (OMEGA-PX1009) with high temperature resistance was installed in the detonation tube to check the actual vapor pressure, and the vapor proportion was estimated with the equation of state. For the propagation of pressure wave, the pressure taps were separated at 3.81-cm intervals along the detonation tube and the PCB dynamic pressure transducers (Type 112A05) were employed. The locations of pressure transducers, which were adjusted for different initial temperature conditions, are shown in the Table 1. One photodiode was also installed at the closed end to detect the onset of detonation (light of flame), t_{ddt}. The signals of the sensors were acquired and stored by the NI-PXI high-speed data acquisition modules, and the typical sampling rate is 500 ksamples/s. However, it is subjective to implement the propagating time because the front of a detonation or combustion wave is not measured as a step rise but is spread over a small time interval. A non-stationary cross-correlation function (NCCF) is used to estimate the propagating time of pressure wave [18]. Note that there were three experiments conducted for each test condition and the average X_{ddt} was

Table 1 Location of pressure transducers

Initial temperature (K)	Location of pressure transducers (mm)
373, 393	800.1, 838.2, 876.3, 914.4, 952.5, 990.6
413, 453	152.4, 190.5, 228.6, 266.7, 304.8, 342.9

obtained, in which the uncertainty is estimated to be 4 %. To confirm the detonation initiation, the cellular structure was also recorded by the soot foil on the inner surface of the detonation tube.

3 Results and discussion

JP-8 is a multi-component fuel that is essentially Jet A-1 with three more additives (a lubricity improver/corrosion inhibitor, an antistatic additive, and a fuel system icing inhibitor). To evaluate vapor proportion at specific pressure and temperature conditions, the surrogate mixture with some pure substances that meet the physical properties (density, specific heat, viscosity and conductivity) is usually adopted [19]. The JP-8 surrogate consists of a lot of specific hydrocarbon, which is shown in the Table 2. With the SUPERTRAPP software developed by NIST [20], the vapor proportion of the mixture of JP-8 and oxygen is shown in Fig. 3. As can be seen, saturated vapor pressure increases with higher pressure. However, higher heating temperature is required for full vaporization. The fully vaporized temperature of JP-8 was between 380 and 410°K as the initial pressure from 0.1 to 0.4 MPa.

At the initial temperature of 373 K, JP-8 was not completely vaporized. Moreover, the vapor proportion is estimated to be 80 % according to the final vapor pressure. When the mixture was ignited, the amplitude of pressure signals was sufficiently lower than that at CJ state. Meanwhile there were no obvious cellular structures observed on the soot foil. Condensed fuel was observed on the bottom of the detonation tube, indicating that there is not enough vaporized fuel to initiate detonation at the initial temperature of 373 K. In addition, the limited length of the detonation tube (1,143 mm) might be another constraint for DDT under this test condition. To increase vapor proportion, the initial temperature was increased to 393 and 413 K. Three extra pressure transducers at 381, 419.1 and 457.2 mm from the closed end were installed. Note that the initial temperature of 393 K was very close to the upper limit of the fully vaporized condition. The injected fuel did not completely vaporize before ignition, and a two-phase condition (95 % of vapor proportion) was present. However, it is considered that some liquid-phase fuel might be accelerated and heated by the shock wave to initiate the detonation wave. As shown in Fig. 4a (DDT process), there were no obvious peak pressure signals and a high degree of random noise was presented. With the visualization by the soot foil, the cellular structure was observed near the open end of detonation tube (about 963 mm from the spark), indicating detonation initiation. Thus, although a portion of the fuel was in a liquid state, presence of enough fuel vapor could result in rapid heating, vaporization, and reaction rates behind the shock wave to produce detonation wave. Moreover, when the heating temperature was increased to 413 K, the fuel was fully vaporized before ignition. The time history of pressure signals (detonation propagation) is shown in Fig. 4b. The peak pressure signals are clearly observed and resemble those of gaseous mixtures, such as propane/oxygen.

Table 2 Component of JP-8 surrogate [19]

Compound	Wt %
Iso-octane	5
Methyl cyclohexane	5
m-Zylene	5
Cyclooctane	5
Decane	15
Butyl benzene	5
1,2,4,5 tetramethyl benzene	5
Tetralin	5
Dodecane	20
1-Methyl naphthalene	5
Tetradecane	15
Hexadecane	10

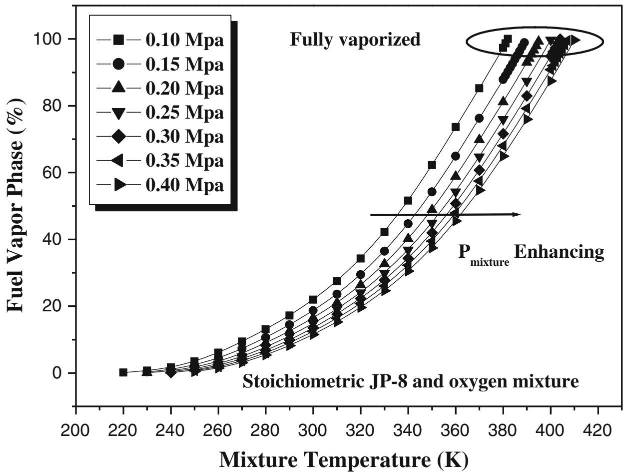

Fig. 3 Equilibrium liquid vapor state for a stoichiometric JP-8 and oxygen mixture at different pressure and temperature conditions

In the estimation of X_{ddt}, Gaydon [21] indicated that the onset of detonation for hydrocarbon/oxygen mixtures shows very strong continuous emission throughout the visible and near-ultraviolet spectrum, which is different from emission from a hydrocarbon/oxygen flame. Such phenomenon is attributed to be due to the higher temperature and pressure jump associated with the formation of detonation. Thus, variations in the intensity and spectrum of the flame emission can be used as a criterion for the onset of detonation. In this study, the photodiode was placed at the center of the closed end to continuously monitor the light profile of the flame, from which the time for the onset of detonation t_{ddt} can be estimated. Then according to the trajectory of pressure

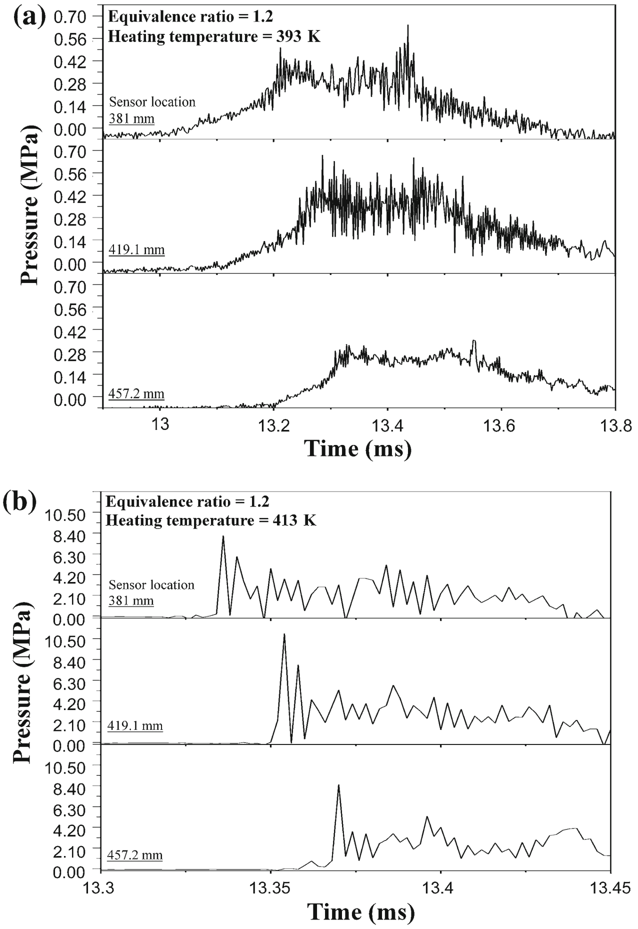

Fig. 4 Examples of pressure history. **a** Heating temperature at 393 K. **b** Heating temperature at 413 K

waves, X_{ddt} can be calculated using (1) as below [22].

$$X_{ddt} = \frac{\tau_{1*}}{\tau_{12}}(X_2 - X_1) + X_1 \tag{1}$$

where X_1 and X_2 are pressure transducer positions, τ_{12} is the propagating time of pressure wave past a pair of sensors, and τ_{1*} is propagating time between t_{ddt} and the arrival time of the pressure wave past the first sensor X_1. Note that the NCCF method was employed to calculate τ_{12} and τ_{1*}. With the equivalence ratio of 1.2, X_{ddt} at different initial temperatures is shown in Fig. 5. The result can be classified into two parts. One is in the two-phase region, in which JP-8 at 393 K was not completely vaporized. X_{ddt} was estimated to be 963 mm. For the fully vaporized region, X_{ddt} at the initial temperatures of 413 and 453 K was 245 and 206 mm, respectively, which is roughly the same as that of the propane–oxygen mixture (X_{ddt}=196 mm at T=293 K) [22].

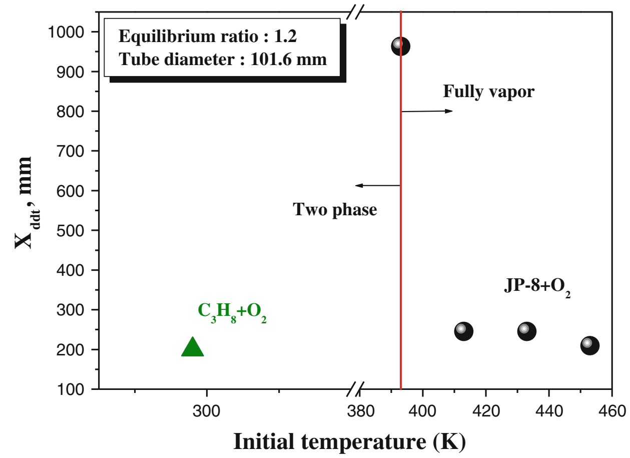

Fig. 5 Effect of initial temperature on X_{ddt}

As the detonation propagates, the triple point tracks form diamond-shaped pattern (detonation cells). The height of a detonation cell is defined as the detonation cell width, which is commonly used to characterize the sensitivity of the mixture to being detonated [23]. A study of Kaneshige and Shepherd [1] indicated that the cell width of a stoichiometric mixture of propane–oxygen at 0.05 MPa and 293 K is about 2.5 mm. In this study, the cellular structure was recorded near the open end of the tube where detonation propagates with a quasi-steady velocity. With the equivalence of 1.2 at 0.1 MPa and 433 K, the cell width is estimated to be about 1 mm, indicating that some detonation properties of the fully vaporized JP-8 with oxygen are similar to those of the propane/oxygen mixture.

4 Conclusions

The non-uniform temperature distributions were observed near the flanges at the closed and open ends of the smooth detonation tube. The electrically heated rods in the flanges were required to reduce the axial temperature variation along the detonation tube. The vapor proportion for the mixture of JP-8 with oxygen is an important factor determining whether the detonation wave would be initiated or not. The single-shot experiments at the atmospheric condition were conducted to investigate the effects of initial temperature on detonation initiation. The results are summarized as below:

1. JP-8 was not completely vaporized (about 80 % vapor) at the initial temperature of 373 K. The detonation wave was not observed.
2. Although a portion of JP-8 was in a liquid state at the initial temperature of 393 K, there was enough fuel vapor (about 95 % vapor) to initiate a reaction that results in rapid heating, vaporization, and reaction rates behind the shock wave for detonation initiation with a longer DDT run-up distance.
3. Detonation initiation was observed at a shorter DDT run-up distance for the mixture of fully vaporized JP-8 and

oxygen when the initial temperature exceeded 413 K. The propagation of detonation wave shows a similar characteristic as that of propane/oxygen mixture.

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