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Effects of jet in crossflow on flame acceleration and deflagration to detonation transition in methane–oxygen mixture

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A B S T R A C T

The fluidic jet turbulator has been a novel perturbation generator in the pulse-detonation engines research field for the past few years. In this paper, an experiment is performed to study the deflagration to detonation transition (DDT) process in a detonation chamber with a reactive transverse methane–oxygen mixture jet in crossflow (JICF). The jet injection arrangement is fundamentally investigated, including single jet and various double jets patterns. Corresponding two-dimensional direct numerical simulations with a multistep chemical kinetics mechanism are employed for analyzing details in the flow field, and the interaction between the vortex and flame temporal evolution is characterized. Both the experiments and simulations demonstrate that the JICF can distinctly accelerate flame propagation and shorten the DDT time and distance. The vortex stream induced by the jet distorts and wrinkles the flame front resulting in local flame acceleration. Moreover, the double jet patterns enhance flame acceleration more than the single jet injection because of the intrinsic counter-rotating vortex pairs and enhanced turbulence intensity.

1. Introduction

Pulsed-detonation engines (PDEs) have been proposed as an advanced and developing propulsion system with potential advantages including high thermodynamic efficiency and structural simplicity [1–3]. Although detonations have outstanding energetic advantages compared to conventional constant pressure combustion processes, a lot of challenges remain to be solved due to their unstable and complex characteristics. One of the challenges for PDE research is the implementation of low energy ignition to initiate stable detonation waves within a short distance and time [4]. The detonation can be formed through the Deflagration-to-Detonation Transition (DDT) process. However, a detonation tube with smooth walls will be too long to accomplish the DDT process for engineering applications.

To shorten the DDT distance, various perturbation enhancement devices have been designed [5]. High-intensity turbulence generation is vital for flame acceleration. Traditionally, solid obstacles have been used to effectively shorten the DDT time and distance [6]. The presence of the obstacles leads to the formation of a laminar vortex ahead of the flame and induces turbulence within the reactant flow. In the initial stage, the flame acceleration is mainly due to flame wrinkling. The main reason for flame wrinkling is the flame-vortex interaction, which is formed behind the obstacles [7]. The obstacles play another significant role to produce localized explosions. When the flame velocity reaches the local sound speed, a shock wave is formed ahead of the flame tip which compresses unburned gas. Then the detonations appear from hot spots created by shock reflections at corners between obstacles and the wall [8].

The goal of most previous studies on obstacles was to initiate a detonation at a shortest DDT length, but they did not consider the issues of practical detonation cycle. In fact, the pressure losses have very important influence on thrust performance in multi cycle PDE. A large blocking ratio increases the time of fresh mixture filling, limiting the operating frequency of PDE [9]. Large obstacles also act as thermal reservoirs, adding and subtracting heat at improper time in the PDE's cycle. Therefore, the design of turbulence enhancement devices for DDT processes needs to balance the acceleration gain and the total pressure loss.

The concept of jet obstacles has been proposed in conventional gas turbine combustor recirculation zone design for ensuring combustion stability, where it leads to less total pressure loss compared to solid flame holder [10]. Inspired by this, the fluidic jet is applied as a substitute for a solid obstacle in the detonation chamber. Several relevant experiments were carried out to study the effect of fluidic jet

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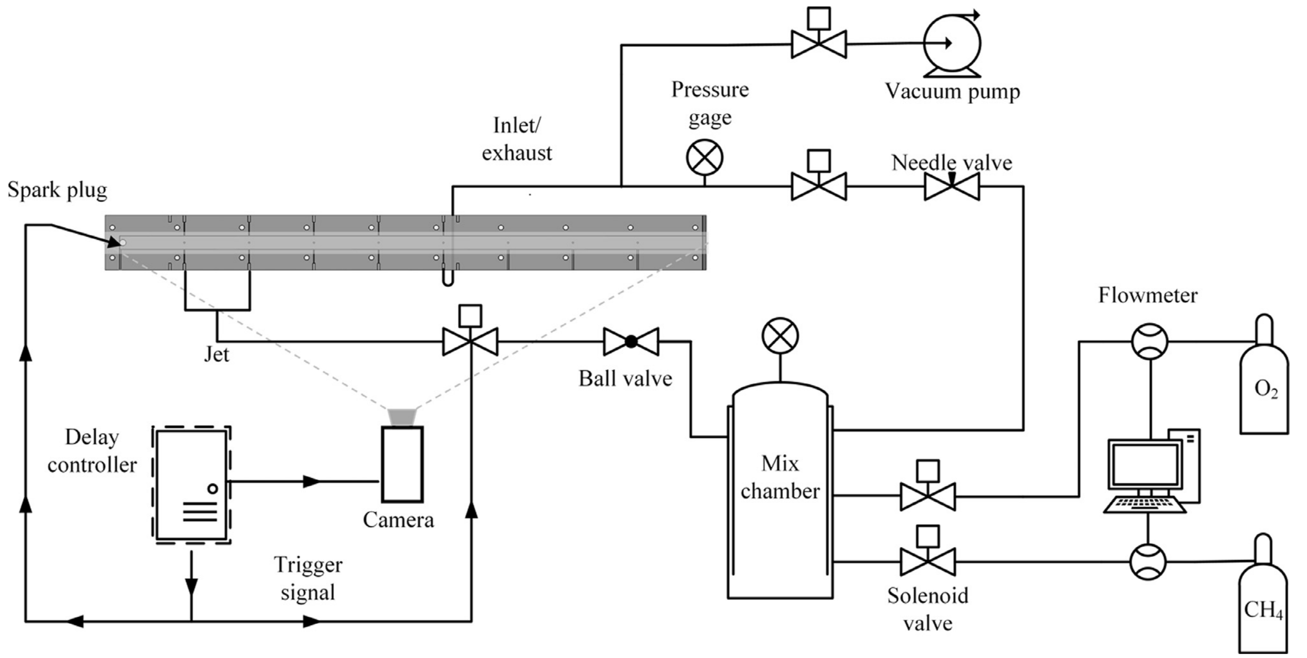

Fig. 1. Schematic of experimental setup.

on the DDT process. When the main flow consists of a stoichiometric hydrogen-air mixture and the jet composition is either premixed stoichiometric hydrogen-air or pure air, the results show that the jet plays the role of a virtual obstacle but suffers from substantially lower total pressure losses than a solid obstacle with similar blockage shape. But there is no discernable difference in DDT distances between the jet composition of air and reactive mixture [11,12]. Whereas in another study, the jet made by pure air deteriorates the local kerosene-air ratio and fuel distribution, which was observed experimentally and found to be disadvantageous for flame propagation. On the other hand, a jet made by a kerosene-air mixture can effectively accelerate the flame-propagation [13]. Apart from that, the experiments, methane-air flame acceleration in duct with JICF, demonstrate that the jet is more effective at transitioning the laminar flame to a fast-propagating turbulent flame than the solid object according to PIV and Schlieren imaging results [14]. This research about fluidic jet influence on the primary stages of the DDT process indicates that the jet induces increased turbulence through flow transport enhancement and entrainment mechanisms. The flow instabilities are strengthened with the jet stream, subsequently the velocity fluctuation and high turbulence intensities increase the reaction rates, leading to higher flame propagation speeds. At the next stage, the turbulent flame accelerates in the broken reaction regime during the jet-flame interaction, where detonation is expected to occur [15,16].

Although a lot of work has been conducted to study the effect of a single fluidic obstacle on flame acceleration and DDT progress, little attention was paid to the jet arrangement. The jets composed by inert gas or oxidizer evidently affected the local concentration and heterogeneity of the reactant, but utilizing the fuel-oxidant mixture jet poses risks in experimental safety. High resolution numerical simulations is a feasible way to get details about the flow field and flame evolution in the DDT process [17]. Two- and three-dimensional simulations with one step Arrhenius chemical model or detailed chemical mechanism both show that solid obstacles in a detonation chamber can induce vorticities and enhance the turbulent intensity downstream. The initial thermal diffusion and hydrodynamic instability play significant roles on flame acceleration. The solid obstacles reflect the precursor shock resulting in hot spots in the preheat region. The hot spots and the local concentration gradient are considered as the main mechanism to trigger the transition to detonation [18–21]. However, the effect of a fluidic jet turbulator on the flame propagation in a DDT process has not been explored by numerical simulations yet.

In this paper, the effects of a reactive mixture JICF on the DDT process are investigated by both experiments and simulations. High speed photography was used to capture flame front position and velocity in the experiments. Detailed reactive flame-jet interactions were explored by numerical simulations. In addition, the discrepancies of the DDT process among various jet injection patterns are analyzed in this work, which aims to enhance the understanding of DDT with fluidic jets and contributes experimental data to identify mechanisms that can be used to optimize further the design of detonation combustors.

2. Experimental setup and numerical methods

2.1. Experimental setup

The test section was designed with a total viewable length of $L = 800$ mm and rectangle cross-section of $W \times H$ (width × height) = 6 mm × 20 mm. The main structure is made of stainless steel. Acrylic glass is used on one side to enable high-speed photography. Its thickness is 5 mm to balance the durability and transmittance. The experimental setup consists of the fuel and oxygen supply system, flow control system, the data acquisition system, ignition system, the test stands and the detonation channel (see Fig. 1). The oxygen-fuel mixture in the detonation channel is ignited by spark plug with 50 mJ ignition energy, which is located at the center of the left end wall. The delay controller is composed of ARM-STM32F103CB development boards and an Ingenex-H3MB-052D solid-state relay. The signal is switched by the relay, whose active time and reset time are less than 1 ms. The jet delay time is defined by the signal transmitting time interval between ignition and injection trigger as depicted in Fig. 2. The jet delay time of all the cases in this study is set to 0.4 ms consistently. The breakdown time delay of the ignitor is about 1 ms. The