On Interaction of Centrally Ignited, Expanding Flame with Isotropic Turbulence at Elevated Pressure

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1 Abstract

A new apparatus for the study of centrally ignited, outwardly propagating flames in quiescent and/or turbulent reactive environment of fuel-oxidizer mixtures, at atmospheric and elevated pressures, is proposed. The apparatus includes a high pressure, symmetrical cruciform fan-stirred premixed combustor, the inner chamber, which is resided in a very large pressure-absorbing safety chamber (the outer chamber). Both chambers are optically accessible, allowing direct visualization and measurement of flame and turbulence interactions. The inner cruciform chamber is constructed by a large horizontal cylindrical vessel equipped with a pair of counter-rotating fans and perforated plates at each end capable of generating intense isotropic turbulence and a vertical cylindrical vessel. The vertical vessel has four large sensitive pressure releasing valves installed symmetrically on its sides, so that the pressure difference between the inner and outer chambers at elevated pressure during explosion can be greatly minimized. Preliminary results, using lean methane-air mixtures at an equivalence ratio ϕ = 0.8 under both quiescent and turbulent conditions, show that turbulent flames seem to propagate more faster at elevated pressure than at atmospheric pressure. This is in opposition to laminar flames where their expanding speed decreases with increasing pressure. As the flame expands from the ignition kernel, cellular instability is observed for both laminar and turbulent flames, of which cellularity is promoted by the effect of elevated pressure and this influence is even more obvious for turbulent flames.

2 Introduction

Turbulent premixed combustion at elevated pressure is crucial to internal combustion engines as the major driving force behind modern combustion research. However, the available data on flame behaviors at high pressure conditions are relatively scarce [1]. To gain fundamental understanding of the high-pressure effects on fuel oxidation mechanisms, various designs of the high-pressure combustion chamber have been proposed for specific experimental studies of flame phenomena [e.g., 1-5]. Of particular interest are those aimed to determine the laminar/turbulent burning velocities at pressures higher than 5 atm. Such burning velocity measurements at elevated pressures can further be classified into two categories: One is based on the stabilized stationary Bunsen-type flames [1,2] and the other obtains data from centrally ignited, outwardly propagating laminar flames [3-5]. As pointed out by Jomaas et al. [6], a prototypical flame configuration that is suitable for a well-controlled study

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of the governing parameters for the onset of cellularity is the centrally ignited, expanding spherical flame. They also reported that the effect of pressure plays an important role on laminar flame behaviors because of its influence on both diffusion and reaction processes which control laminar flame propagation [6]. Does the same pressure effect be applicable to turbulent flame propagation? This question motivates the present work that aims to devise a high-pressure premixed turbulent combustor for a well-controlled study of interactions of centrally ignited, outwardly propagating flames with intense isotropic turbulence.

Isotropic turbulence is the simplest turbulence and it can only exist in theory and modeling. The best one can do in the laboratory is to produce a near-isotropic turbulent flow with characteristics closely matching that assumed by the theory. These characteristics include such as roughly equal magnitudes of rms turbulent intensities in all three directions with negligible mean velocities, values of skewness and flatness essentially equaling to zero and three, and energy spectra of fluctuating velocity components in all three directions exhibiting –5/3 decaying slopes over a broad range of spatiotemporal scales. Such nearly isotropic turbulent flow has been established in a novel fan-stirred cruciform burner for the study of premixed turbulent combustion at atmospheric pressure [7]. It was found that there is an ignition transition based on quantitative measurements of minimum ignition energy (MIE) owing to different modes of combustion [8,9]. Before the transition, MIE only increases gradually with turublent intensities u'/S_L, where S_L is the laminar burning velocity. Above the transition when values of u'/S_L are greater than some critical values varying from 16 to 27 depending on the equivalence ratio ϕ, MIE increases abruptly. This MIE transition proves the existence of both thin and broken reaction zones regimes proposed by Peters for a new regime diagram of premixed turbulent combustion. Hence, we apply essentially the same cruciform configuration as in Ref. [7] together with the ignition arrangement as given in Refs. [8,9] for the present high-pressure combusiton study.

3 Experimental

Figure 1 shows a newly-built high-pressure absorbing cylindrical chamber (the outer chamber) with a diameter and a length of about 1.1 m and 2.0 m, respectively. The sketch of the aforementioned cruciform high-pressure combustor (the inner chamber) is superimposed on Fig. 1 along with other essential auxiliary systems including the high-power spark-ignition system, the high-speed image acquisition system, the shaft water cooling system, and the high pressure gas supply system. These systems and the door of the outer chamber as seen on the left of Fig. 1 are all electrically controlled. Though the inner cruciform chamber is similar to the original design of previous studies [7], some modifications have to be made in order to adapt the combustor to a reactive environment at elevated pressure. Here the inner chamber is constructed by two mutually crossing cylindrical vessels with a cruciform shape, where the robust horizontal vessel has a diameter of 245 mm and a length of 420 mm and the vertical vessel is 600 mm long with an inner diameter of 120 mm. Two identical eight-blade counter-rotating fans equipped at two ends of the horizontal vessel are independently driven by two 10-HP electric motors which are synchronized to the same rotational speed by the frequency converters. Due to the high fan frequency achieved (as high as 180 Hz), both motor shafts are continuously water-cooled during operating. A large volume up to $15 \times 15 \times 15$ cm^3 of intense near-isotropic turbulence can be generated in the core region between two perforated plates of the inner combustor [7], where the adjustable spark-electrode is located at the central point of near-isotropic region. In this study, two thin (2-mm) stainless-steel electrodes with needle ends having a fixed gap of 3 mm are used. The discharge energies across the electrodes up to 300 mJ can be controlled and adjusted. Four quartz windows are located at circumferential front back and as well as top and bottom of the inner chamber, each window 120 mm in diameter and 75 mm in thickness. Similarly, the outer chamber also has four corresponding quartz windows in order to provide the optical access for the use of schlieren imaging or particle image velocimetry. All materials used are stainless steel with appropriate thickness to endure the instant of high pressure from explosion. In addition, four automatic pressure releasing valves are specially designed and built on the upper and lower parts of the vertical vessel of the inner chamber with two in front and the other two in back (see Fig. 1). These pressure releasing valves can be immediately turned on as long as the pressure of the inner chamber is about 0.25 atm greater than that of the outer chamber. This arrangement prevents the danger of the sudden pressure rise inside the inner combustor. Before a run, both chambers are evacuated. Then step by step while remaining a constant pressure difference of 0.1 atm between the outer and inner chambers during the gas filling process, the outer chamber is first filled with dry air and next the inner combustor is filled with lean methane-air mixtures ($\phi = 0.8$) until the wanted elevated pressure varying from 1 atm to 12 atm is achieved for both chambers. A run begins by centrally igniting the reactive mixtures either under quiescent condition without fan-stirring or at various turbulent conditions with different fan rotating frequencies. The kernel initiation and subsequent flame development are then recorded by a CMOS camcorder (5000 frames/s; 512×512 pixel^2).

4 Preliminary Results and Discussion

Figure 2 shows instantaneous images of lean CH_4/air mixtures at various initial pressures of 1, 3, 5, 7 and 10 atm under both laminar and turbulent conditions, where all images have a view field of 140 mm x 140 mm. For laminar flames as shown on the first row of Fig. 2, it can be easily seen by comparing these images taken at the same instant of 60 ms except that at 1 atm (30 ms) that the expanding speeds of these laminar spherical flames decrease with increasing initial pressures. Furthermore, as the laminar flame expands from the ignition kernel, cellular instability is observed because the Lewis number defining as the ratio between thermal and mass diffusivities of mixtures is less than unity for lean methane-air mixtures. For turbulent flames as shown on the second row of Fig. 2, as a typical case, using a fan-frequency of 30 Hz having a rms turbulent fluctuating velocity of 0.89 m/s, turbulent flames seem to propagate more faster at elevated pressures than at atmospheric pressure in opposition to laminar flames. Moreover, cellularity seems to be promoted by the complex interaction between turbulence and the effect of elevated pressure possibly resulting in a higher propagation speed. However, more experiments still need to be conducted in order to confirm such conclusion.

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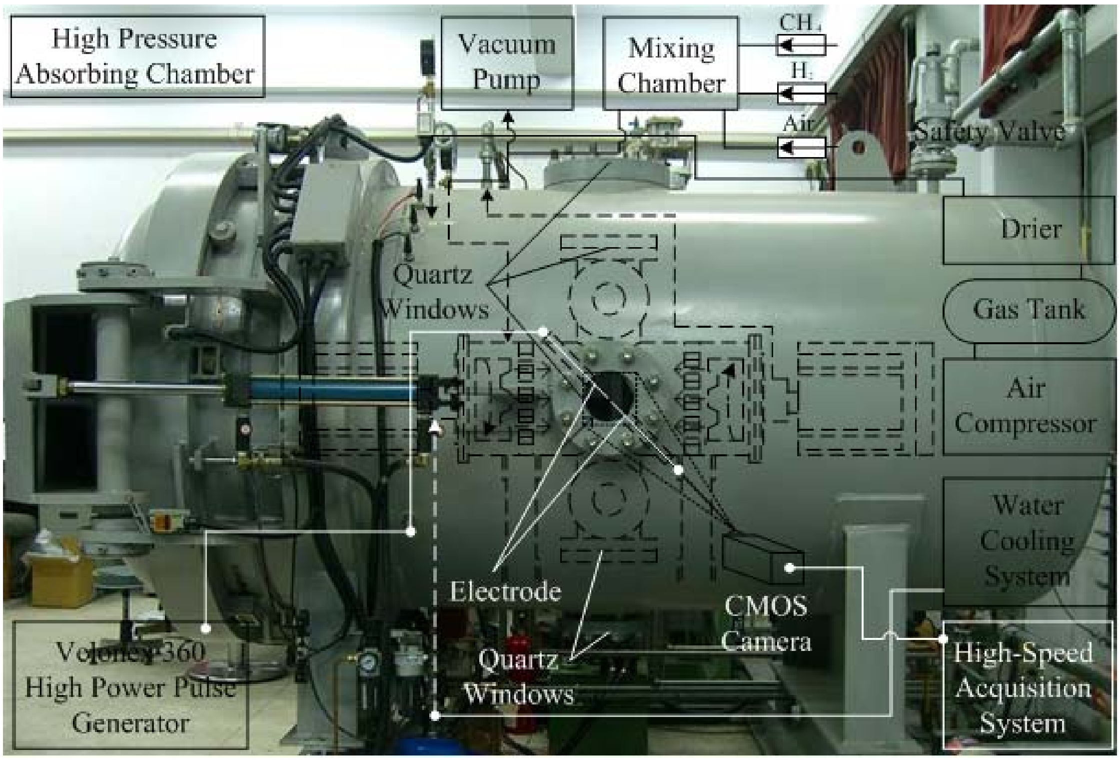

Figure 1. A pressure absorbing safety chamber with a high pressure inner combustor placed inside.

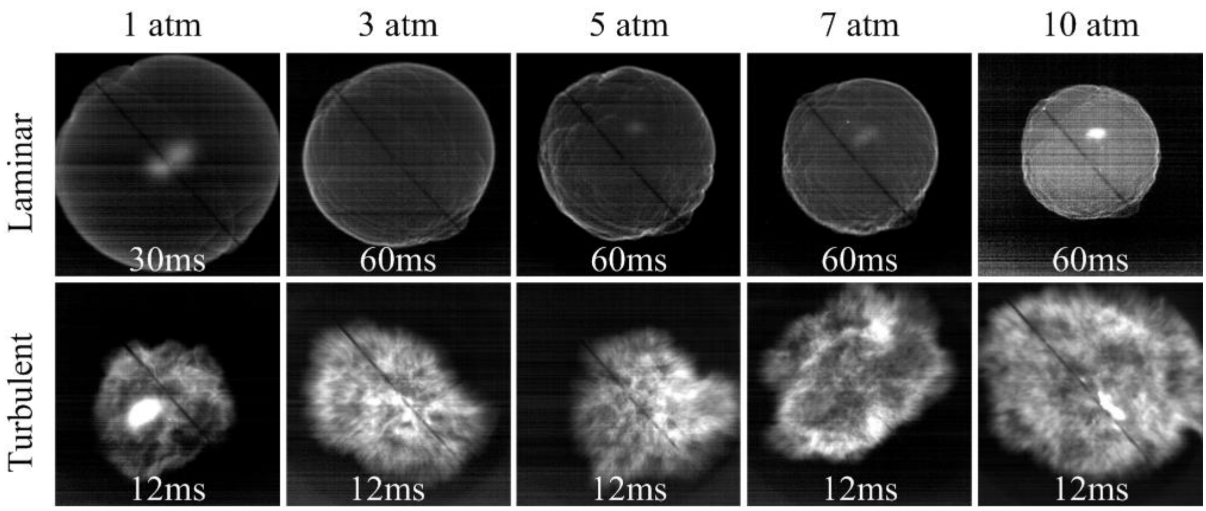

Figure 2. Instantaneous images of centrally ignited, outwardly propagating flames taken at the same instant, 30 or 60 ms for laminar flames and 12 ms for turbulent flames, at various initial pressures from 1 atm to 10 atm.