High-Pressure Turbulent Burning Velocity Measurements at Constant Reynolds Numbers

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1 Abstract

Turbulent combustion at elevated pressure is one of influential yet knowledge-lacking fields in combustion research, and may be one of the cornerstones of the next combustion era. Measurements of turbulent burning velocities (S_T) may be the most general approach to the understanding of high-pressure turbulent combustion. Our previous findings indicate that increasing pressure has a promotion effect on S_T, due to the enhancement of flame instabilities via the thinner flame at elevated pressure. However, increasing pressure also increases the turbulent Reynolds number (Re_T) due to the decrease of kinematic viscosity. The present study therefore aims to determine whether such S_T enhancement by increasing pressure is due to the effect of increasing Re_T. Using the same experimental methodology, this work presents the S_T measurements of lean CH_4-air mixtures at $\phi = 0.8$ and different initial pressure varying from $p = 0.1$ MPa to $p = 1.0$ MPa under various turbulent conditions, in which values of Re_T are kept constant. Results show that S_T decreases with increasing p in minus exponential manners at any constant value of Re_T, having similar pressure dependence of laminar burning velocities S_L. Besides, S_T increases with increasing Re_T at any constant value of p. It is also found that the normalized turbulent burning velocities (S_T/S_L) behave approximately independent of p at any constant value of Re_T. However, the values of S_T/S_L still increase with increasing Re_T at any constant value of p. The present result clearly shows an important message that Re_T may still be a suitable indicator for the coupling effect of turbulence-pressure interaction on turbulent burning enhancement. These results should be beneficial to our further understanding of high-pressure turbulent combustion.

2 Introduction

Turbulent premixed combustion at elevated pressure is crucial to the modern development of gas turbine combustors and internal combustion engines. However, information about turbulent flame behaviors at elevated pressure is still relatively sparse due to the lack of safe, compact, reliable experimental apparatuses for high-pressure turbulent combustion, especially those designed for measurements of high-pressure turbulent burning velocities (S_T).

Recently, a few high-pressure turbulent combustion facilities have been used [1-4]. These facilities in turn use expanding turbulent flames with pressure releasing [1], stabilized turbulent Bunsen flames [2,3], and explosive turbulent flames without pressure releasing [4] for the measurements of S_T. Although the turbulent flame configurations used for S_T measurements are not the same in Ref. [1,2,4], all experimental results show that S_T increases with increasing pressure. The only exception is Ref. [3] showing no influence of pressure on S_T. It is suggested for methane flames that such S_T enhancement by pressure is attributed to additional flame surface area increment induced by the enhanced hydrodynamic instability due to the decrease of kinematic viscosity at elevated pressure [1]. However, increasing pressure can also increase the turbulent Reynolds number (Re_T) because of the decrease of kinematic viscosity. In view of the above considerations, whether such S_T enhancement by increasing pressure is primarily due to the effect of increasing Re_T is thus an important question.

Using the same high-pressure turbulent combustion facility [1], the present study aims to measure turbulent burning velocities of lean CH_4-air mixtures at $\phi = 0.8$ and different initial pressure varying from $p = 0.1$ MPa to $p = 1.0$ MPa under various turbulent conditions, in which values of Re_T are kept constant. This study then aims to address two key questions: (1) What is the effect of elevated pressure on S_T at constant values of Re_T? (2) Is Re_T still an effective parameter for the description of turbulence-pressure interaction?

3 Experimental

Figure 1 shows the recently built high pressure premixed combustion facility [1], where the high pressure turbulent cruciform burner (inner burner) is depicted in dash lines and placed inside of the large high pressure absorbing chamber (outer chamber). The outer chamber has a maximum inner diameter of 1.1 m, a chamber length of about 2 m, and a volume of about 2.25 m^3. The inner burner originates our previous design of the turbulent cruciform burner [5], which is constructed by two cross cylindrical vessels. The horizontal vessel has an inner diameter of 245 mm and a length of 420 mm, while the vertical vessel is of 120 mm in inner diameter and 600 mm in length. Two identical eight-blade custom fans are equipped at the opposite ends of the horizontal vessel and independently driven by two 10-HP electric motors. Two identical perforated plates with a 36% solid ratio are also installed ahead of these two fans in order to generate turbulence. The fan speeds can be adjusted and synchronized up to a highest fan frequency (f) of 182 Hz by two individual frequency converters. The motor shaft sealings are continuously water-cooled during operation to protect them from overheating damage. As the fans are counter-rotated at the same speed, a large volume up to $150 \times 150 \times 150$ mm^3 of nearly homogeneous isotropic turbulence can be generated in the core region of the inner burner, having zero mean velocities and energy spectra with -5/3 decaying slope [5]. The characteristics of this turbulence have already been confirmed in our previous studies via LDV and PIV measurements [5,6]. Moreover, the associated turbulent characteristics such as u' and L_I in this fan-stirred cruciform burner have been proven to be insensitive to pressure via PIV measurements [1], so that previous turbulent characteristics obtained by extensive LDV and PIV measurements at the atmospheric pressure condition [5,6] can be used even at the elevated pressure condition.

In order to safely handle the explosive gas expansion generated by intense turbulent combustion at elevated pressure, the inner burner is not only constructed using reinforced structures, but also equipped symmetrically with four sensitive pressure-releasing valves on its vertical vessel as shown in Fig. 1. These sensitive pressure-releasing valves are designed to be immediately opened as the pressure rise inside the inner burner is about 0.02 MPa. Therefore, these pressure-releasing valves not only prevent danger of the explosive pressure rise inside the inner burner, but also provide an approximately constant pressure environment for both laminar and turbulent flame propagation during pressure releasing. Besides, the silica gel plates are also adopted as sealing material to ensure the gas-tight of the inner burner, which is confirmed by maintaining a near vacuum state inside the inner burner for around one minute while the outer chamber is kept at atmospheric pressure.

Also plotted in Fig. 1 are schematics of other complementary systems including the electrical controller, a high-voltage pulse generator with adjustable voltage up to 25 kV, an air compressor equipped with contaminant-removing filters and a dehumidifier, the combustible mixture supply system, the vacuum pump and gas exhaust system, the water cooling system, a separate high-pressure fan-stirred mixing chamber, and the high-speed high-resolution image acquisition system. The gap-adjustable spark-electrode is positioned at the central region of near-isotropic homogeneous turbulence in the inner chamber. For simplicity, we keep the electrode gap constant for all experiments conducted here at about 2.6 mm. There are four pairs of associated large quartz windows installed at front and back as well as top and bottom of the high pressure premixed combustion facility, allowing flexible optical measurements, such as the direct visualization and the PIV measurement of reacting flows.

In this study, lean methane-air premixtures at $\phi = 0.8$ are used. We apply a thin (2-mm in diameter) stainless-steel electrode, having needle ends (≈ 0.1 mm) and 1-mm spark gap, which is located at the center of uniform turbulence region of the inner burner. The discharging energy released into the electrode gap can be adjusted from less than 0.1 mJ to higher than 200 mJ with spark duration time no greater than 100 µs. The realization steps of the high-pressure explosion experiment are as follows. In the beginning, both the inner burner and the outer chamber are purged by dry clean air and then the inner burner is deeply evacuated. During the process of gradually filling the combustible gas mixtures into the inner burner to the wanted pressure condition, the outer chamber is simultaneously pressurized by air at a pressure value at least equivalent to or slightly greater than the pressure inside the inner burner. Such procedure can prevent the combustible gas from leaking into the outer chamber via the sensitive pressure-releasing valves. A run then begins by centrally igniting the combustible mixture at elevated pressures varying from p = 0.1 MPa to p = 1.0 MPa under various turbulent flow conditions with constant values of Re_T.

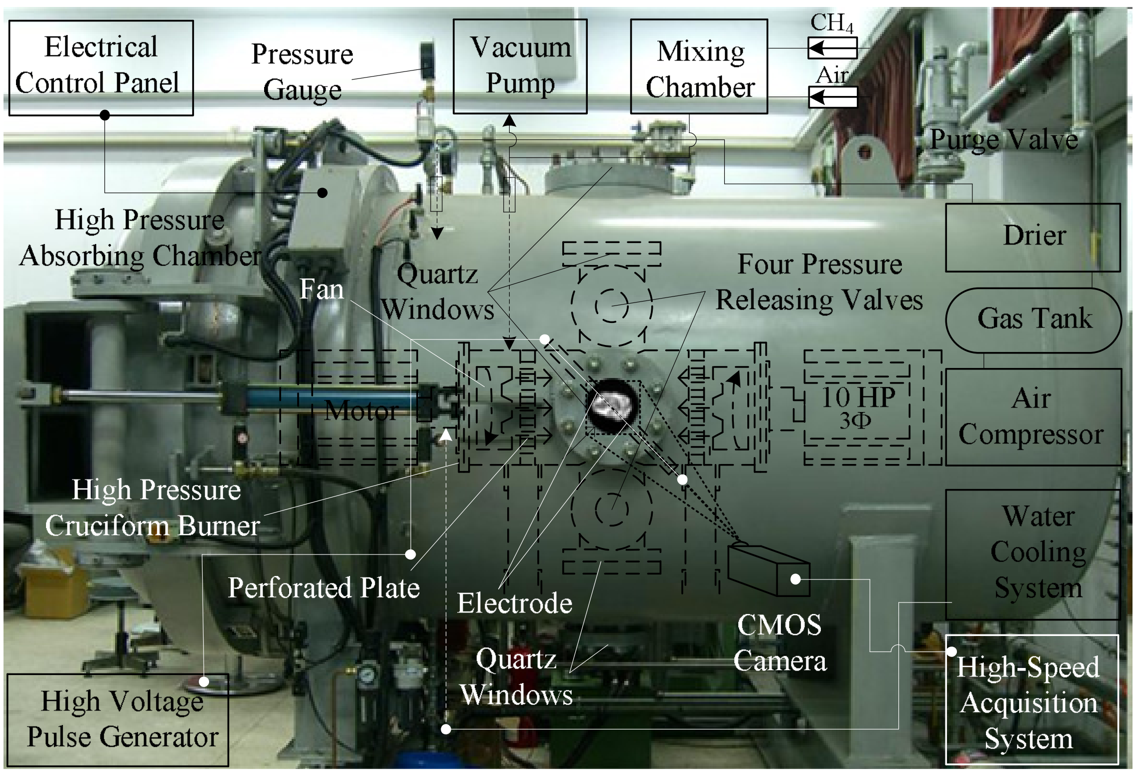

Figure 1. High pressure premixed combustion facility, including the high-pressure turbulent cruciform burner (inner burner) and the high-pressure absorbing chamber (outer chamber).

The developments of centrally-ignited expanding flames in a large view field of about 140 mm × 140 mm are directly imaged by the high-speed high-resolution Phantom v310 CMOS camera. An instantaneous image of an expanding turbulent flame is superimposed on the central observation window of Fig. 1 as a typical example. The values of laminar burning velocities (S_L) used in this study are directly referred to those measured in Ref. [1], except for the value of S_L at atmospheric pressure which has been re-determined. However, the procedure for S_L determination is briefed as follows. In the beginning, the instantaneous stretched laminar flame speed (S_F) should be calculated from the time

(t) evolution of the effective flame radii (r), that is, $S_F = dr/dt$ [1]. Here $r = (A/\pi)^{0.5}$ is calculated using the binarized flame images, where A is the product gas projection area in a binarized image. The corresponding mean stretch rate (α) of a spherical flame can then be estimated by $\alpha = 2S_F/r$ [1]. In order to avoid the possible influences from the ignition process, the effective flame radii less than 10 mm are not taken into consideration [1]. In the plot of S_F versus α, a linear-fit line segment can be best drawn in some appropriate data range of which the spherical flame is only subject to the inherent weak stretch. Then the unstretched flame speed ($S_{F\infty}$) can thus be determined by the linear extrapolation to the zero-stretch point ($\alpha = 0$). After correcting the burned gas density (ρ_b) back to the unburned one (ρ_u), the S_L can finally be obtained, that is, $S_L = (\rho_b/\rho_u)S_{F\infty}$. As to the turbulent expanding flames, the same procedure is performed to obtain the temporal variation of r, and S_F can thus be determined by the slope in such r-t plot. Then values of S_T are immediately determined via density correction, that is, $S_T = (\rho_b/\rho_u)S_F$. For turbulent expanding flames, however, the threshold radius for the flame speed analysis is changed from 10 mm to 20 mm in order to ensure that turbulent flames at such size can be free from the possible influences of spark ignition and turbulent kernel growing [1]. It should be noted that fully-developed or constant turbulent flame speeds may hardly be observed due to the continuous flame acceleration caused by the possible effects of flame instabilities and turbulent flame development, especially at high pressure. Therefore, any of the present values of S_T can only be regarded as the mean velocity at which a turbulent flame propagates.

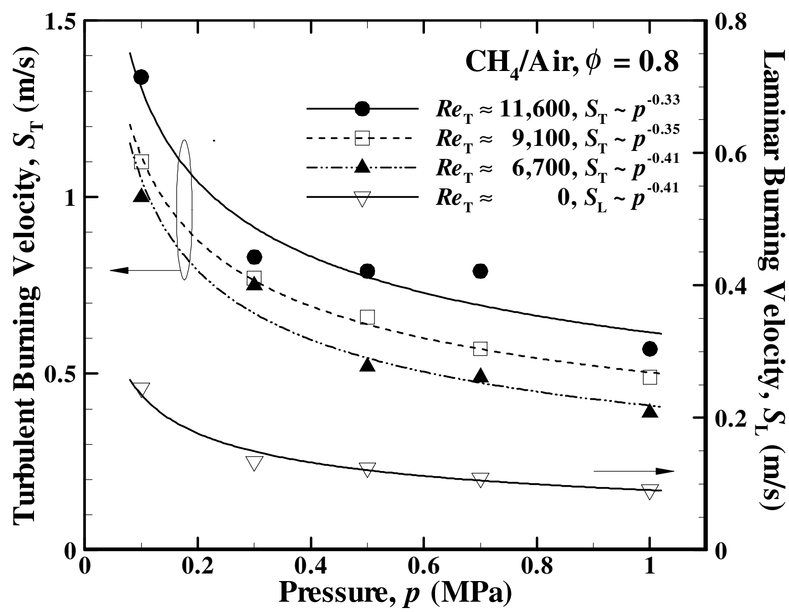

Figure 2. Variations of turbulent and laminar burning velocities with initial pressure at constant values of turbulent Reynolds numbers.

4 Results and Discussion

Figure 2 presents the measured values of S_T as a function of p at constant values of Re_T. Also shown in Fig. 2 are the associated values of S_L which are extracted from our previous measurements in Ref. [1], except for the atmospheric value of S_L. It shows in Fig. 2 that values of S_T decrease with increasing p in minus exponential manners at any constant value of Re_T, having similar pressure dependence of S_L. It can also be clearly seen in Fig. 2 that S_T increases with increasing Re_T at any constant value of p. The result in Fig. 2 may provide us a possible answer to the first key question of the present study. It indicates that as values of the turbulent Reynolds number are kept constant, the effect of elevated pressure can decrease the turbulent burning velocities, just like it decreasing the laminar burning velocities ($Re_T \approx 0$). Figure 3 presents the normalized turbulent burning velocities (S_T/S_L) as a function of the pressure ratio (p/p_0), where $p_0 = 0.1$ MPa. It is found in Fig. 3 that values of S_T/S_L are approximately independent of p/p_0 at any constant value of Re_T. Besides, values of S_T/S_L still increase with increasing Re_T at any constant value of p. Therefore, the result in Fig. 3 may give us a possible answer to the second question of the present study. It not only shows that the normalized turbulent burning velocities do not change with pressure for constant-Re_T conditions, but implies that turbulent Reynolds number may still be a suitable indicator for the coupling effect of turbulence-pressure interaction on turbulent burning enhancement. More experiments will be continued to check the aforementioned remarks.

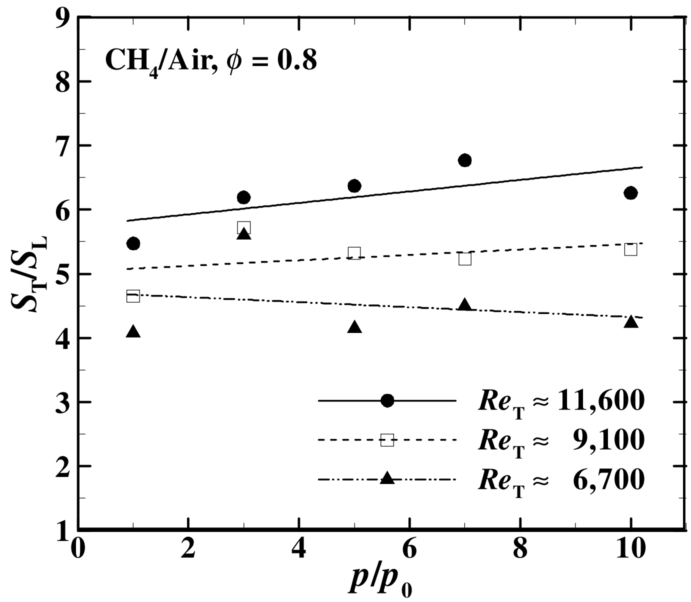

Figure 3. Normalized turbulent burning velocities as a function of the pressure ratio at constant values of turbulent Reynolds numbers, where $p_0 = 0.1$ MPa.

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