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Flame morphology and self-acceleration of syngas spherically expanding flames

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ABSTRACT

The self-acceleration of spherically expanding flames were investigated using a constant volume combustion chamber for $CO/H_2/O_2/N_2$ mixtures over a wide range of initial pressure from 0.2 to 0.6 MPa, CO/H_2 ratio from 50/50 to 10/90 and equivalence ratio from 0.4 to 1.5. The adiabatic flame temperature was kept constant by adjusting O_2/N_2 ratio at different equivalence ratios. Schlieren images were recorded to investigate the flame front evolution of spherically expanding flames. Local acceleration exponents were extracted using a proper equation to study the process of flame self-acceleration. Results show that the flame cells develop on the smooth flame fronts and finally reach fractal-like structures due to the hydrodynamic and diffusional-thermal instabilities, resulting in flame self-accelerative propagation. The critical Peclet number corresponding to the onset of self-acceleration, Pe_{cr} increases nonlinearly with the Markstein length, *Ma*. The observation further reveals that the onset of self-acceleration is mainly controlled by the diffusional-thermal effect. There exists two distinct flame propagation regimes in the self-acceleration, namely quick transition accelerative and quasi self-similar accelerative regimes. The quick transition regime is controlled by the destabilization effect of hydrodynamic perturbation and stabilization effect of flame stretch. While the quasi self-similar regime is primarily affected by the cascading process of flame front cells controlled by hydrodynamic instability. The self-similar acceleration exponent, α_s varies with the initial pressure and Lewis number, *Le*. The values of α_s are measured to be 1.1–1.25 (smaller than 1.5), indicating the flame dose not attain self-turbulization.

Introduction

Syngas with the main components of H_2 and CO which can be converted from coal, biomass and diversity feedstocks is a promising clean low carbon fuel used in gas turbines, internal combustion engines and industrial gas burners [1–4]. Syngas with a high H_2 content is a good choice to mitigate the CO_2 emission. However, premixed syngas lean flames with a high H_2 content are often subjected to combustion instabilities, especially under elevated pressures. Instability of a flame front evolution deserves special attention since it is a key point responsible for knocking in engines and also an important phenomenon for accidental gas explosions [5,6]. From an academic point of view, flame instability is an important point in both laminar and turbulent flame propagation dynamics.

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The hydrodynamic instability coupled with diffusional-thermal effect creates significant acceleration in spherically expanding flames through the formation of cellular structures over the flame front. The flame cells on the flame front increase the total area of the flame surface and promote the global flame propagation speed compared with that of the smooth flame, since the local front propagation speed of cellular flame remains largely at the constant laminar flame speed [7]. Furthermore, the flame cells continuously evolve and distribute over the entire flame front as the flame expands outwardly, the flame propagation speed increases continuously, leading to the possibility of flame self-acceleration. In the initial stage of flame acceleration and the flame radius is small, the flame evolution is expected to be dominated by small scale diffusional-thermal instability, which is controlled by the imbalance in the diffusion processes of heat and mass. As the flame expands, the hydrodynamic instability, which is caused by the large density change across the flame front, progressively dominates the flame accelerative dynamics.

Flame instability and accelerative dynamics have been studied extensively. Matalon and co-workers [8–10] gradually developed the linear theories to analyze the onset, growth rate, and cell size of intrinsic instabilities of spherically expanding flames. In general, the experimental results can be predicted qualitatively. Unfortunately, large discrepancies still exist between the experimental data and calculated results from linear theories [11,12]. The linearized solutions could not quantify the flame front cellularization and acceleration because these phenomena are essentially nonlinear [13]. Considering the limitations of linear theories, the acceleration of spherically expanding flames has usually been quantified by assuming a fractal type evolution of cellular flame front. Gostintsev et al. [14] investigated the self-acceleration of spherically expanding flames with various sources of large-scale experimental data. The flame self-similar regime was found in the flame front propagation, and the self-similar propagation was quantified through a power-law dependence of flame radius on time,

$$r = r_0 + At^{\alpha} \quad (1)$$

where r and r_0 are the instantaneous flame radius and the radius for best linear fitting, respectively. A is a constant depending on the given mixtures and α is the acceleration exponent. The acceleration exponent is related to the fractal dimension of flame front, $D = 3-1/\alpha$. They assumed the acceleration exponent is 3/2 for all experiments. In addition, the Kolmogorov turbulence has a fractal character and the fractal dimension is estimated to be 7/3 [15]. Consequently, if the acceleration exponent of spherically expanding flame reaches 3/2, the flame acceleration has possibly reached self-turbulization. However, subsequent studies found the acceleration exponent varies from 1.1 to 1.5, and depends on the mixtures and initial conditions [16–20]. The acceleration exponent of 1.5 can be attained only under limited conditions. Recently, Kim et al. [21] investigated the acceleration of large scale spherically expanding flames under normal conditions. The results showed that the acceleration exponent increases with flame radius and likely reaches a constant value when the flame radius is much larger than the critical onset radius. This implies the possibility existence of a transition stage before the flame propagates to a self-similar regime. Unfortunately, the measured acceleration exponent gives a large oscillation with increasing flame radius, and as such it is difficult to investigate the details of self-acceleration. Subsequently, small-scale spherically expanding flames were conducted to study the flame evolution and self-acceleration at elevated pressures [22]. The transition and self-similar stages are confirmed in the flame self-acceleration. However, they found the acceleration exponent of transition stage is larger than that of self-similar stage. This implied that the acceleration exponent decreases with the flame radius in the transition stage and then reaches a constant value in self-similar stage. Thus, there is still no consensus on the flame accelerative dynamics, especially in the transition stage. In addition, the experimental investigations on the flame self-acceleration are always affected by the coupled effects of the hydrodynamic and diffusional-thermal instabilities. Therefore, the separate effects of hydrodynamic and diffusional-thermal instabilities on flame accelerative dynamics is still not clear.

In view of these considerations, the objective of this study is to conduct well-controlled experiments to study the accelerative dynamics of spherically expanding flames. The following questions would be addressed:

1. Does the transition stage exist in flame acceleration?
2. If the transition stage exists, dose the acceleration exponent whether increase or decrease as the flame expands in the transition stage?
3. What are the effects of hydrodynamic and diffusional-thermal instabilities on flame transition and self-similar stages?

To accomplish these objectives, the evolutions of syngas spherically expanding flames were obtained using a constant volume combustion chamber over a wide range of Lewis number under elevated pressures up to 0.6 MPa. The syngas with a high H_2 content was applied in this work also considering the thin flame thickness and wide range of Lewis number. The experimental conditions were carefully controlled to study the separate effects of hydrodynamic and diffusional-thermal instabilities on flame acceleration.

Experimental and calculation methods

Details of the typical cylindrical-type constant volume combustion chamber have been described elsewhere [23,24], and will be introduced here in brief. The experimental setup mainly consists of a combustion bomb, fuel/oxidant supply system, ignition electrodes, heating system, high-speed schlieren system, and data acquisition system, as shown in Fig. 1. The combustible mixtures are filled in the combustion chamber with inner diameter of 180 mm and inner length of 210 mm, and then ignited by two centrally located electrodes. The flame propagation schlieren images are recorded using a high-speed camera (Phantom V611) operating at 10 kHz through two quartz windows with diameters of 80 mm mounted at the ends of combustion chamber. In addition, a heating tape is wrapped on the cylinder chamber to heat