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Experimental investigation on the onset of cellular instabilities and acceleration of expanding spherical flames

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ABSTRACT

We experimentally investigated the cellular instabilities of expanding spherical propagation of hydrogen–air, methane–air, and propane–air flames. Using image-thresholding technique, the formations and developments of a cell on a flame surface were investigated. The size of the observed cell due to the hydrodynamic instability was larger than those generated by the diffusional–thermal instability. The critical flame radius and critical Peclet number for the onset of instability were evaluated. These critical values for hydrogen–air and methane–air flames increased with increasing concentration. The values decreased with increasing initial pressure because the flame thickness decreased with increasing initial pressure. The ratio of the increase in the burning velocity increased with increasing initial pressure, although that of the hydrogen–air flames only increased with decreasing concentration. The results demonstrated that acceleration of the flame speed is affected by the intensity of the diffusional–thermal and hydrodynamic instabilities.

Introduction

A wrinkled flame has a larger surface area than a smoothly propagating flame and results in acceleration of the flame propagation. Because the intensity of a blast wave depends on the flame propagation and such acceleration might cause the strong blast wave to lead to considerable damages, the acceleration dynamics are important parameters for an appropriate risk assessment of accidental gas explosions [1]. Flame wrinkling is known to be spontaneously generated by cellular instabilities such as diffusional–thermal and hydrodynamic instabilities, although the gas is initially in homogeneous mixing conditions. The transition to cellularity in expanding spherical flames has been studied [2–8]. Bechtold et al. [2] analyzed the influence of diffusional–thermal and hydrodynamic instabilities on the stability of spherical flames. Bradley et al. [3,4] investigated the onset and growth of instabilities considering the theory suggested by Bechtold et al [2]. In addition, Bradley et al. [5] studied the evolution of cells of iso–octane–air flames and demonstrated that the cracks on the flame surface at a low Markstein number are fractured. The structure of a cellular flame due to cellular instabilities has been studied [6–8]. Sivashinsky derived the asymptotic

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nonlinear integrodifferential equation for cellular instabilities of the flame [6]. Using this equation, the cellular structure of a flame was numerically reproduced [7,8]. The numerical results showed that the cells due to hydrodynamic instability merged and assumed a large single-cusp shape, although those due to diffusional–thermal instability constantly subdivided. Experimental observations on these phenomena are advantageous to understand the effects of instabilities on the cellular developments of the flame and acceleration.

For the onset of cellular instability, the critical points represented as the critical Peclet number $Pe_c = r_c/\delta$, which is the critical flame radius r_c scaled by flame thickness δ, have been theoretically and experimentally investigated [9–19]. The values of several premixed flames are defined by the effects of the flame stretch on the flame speed as well as the flame images. The critical Peclet number for the onset of instability that considers the hydrodynamic and diffusional–thermal effects was evaluated by Addabbo et al. [9]. They plotted the peninsula of instability for spherically expanding flames, which shows the range of unstable flames as a function of the Peclet number. Furthermore, experimental and theoretical investigations of the critical Peclet number for the onset of cellular instabilities of hydrogen–propane flames at elevated pressures were conducted [10–12]. The results show that the critical Peclet number linearly varies with the equivalence ratio [10,11] and initial temperature [12]. In addition, we note that the values of the critical Peclet number are affected by the mixtures and ingredient of the gas [13,14]. For hydrogen–air and propane–air flames, the critical radius for the onset of instabilities is also shown to have different tendency, due to the diffusional–thermal effects [13–16]. The critical Peclet number is also affected by the initial pressure related to hydrodynamic effects [16–21]. The evaluated critical Peclet number is correlated with the Markstein number, i.e., $Ma = L/\delta$, where L is the Markstein number, as well as the concentration [16,19,20]. The critical point for the onset of instability remains a subject of current investigations [17–19]. In particular, further research on the effects of instabilities on the cellular development and effects of flame instabilities on the acceleration of the flame speed is important. Although the flame acceleration for the onset of instability was investigated by a number of theoretical and experimental studies [9–21], further research on this issue is needed for appropriate risk assessment against accidental gas explosions.

In view of the abovementioned consideration, the purpose of this study is to investigate the effects of flame instabilities on spherically propagating flames. The first objective of the present study, which is the cell evolutions due to diffusional–thermal and hydrodynamic instabilities on the flame surface, is analytically and experimentally investigated. The other objectives of the present study are the evaluations of the critical Peclet numbers for the onset of flame instability and the effects of flame instabilities on the acceleration of the flame speed.

Experimental setup

In the present study, the experiments were performed in a spherical bubble with hydrogen–air mixtures and in a spherical combustion chamber with an inner diameter of 0.70 m to observe the developments of wrinkling on the flame surface. For the soap-bubble experiment, the experimental apparatus consisted of a gas-supply system with designed bubble apparatus, an ignition system, and a high-speed Schlieren photography system shown in Fig. 1. More detailed information on the apparatus design and experimental procedure can be found in Ref. [22]. The flame images were photographed using a high-speed camera at 5000 frames per second. To investigate the effects of the flame front instabilities, particularly the hydrodynamic instability on the cellular flame surface, a large-volume vessel consisting of 150 mm quartz-glass windows on the sidewalls of the chamber was manufactured, as shown in Fig. 2. The total volume of the chamber was 180 L. The propagating flame of the hydrogen–air mixture was imaged using shadow photography and recorded using a high-speed camera at 3000 frames per second. The hydrogen and air were supplied at their individual partial pressure, and a sample was taken from the top and bottom of the chamber using a concentration meter. The mixture was ignited by an electric spark at the center of the chamber. These experiments were conducted under quiescent conditions at initial pressure ranging from 0.05 to 0.20 MPa.

Results and discussion

Evolution of cellular structure and cell size

Fig. 3 shows the Schlieren image observation of the developments of the cells on the surface of the hydrogen–air flame with $\phi = 0.8$, where ϕ is the equivalence ratio, at 0.1 MPa. The images of the cellular formations of the hydrogen–air flame are analyzed using image-thresholding technique, which isolates the objects by converting the grayscale images into binary images. In the present study, a part of the flame image is focused to analyze the image of the wrinkled flame. The threshold images of the cellular formation of the hydrogen–air flame with $\phi = 0.8$ at 0.1 MPa are shown in Fig. 1. The cell boundary of the threshold images is shown by the white line, which indicates the cell developments. The onset of cracks on the surface is formed by the electrodes, and the

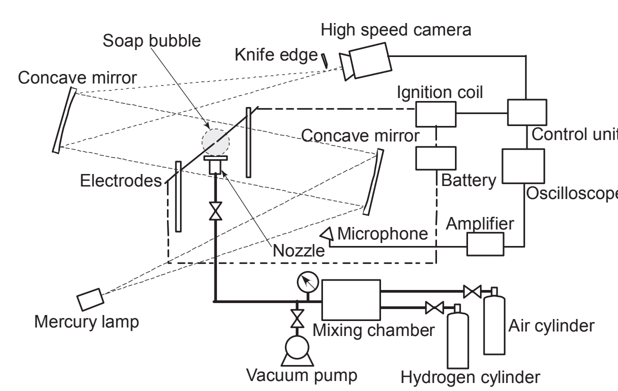

Fig. 1 – Experimental apparatus of soap bubble method [22].