Combustion and Flame 160 (2013) 1276–1286

Contents lists available at SciVerse ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Onset of cellular flame instability in adiabatic $CH_4/O_2/CO_2$ and CH_4/air laminar premixed flames stabilized on a flat-flame burner

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ARTICLE INFO

Article history:
Received 28 August 2012
Received in revised form 11 December 2012
Accepted 7 February 2013
Available online 12 March 2013

Keywords:
Cellular premixed flame
Oxy-fuel combustion
Heat flux method
Flat-flame burner
Hydrodynamic instability

ABSTRACT

This paper presents numerical and experimental studies on the onset and evolution of laminar cellular flames of $CH_4/O_2/CO_2$ (oxy-fuel) and CH_4/air mixtures under adiabatic conditions, stabilized in the proximity of a flat-flame burner at atmospheric pressure. In the numerical simulations, a two-dimensional domain with periodicity at the transverse far field boundaries is resolved using a high accuracy finite difference method and employing a detailed chemical kinetic mechanism and detailed transport properties. In the experiments a specially designed adiabatic flat-flame burner, a so-called heat flux burner, is employed. A key parameter, the standoff distance between the flame front and the burner exit plate, is identified. A critical standoff distance is found, above which cellular flame instability is observed. It is shown that the critical standoff distance is closely related to the density ratio and the laminar flame thickness for each flame studied. The observed onset of cellular flames is governed by the hydrodynamic instability mechanism, which is generally suppressed by the burner when the flame is very close to the burner plate. Diffusive-thermal effects play an important role in the flame instability when the flame is far from the burner. The critical standoff distance has no clear correlation with the Lewis number, indicating a less significant effect of diffusive-thermal instability on the flames near the burner.

1. Introduction

In the past decades flat-flame burners have been developed for measuring the laminar flame speed of unstretched premixed flames [1–3]. With a flat-flame burner unstretched flames can be generated experimentally, and it provides an improved accuracy of laminar flame speed with a typical error within ±1 cm/s for atmospheric methane/air flames. It is however frequently observed that, under certain conditions, laminar premixed flames stabilized on flat-flame burners can develop to cellular shapes [1,4–7]. A key issue is how to suppress the onset of cellular shapes to ensure an unstretched flame condition.

Botha and Spalding were the first reporting systematic experimental observations of cellular flames in propane/air mixtures issued from a cooled porous plug flat-flame burner [1]. They found that cellular flames could appear at all equivalence ratios and the cell size varied with the inflow velocity. Gorman et al. [4–7] reported that cellular flames on a circular porous plug burner could be at several states; at certain values of the flow rate and equivalence ratios a transition was observed from a steady ordered state of cellular flames to a state in which the cells rotated around the axis of the burner. In the above-mentioned cooled porous plug flat-flame burner, the inflow speed and hence the heat loss from the flame to the burner was adjusted for the flame to stabilize at the burner. The inflow speed and heat loss rate profile was used to extrapolate for an adiabatic flame speed. Due to heat loss the flame thickness increases and the ratio of density or temperature across the flame decreases. This was shown to suppress the cellular instability [8].

Theoretical analyses [9–13] and numerical simulations [14–23] of freely propagating laminar premixed flames (far from the burner) show that the hydrodynamic and diffusive-thermal mechanisms can trigger cellular flames. Thin flames with high density ratios between gases on the unburned and burned side of the flame are unconditionally unstable due to deviation of flow streamlines across oblique flames (hydrodynamic effect [9,10]). In addition to this, fuel lean flames with Lewis number well below unity (e.g. lean hydrogen/air flames) tend to redistribute heat and fuel/air ratio at the flame front such that the flames become increasingly cellular (diffusive-thermal effect [12,13]), whereas flames with Lewis number larger than unity tend to be pulsating [24] owing to diffusive-thermal effect. Recent reviews on this topic can be found in [25–28].

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http://dx.doi.org/10.1016/j.combustflame.2013.02.011

When the flames are constrained to the proximity of a flat-flame burner the conditions of momentum and scalar transports are different from that of freely propagating flames, and thus the onset of cellular flames near burners requires further investigations. Previous theoretical works have been focused on the diffusive-thermal effects (i.e. assuming constant density in the flow field) on flame instability in porous plug burner flames with heat loss to the burners. For small wave number disturbance Buckmaster [24] developed a dispersion relation based on a high activation energy asymptotic analysis and one-step chemistry, which reveals that for mixtures with Lewis number less than unity the porous burner tends to suppress the cellular flame instability whereas for mixtures with Lewis number larger than unity the burner can enhance the onset of cellular instability when the flame is not very close to the burner plate. There is a minimum standoff distance from the flame to the burner plate within which the cellular instability can be suppressed even in mixtures with Lewis numbers higher than unity. The recent works of Kurdyumov et al. [29,30] reveal the diffusive-thermal effect on the onset of pulsating flames near the porous plug burner; it was found that with thicker burner plate and higher density ratio the flames are easier to develop to a pulsating mode, and radiative heat loss from the flame can further promote the onset of pulsating flames and cellular flames.

In previous theoretical studies heat loss from the flame to the burner plays an essential role in the flame instability, for example, the analysis of Joulin [31] indicated that the pulsating instability was a result of the time lag of the travelling temperature disturbances between the burner surface and the flame front. In adiabatic flat-flame burners there is no heat loss to the burner and thus the onset of flame instability is expected to be different from that in the cooled porous plug burners. In the experimental studies presented in this paper we show that the burner plate temperature of an adiabatic burner, which is controlled by the heating fluid temperature of the burner, is a key parameter controlling the onset of cellular instability; when the temperature of the heating fluid (and hence the burner plate temperature) is high the flames tend to be of a flat shape, whereas decreasing the temperature of the heating fluid tends to trigger the onset of cellular flames for various combustible mixtures. In a previous study of adiabatic laminar flame speed of $CH_4/O_2/CO_2$ (oxy-fuel) mixtures with the heat flux burner, Konnov and Dyakov [32] observed cellular flames with large cells in some of the oxy-fuel flames at different equivalence ratios. However, no cellularity was found in a study of CH_4/air flames using the same burner [33]. Further investigations are needed to understand the onset and development of the cellular flame instability for flames stabilized on the adiabatic flat-flame burners.

The purpose of this work is to examine the mechanism responsible for the onset of cellularity in lean, stoichiometric and rich oxy-fuel flames and methane/air flames under atmospheric conditions stabilized on an adiabatic flat-flame burner. Numerical simulations with detailed chemistry and transport properties are carried out together with experiments using the heat flux method. For all mixtures studied including the methane/air mixture, it is demonstrated that cellular flame structures can be induced owing to hydrodynamic instability and the diffusive-thermal effect plays a relatively moderate role when the flame is near the burner. A key parameter, the standoff distance between the flame and the burner exit plate, is identified. The burner suppresses the cellular instability if the standoff distance is below a critical value.

2. Experimental setup

The heat flux method and the flat-flame burner have been described previously [2,32,33]; here, only the most relevant details are repeated. The key components of the burner are the burner plate and the plenum chamber. Fuel and oxidizer are well mixed before being supplied to the plenum chamber. The plenum chamber has a water-cooling system to control the initial temperature of the fuel/oxidizer mixture at a given value (in the present experiment at 298 K). A 2 mm thick burner plate perforated with small holes is attached to the burner outlet. The diameter of the burner mouth is 30 mm. The burner head has a heating jacket supplied with a separate thermostated water to keep the temperature of the burner plate (T_p) constant. In the present experiments this temperature is varied from 308 K to 368 K, to heat the fuel/oxidizer mixture by the plate and thus to compensate the heat loss from the flame to the burner. It is shown that increasing the burner plate temperature brings the flame closer to the burner in order to maintain a zero net heat flux, and in this way the standoff distance of the flame can be controlled. Figure 1 shows a photo of the burner and a side-view of a typical cellular flame.

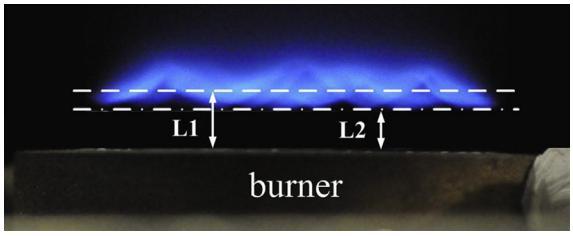

Fig. 1. Side-view of a cellular flame and the burner plate.

In the experiments, the following data are collected: (a) the distance from the center of the luminescence zone of the flame to the burner exit plane (L_1, Fig. 1); (b) the evolution of the flame shape; (c) the distance between the burner exit plane to the lowest boundary of the luminescence zone (L_2, Fig. 1), and (d) the mass flow rate at the adiabatic flame condition. When the flame is stabilized the two distances (L_1, L_2) are recorded using a side-view camera, which is placed as close as possible to the flame to allow for a fine resolution of the distances. After calibration it is found that one pixel in the images corresponds to the length of 0.015 mm. A second camera is used to record the top-views of the flames to characterize the cell shape.

For a given fuel/oxidizer mixture, a flat flame can be obtained by increasing the burner plate temperature. The corresponding distances (L_1, L_2) at the flat flame condition is denoted as $L_{1,0}$, and $L_{2,0}$. The standoff distance (L) and cell magnitude (A) for the flames at other burner plate temperatures are defined based on the distances (L_1, L_2) and the corresponding ones at the flat-flame condition ($L_{1,0}$ and $L_{2,0}$), $A = (L_1–L_2) – (L_{1,0}–L_{2,0})$, and $L = L_1–(L_{1,0} – L_{2,0})$. This ensures that the cell magnitude A becomes zero when the flame becomes flat.

Uncertainties in the measured standoff distance and cell amplitude come from the following three major error sources. First, when analyzing the images a reading off error is introduced. The thickness of the luminescence zone of a flat flame is typically 20–30 pixels. When determining the center of the luminescence zone an uncertainty of 4 pixels can be introduced, which results in an error of the standoff distance and the cell amplitude about 0.06 mm. Second, the burner plate temperature (T_p) has an error, which is estimated to be up to 0.2 K. This error can result in an error in the standoff distance and cell amplitude. With an increase of T_p by 1 K a decrease of the standoff distance up to 0.12 mm is observed. Thus, an error in T_p of 0.2 K yields an error of 0.024 mm in the standoff distance and cell magnitude. Third, the mass flow rate controller, MFC, has an uncertainty about 0.8% deviation of actual set-point, including 0.2% deviation of maximum flow. The resulting error in the standoff distance and cell amplitude due to the MFC is evaluated to be up to 0.03 mm.