Measurement of propagation speeds in adiabatic cellular premixed flames of $CH_4 + O_2 + CO_2$

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Abstract

Experimental measurements of the propagation speed of adiabatic flames of methane + oxygen + carbon dioxide are presented. The oxygen content $O_2/(O_2 + CO_2)$ in the artificial air was 31.55% and 35%. Non-stretched flames were stabilized on a perforated plate burner at atmospheric pressure. A heat flux method was used to determine propagation speeds under conditions when the net heat loss of the flame is zero. Under specific experimental conditions the flames become cellular; this leads to significant modification of the flame propagation speed. The onset of cellularity was observed throughout the stoichiometric range of the mixtures studied. Measurements in cellular flames are presented and compared with those for laminar flat flames. Cellularity disappeared when the flames became only slightly sub-adiabatic. Visual and photographic observations of the flames were performed to quantify their cellular structure. Increasing the oxygen content in the artificial air and increasing the temperature of the burner plate led to increase of the number of cells observed.

1. Introduction

Two different causes of the cellular instability in initially planar premixed flames are usually considered, namely, hydrodynamic (or Landau–Darrieus) and diffusive-thermal mechanisms. Hydrodynamic instabilities are induced by changes in density due to thermal expansion of the burned gas and they are usually associated with large-scale flames. Cellular structures observed in systematic experimental studies performed by Markstein [1,2] and others were often used as illustration of the diffusive-thermal instability in many classical textbooks on combustion. The mechanism of the diffusive-thermal instability was first proposed by Zeldovich [3] and further received substantial theoretical attention [4–8].

The phenomenological model [3] and earlier analyses using activation-energy asymptotics showed that the cellular instability can occur if the diffusivity (D) of the deficient reactant is larger than the thermal diffusivity (α), that is the Lewis number ($Le = \alpha/D$) is less than unity. This leads to the conclusion that fuel-lean flames of heavy hydrocarbons and fuel-rich flames of hydrogen and methane should be stable.

However, some experimental observations were found in apparent contradiction with the above consideration. For instance, cellular instability was observed from lean to moderately rich hydrogen + oxygen + nitrogen mixtures [9]. The "hydrogen anomaly" can be qualitatively explained by the preferential diffusion of reactant species. The mechanism of the preferential diffusion was first described by Manton et al. [10] and further explored by linear stability [9,11] and phenomenological [12,13] analyses. The preferential diffusion model suggests that the hydrogen + air flames should

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be unstable for equivalence ratios (ϕ) below 1.8, since these flames have a maximum burning velocity near this value. However, the transition between stable and unstable flames was found near $\phi = 1.4$ [14] or below this value [9,15,16]. Earlier models of the diffusive-thermal instability also failed to explain the cellular instability in the near-stoichiometric mixtures of heavy hydrocarbons when the slope of the burning velocity curve with respect to concentration of the more diffusive component is close to zero [12].

Another interesting phenomenon was observed in propane + air flames stabilized over a porous-plug burner 50 years ago. The cellular instability appeared throughout the stoichiometric range of these mixtures [17] contrary to the predictions of diffusive-thermal or preferential diffusion models. The onset of cellularity in these flames has been explained by the hydrodynamic influences within the flame holder [18]. The importance of the coupling of diffusion and hydrodynamics was emphasized by Markstein [2], and significant progress in the analytical investigation of the coupling problem has been achieved since then [8,19,20]. The experimental study of the interaction between cellular flames and flat flame burner [17] was extended by Vantelon et al. [21] and by Gorman and coworkers [22–26]. The flames in all these earlier studies were non-adiabatic; major attention has been paid to classification and to quantification of the cellular patterns. The goal of the present work therefore was to measure adiabatic propagation speeds of premixed cellular flames of methane + oxygen + carbon dioxide, stabilized using a heat flux method.

Premixed planar flames stabilized on flat burners are intuitively attractive for experimental study of flame structure and flame burning velocity, since they resemble steady one-dimensional adiabatic free flames propagating in the doubly infinite domain. In the laboratory, however, a planar flame is stabilized through heat loss to the surface of the burner, where fresh mixture is introduced. Then the flame becomes adiabatic only in the

limiting case of zero heat loss to the burner when the flame turns unstable. The method proposed by Botha and Spalding [17] for the determination of the laminar burning velocity by linear extrapolation of the burning velocities with various heat losses to zero heat loss was based on this consideration. A new method of adiabatic flame stabilization on flat burner was introduced by de Goey et al. [27]. This method is based on balancing the heat loss required for flame stabilization with the convective heat flux from the burner surface to the flame front. It was demonstrated that the heat flux method is suitable for determining the adiabatic flame temperature and burning velocity [28–30].

Experimental measurements of the adiabatic burning velocity for laminar flat flames of methane + oxygen + carbon dioxide were reported recently [31]. It was noticed that under specific experimental conditions these flames became cellular, leading to significant modification of the flame burning velocity. The results shown below were originally presented at the Third Mediterranean Combustion Symposium [32]; since then the measurement of propagation speeds in adiabatic flat and cellular premixed flames of $C_2H_6 + O_2 + CO_2$ were published [33]. To avoid unnecessary duplication, description of the experiments and justification of the applicability of the heat flux method is limited to the essential details only. Then the experimental measurements in cellular flames are presented and compared with those for laminar flat flames [31].

2. Experimental details

The experimental setup for stabilizing an adiabatic flame using the heat flux method has been described elsewhere [29,33,34]; however, the most relevant details are repeated below. The scheme of the burner is shown in Fig. 1. It consisted of the burner head mounted on a plenum chamber. The 2 mm thick burner plate perfo-
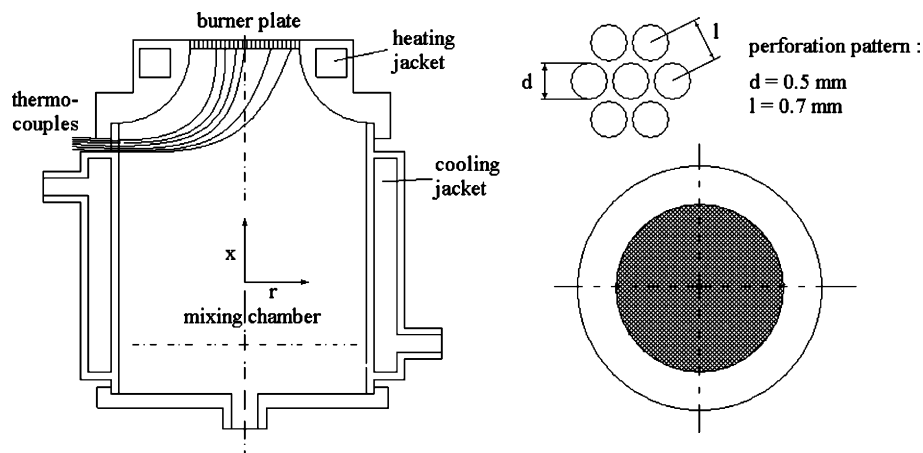

Fig. 1. The perforated plate burner.