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Combustion and Flame 151 (2007) 321–332
Combustion and Flame
www.elsevier.com/locate/combustflame

Scaling of cell size in cellular instabilities of nonpremixed jet flames

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Received 10 December 2006; received in revised form 6 May 2007; accepted 12 May 2007

Available online 16 July 2007

Abstract

Systematic experiments have been undertaken to study the parameter dependence of cellular instability and in particular the scaling of the resulting cell size in CO_2-diluted H_2–O_2 jet diffusion flames. Cellular flames are known to arise near the extinction limit when reactant Lewis numbers are relatively low. The Lewis numbers of the investigated near-extinction mixtures, based on the initial mixture strength ϕ_m and ambient conditions, varied in the ranges [1.1–1.3] for oxygen and [0.25–0.29] for hydrogen (ϕ_m is defined here as the fuel-to-oxygen mass ratio, normalized by the stoichiometric ratio). The experiments were carried out both in an axisymmetric jet (AJ) burner and in a two-dimensional slot burner known as a Wolfhard–Parker (WP) burner with an oxidizer co-flow (mostly 100% O_2) of fixed low velocity. First, the region of cellular flames adjacent to the extinction limit was characterized in terms of initial H_2 concentration and fuel jet velocity, with all other parameters fixed. Then, the wavelength of the cellular instability, i.e., the cell size, was determined as a function of the fuel jet velocity and the initial mixture strength ϕ_m. For conditions not too close to extinction, this wavelength is found to increase with the square root of the vorticity thickness of the jet shear layer and roughly the $1/5$ power of ϕ_m. Very close to extinction, this scaling breaks down and will likely switch to a scaling with the flame thickness, i.e., involving the Damköhler number.
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Keywords: Diffusion flames; Hydrogen; Cellular instability

1. Introduction

This paper is concerned with the cellular instability occurring in jet diffusion flames. The basic mechanism of this thermal-diffusive instability is shown in Fig. 1: if, within a sufficient thickness of the reaction zone, the temperature and the heat release perturbations are in phase, mutual reinforcement occurs. Since the overall reaction rate is diffusion-limited, any local increase of reaction rate and temperature must be compensated for by zones of reduced reaction rate and temperature, hence the formation of cells that become local heat sources and reactant sinks. The mechanisms working against the cellular instability are therefore diffusive heat loss from the hot cell cores and insufficient nonuniform redistribution of reactants toward them. Hence, cellular instability is observed when thermal diffusivity is low and the re-

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doi:10.1016/j.combustflame.2007.05.004

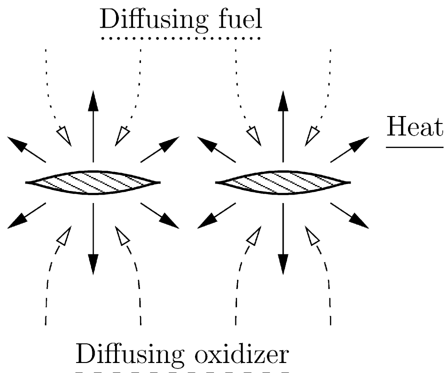

Fig. 1. Schematic of the thermodiffusive cellular instability of a diffusion flame. The hatched regions represent cells where heat release is reinforced by rising temperature. Mechanisms working against the instability: heat loss (solid arrows) and nonuniform diffusive reactant supplies (dashed and dotted arrows).

actant diffusivities are high, i.e., provided the fuel and oxidizer Lewis numbers, Le_F and Le_O (defined as the ratios between thermal diffusivity and mass diffusivity), are small, typically <1. However, the complete analysis of this cellular instability is complex, as it involves a large number of parameters: the Damköhler number (Dam, defined as the ratio of characteristic diffusion time and chemical reaction time); the Lewis numbers Le_F and Le_O; the initial mixture strength (ϕ_m); and the hydrodynamic parameters characterizing the jet flow, which adds convective transport to the diffusive transport of heat and species discussed above. Few experimental observations of cellular instability in jet diffusion flames exist [1–7], and in several studies the cells were of secondary importance. Nevertheless, all the above experiments agree that cellular instability is only observed near the extinction limit (associated with low Damköhler number) for reactant Lewis numbers typically less than unity. Chen et al. [5] performed a systematic study of the effect of Lewis number for a WP burner. Later, Füri [6] and Lo Jacono et al. [7] reported the effect of initial mixture strength on pulsating and cellular instabilities in an AJ burner. However, in none of the above studies has the influence of the hydrodynamics on the onset and characteristics of cellular instability been studied systematically.

The wavelengths of the cellular patterns previously observed in different burner geometries are summarized in Table 1. These experiments confirm the expectation that the cellular regime is associated with relatively low Le_O but more importantly with low Le_F. The condition of low Lewis numbers for cellular instability, obtained with qualitative arguments around Fig. 1, has also been confirmed by several stability analyses for idealized diffusion flames [8–10] *without hydrodynamic effects*. In these theoretical studies the only length available to scale the wavelength of the cellular instability is the flame thickness. In the jet diffusion flames considered here, there are additional hydrodynamic length scales, such as the jet shear layer thickness and jet width, that are likely to influence the wavelength of the cellular instability. There is evidence, to be discussed later, that *very near extinction*, where the flame thickness increases rapidly with decreasing Damköhler number, the wavelength of the cellular instability eventually becomes comparable to the flame thickness and hence scales principally with the latter. It is also noted in passing that the number of realizable stable cellular modes has been found to increase very near the extinction limit [7]. Since this "very near extinction" regime will be shown to occupy only a small fraction of the parameter space with cellular instability, we will concentrate on the cellular regime near but not very near extinction and investigate in this regime the influence of hydrodynamic parameters, particularly of the jet shear layer thickness, on cell size. The remainder of the paper is organized as follows: After a brief description of the experimental setup and the characterization of the different jet flame facilities, the experimental procedure and the results are presented in the main section which is followed by the conclusions.

Table 1
Previously published wavelengths of cellular instability for various reactants and burners (AJ, WP, and CF stand for axisymmetric jet, Wolfhard–Parker, and counterflow burner, respectively)

Reference	Burner	Fuel	Inert	Le_F	Le_O	λ (cm)
Garside and Jackson [1,2]	AJ	H_2	CO_2	0.27	1.13	0.7
Dongworth and Melvin [3]	WP	H_2	N_2	0.31	1.21	1.0
Ishizuka and Tsuji [4]	CF	H_2	N_2	0.30	1.20	0.7[a]
Chen et al. [5]	WP	H_2	N_2	0.32	1.25	0.7–1.6[b]
Füri [6]	AJ	CH_4	SF_6	0.50	0.50	0.4
Füri [6]	WP	CH_4	SF_6	0.50	0.50	0.32
Lo Jacono et al. [7]	AJ	H_2	CO_2	0.27	1.2	0.4–0.6

[a] Taken from [8].
[b] Several exit velocities.

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