Combustion and Flame 160 (2013) 1102–1111

Contents lists available at SciVerse ScienceDirect

Combustion and Flame

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

On preheating and dilution effects in non-premixed jet flame stabilization

Sylvain Lamige [a,*], Jiesheng Min [b], Cédric Galizzi [a], Frédéric André [a], Françoise Baillot [b], Dany Escudié [a], Kevin M. Lyons [a,c]

[a] Université de Lyon, CNRS, INSA-Lyon, CETHIL, UMR5008, F-69621 Villeurbanne, France
[b] CORIA – UMR6614, CNRS-Université et INSA de Rouen, Saint-Étienne de Rouvray, France
[c] North Carolina State University, Dept. of Mechanical and Aerospace Engineering, Raleigh, NC 27695-7910, USA

ARTICLE INFO

Article history:
Received 5 July 2012
Received in revised form 9 November 2012
Accepted 30 January 2013
Available online 1 March 2013

Keywords:
Non-premixed combustion
Flame stability
Stability limits
Hysteresis
Preheating
Dilution

ABSTRACT

The impact of preheating and dilution on methane/air non-premixed flame stability are studied experimentally. Six preheating levels are considered for initial reactant temperature between 295 K and 850 K in a round jet configuration. Four diluent gases are added on the air-side, either CO_2, N_2, Ar or a (CO_2 + Ar) mixture having the same molar heat capacity as N_2. For undiluted flames, jet transition velocities between attached and lifted states are investigated depending on initial reactant temperature. The hysteresis zone defined by these stability limits is shifted towards higher jet velocities with preheating. Whereas jet and coflow temperatures were identical in similar previous experiments, the present work allows examination of the thermal effects from either fuel or oxidizer streams. Flame stability is described based on the propagative aspects of the flame leading-edge, by analogy with the temperature dependency of the laminar burning velocity of a stoichiometric mixture. Results show that the jet temperature has a major influence on the lifting of an attached flame, whereas the coflow temperature remains important for the reattachment of a lifted flame. In addition, flame stability experiments have been performed at high levels of both preheating and dilution. Stability maps of critical dilution ratios at lifting have been obtained with preheating. It appears that the ability of a diluent to break flame stability keeps the same relative order as at ambient temperature. It is even enhanced with preheating because higher temperature widens the gap between diluent molar heat capacities Cp. The Cp approach is however not sufficient to interpret the temperature dependency of the relative influence of the different dilution effects. Furthermore, the role played by the jet flow regime on attached flame stability in dilution-induced lifting experiments is highlighted when dilution is coupled with preheating.

1. Introduction

Stabilization mechanisms of non-premixed flames have been investigated for many years. As reviewed by Lyons [1], Chung [2] and Lawn [3], several stabilization theories arose to explain characteristics of lifted flames, the three primary models being based on (a) fuel/air premixedness, (b) local flame extinction and (c) large eddy or large-scale mixing (see e.g. Kalghatgi [4], Donnerhack and Peters [5] and Miake-Lye and Hammer [6], respectively). Under certain conditions, the same jet exit velocity can lead to two distinct stabilization positions of the flame, either rim-stabilized (often less than 1 mm from injector tube lip) or lifted several nozzle diameters downstream in the flow. This hysteresis behavior of non-premixed flames between attached and lifted states was first reported by Scholefield and Garside [7]. They interpreted the hysteresis phenomenon from an aerodynamic point-of-view, supported by internal jet transition between laminar and turbulent regimes. From a lifted state, they found that reattachment occurred when the base of the lifted flame reached the top of the laminar part of the jet. A hysteresis phenomenon then occurs because the laminar portion of the jet is reduced for a lifted flame compared to the same exit velocity of an attached flame, as the flame sheet is no longer present to relaminarize the jet flow. In short, the hysteresis zone makes it important whether one approaches stability by turning up, or turning down, the jet flow; different axial positions will be possible for stabilization dependent on the direction in which the region is approached. Stability limits are therefore expressed in terms of lifting and reattachment velocities, as well as blow-out (extinction of a

---

* Corresponding author. Adress: Centre de Thermique de Lyon (CETHIL) – UMR5008, Bât. Sadi Carnot, 9 rue de la Physique, INSA-Lyon, Villeurbanne Cedex F-69621, France. Fax: +33 (0) 4 72 43 88 11.

E-mail addresses: sylvain.lamige@insa-lyon.fr (S. Lamige), jiesheng.min@edf.fr (J. Min), cedric.galizzi@insa-lyon.fr (C. Galizzi), frederic.andre@insa-lyon.fr (F. André), baillot@coria.fr (F. Baillot), dany.escudie@insa-lyon.fr (D. Escudié), lyons@ncsu.edu (K.M. Lyons).

0010-2180/$ - see front matter © 2013 The Combustion Institute. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.combustflame.2013.01.026

Nomenclature

Cp	molar isobaric heat capacity, J/(mol K)
D_i	injection tube internal diameter, mm
H	stabilization height, mm
K	diluent coefficient relative to CO_2, dimensionless
Q	flow rate, NL/min
$S_{L,st}$	stoichiometric laminar burning velocity, m/s
T	measured temperature, K
T_s	heater set-point temperature, K
U	mean flow velocity, m/s

Greek symbols

α	temperature power exponent (for laminar burning velocity), dimensionless
δ	injection tube lip thickness, mm

Exponents

°	undiluted

Subscripts

0	at room temperature
a	reattachment (for velocity)
air	relative to the air
Ar	argon
CO_2	carbon dioxide
CO_2 + Ar	CO_2 and Ar mixture having the same molar specific heat capacity as N_2
fuel	relative to the fuel (methane)
l	lifting
N_2	nitrogen
ox	relative to the oxidizer
ox(diluent)	relative to the oxidizer with dilution by (diluent)
ref	reference (for temperature)
S	relative to laminar burning velocity

lifted flame) and blow-off (direct extinction of an attached flame with no lifted state) velocities. Later studies have been undertaken on stability limits including for instance effects of coflow [8–10] or nozzle size [9,10], which affected mostly the lifted flame and its reattachment but not significantly the attached flame. While of fundamental interest, this issue is important for burner operating/turndown considerations.

Complicating these aforementioned stabilization issues, which have been investigated in room temperature air coflow scenarios, industrial needs for increased efficiency led to practical increases in reactant temperature. Thus, the combustion efficiency is increased, but often along with an increase in the emission of pollutants, such as NO_x. Therefore, with growing interest in cleaner technologies, exhaust gas recirculation has been used instead of direct preheating, either external or internal, eventually giving birth to the flameless combustion regime [11]. The use of such combustion systems involves modifications of stabilization mechanisms, by thermal effects alone, in case of direct air preheating (due to the increase in reactant temperature), or coupled with dilution effects in case of exhaust gas recirculation. In turn, dilution effects combine the impact of pure dilution (reduced oxygen concentration), thermal effects (through the diluent specific heat capacity and thermal diffusivity, and through modification of radiation transfer) and chemical effects (by addition of chemical agents to the chemical chain reaction). It appears therefore crucial to better understand conditions leading to transition between the different combustion regimes for interpreting non-premixed flame stabilization in light of reactant temperature effects coupled with dilution effects.

The axisymmetric round jet flame configuration is well suited for experiments aimed at understanding flame stabilization physical phenomena. Early experiments on preheating reactants of a non-premixed methane/air flame were performed by Burke and Schuman [12]. By using two preheating temperatures, they experimentally found that preheating reactants had a slight effect on flame height, which they found lower compared to ambient conditions. These authors anticipated two effects due to preheating: an increase in bulk flow velocities, due to a decrease in density at identical reactant inlet flow rates, and an increase in the diffusion coefficient. From their theoretical approach, they expected these effects to neutralize themselves in terms of flame height. Their experiments lacked however some accuracy in that the reported preheating temperatures globally represent the furnace temperature, but gave no detailed information on the actual reactant temperatures. In a more detailed work concerning reactant temperature, Takeno and Kotani [13] noted modifications of stability limits with reactant preheating. These authors observed two different steps with increase in jet velocity for hydrogen in air, as well as for city gas in air when sufficient preheating was applied. Above a critical jet velocity, only the laminar part of the flame remained attached to the burner rim, whereas the part above the breakpoint was extinguished. With a further jet velocity increase, the length of that remaining attached part of the flame diminished and eventually extinguished as well. Concurrently, flameless combustion led to research on temperature effects, but mostly turned towards emission of pollutants under high temperature and diluted reactants (see e.g., Wünning and Wünning [14]), where high temperature is defined by Katsuki and Hasegawa [15] as the auto-ignition limit of a given air–fuel mixture. However, as reminded by Oldenhof et al. [16], stabilization mechanisms in flameless combustion remain somewhat different from those in conventional lifted jet flames. Kim et al. [17,18], experimentally studying a propane jet flame in a preheated air environment, emphasized that the stoichiometric laminar burning velocity $S_{L,st}$ was a key parameter in flame stabilization and stability. Their results for lift-off height were in agreement with both premixed [4] and large-scale mixing [6] models, provided that temperature-dependent properties were evaluated at initial reactant temperature instead of burned gas temperature as proposed in the original correlations. Overall, preheating has a significant stabilizing effect as previously reported on a non-premixed methane/air flame (see Lamige et al. [19]).

As for dilution, distinct issues are commonly found in the literature concerning either fire safety (e.g., Takahashi et al. [20]) or new combustion technologies based on exhaust gas recirculation (e.g., [21]). It has already been reported that air-side dilution in a coflow jet flame was much more effective than fuel-side dilution in altering flame stability. The relative influence of the three effects occurring with CO_2-dilution has been determined by Guo et al. [22]: pure dilution (68%) appears as having the most important impact on flame stabilization, followed by thermal (22.5%) and chemical (9.5%) effects. Radiation and transport effects were found to be negligible in this flame configuration. As concerns soot reactivity [23], these three effects account for 45% (thermal), 35% (dilution) and 20% (chemical) in a CO_2-diluted ethylene flame. It has been shown at room temperature [24,25] that when induced by dilution, flame lifting is controlled by the critical flow rate ratio $(Q_{diluent}/Q_{air})_{lifting}$. The use of three different diluents, namely CO_2, N_2 and Ar, allows to classify their ability to break anchored flame stability.