Experimental Thermal and Fluid Science 56 (2014) 45–52

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Burner lip temperature and stabilization of a non-premixed jet flame

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ARTICLE INFO

Article history:
Available online 16 November 2013

Keywords:
Non-premixed flame
Stabilization
Attachment height
Heat transfer
Burner material
Lip temperature

ABSTRACT

This experimental study addresses issues on heat transfer between the nozzle and the base of a non-premixed methane/air jet-flame. The burner lip temperature as well as temperature gradients at the top of the straight tube burner are systematically thermocouple-monitored, along with axial and radial positions of the flame attachment location by means of CH^*-chemiluminescence imaging. The effects on lip temperature are tested for several parameters: flame state, either attached or lifted; aerodynamic conditions, over a very wide range of fuel injection velocities, covering both laminar and turbulent pipe flow for the inlet fuel, as well as momentum and velocity ratios between fuel and coflow both lower and greater than unity; nozzle rim coating, either uncoated or black-coated; initial reactant temperature, with preheating temperatures from 295 K to 1000 K; and burner material thermal conductivity, between 2.7 and 400 W/(m K).

The observed phenomena are described and discussed in relation with changes of these parameters. Some conclusions are also drawn as for the relative importance of the different modes of heat transfer in the flame attachment zone, towards a better understanding of the flame stabilization process. In particular, flame attachment height measurements reveal a critical value towards high lip temperature obtained with low burner thermal conductivity. Eventually, this work allowed identification of four regions depending on fuel injection velocity, each associated with particular evolutions in terms of flame location and lip temperature.

1. Introduction

The combustion literature has long been reporting on studies on stabilization mechanisms of non-premixed jet-flames. Early work of Vranos et al. [1] allowed classification of various regimes of combustion depending on the relative velocities of jet and coflow. Some of those regimes are universally recognized, such as the lifted flame regime whose stabilization mechanisms have been reviewed by Lyons [2], or the conventional attached flame regime. Studying the lifting process of attached flames may help to better understand their stabilization mechanisms, as in the comprehensive work of Takahashi and Schmoll [3]. For that matter, Otakeyama et al. [4] showed that flame stability was strongly affected by the lip thickness. Besides significant alteration in terms of aerodynamics, the use of different lip thicknesses is also expected to play an important role concerning heat transfer at burner. Even so, it has been shown by Kawamura et al. [5] that the heat generated in the base of the flame was transferred to the fuel jet stream in a greater extent than to the coflow air stream or to the burner wall. Moreover, most of the heat reaching the burner must come back somewhere in the flame, through either the fuel stream or the entrained air [6].

In a numerical study, Kurdyumov et al. [7] put forward that the burner wall temperature was unaffected by the heat it received from the flame. The conditions for diffusion flame attachment and lift-off have also interested other theoretical and numerical work [8,9]. Several numerical strategies have been developed to ensure proper flame stabilization close to the burner lip. Well-defined initial boundary conditions are obviously essential in flame computations; nevertheless, burner material and at times dimensions are not always explicitly stated.

Correct consideration of effective boundaries is obviously made difficult by the scarcity of relevant experimental data. However, some studies deserve to be mentioned, such as the one of Gülder et al. [10] concerning the effects of nozzle material properties on soot formation. Burner temperatures in excess of 100 °C were measured at 3 mm upstream of top, and a change in burner material significantly modified the temperature gradient in the burner wall as

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http://dx.doi.org/10.1016/j.expthermflusci.2013.11.008

Nomenclature

D_i	burner tube inner diameter, mm
H_a	flame attachment height, mm
Q_{tube}	one-dimensional conductive heat flux in the tube, W/m^2
$Re_{D,fuel}$	jet Reynolds number based on D_i, dimensionless
Re_δ	Reynolds number based on δ, dimensionless
T	measured reactant initial temperature in the jet exit plane, K
T_{lip}	temperature measured at the burner lip, K
$T_{ox,ref}$	reference oxidizer initial temperature, K
$T_{TC\#}$	temperature measured in the tube at a position upstream from the lip, K
U	mean flow velocity, m/s
d_{TC}	distance inter-thermocouples, mm
r_a	flame attachment radius, mm
δ	burner lip thickness, mm
λ_{burner}	burner thermal conductivity, W/(m K)
ν	kinematic viscosity, m^2/s

Subscripts

fuel	relative to the fuel jet stream
lifting	at lifting conditions of an attached flame
max	relative to the maximum value over U_{fuel} variation range
min	relative to the minimum value over U_{fuel} variation range
ox	relative to the oxidizer coflow stream

well as the flame sooting behavior. More recently, Fujiwara and Nakamura [11] investigated the effects of preheating and burner material on microflame stability. They found that the minimum fuel flow rate required to sustain combustion decreased with lower thermal conductivity of the burner wall λ_{burner}, as well as with higher preheat temperature. They also found that the flame attachment height H_a (distance between the burner top and the very flame base) in such conditions, or minimum quenching distance, decreased accordingly with lower λ_{burner} and higher preheat temperature. This clearly indicates that thermal effects have also to be taken into account. While studying a preheated non-premixed jet-flame, Lamige et al. [12] have shown that both streams did not have the same relative thermal influence on flame stability, depending on which transition separating combustion regimes was under consideration. In particular for the lifting of an attached flame, the initial temperature of the fuel stream turned out to weigh more than that of the air coflow. Since the burner wall physically separates both streams, measurement of its temperature appears another step forward, still towards a better understanding of flame stabilization mechanisms. Eventually, the position of flame attachment relative to the burner wall is certainly another subject not so well documented in the literature, yet such data are inherently related to stabilization mechanisms. Aerothermochemical coupling indeed occurs in the region of flame stabilization, as evidenced for instance by the great changes in H_a induced by oxidizer-side dilution [13].

The present paper therefore aims at contributing experimental data for both the temperature of the burner lip and the location of the flame attachment point, for various burner materials over a wide range of fuel injection velocities, and with variation of flame state, rim coating and reactant initial temperature. Some major findings provide a valuable basis for further discussion on aerothermochemical coupling in the stabilization zone of an attached flame, by variation of the relative weight of heat transfer modes.

2. Experimental set-up

Experiments have been conducted employing the apparatus illustrated in Fig. 1a, largely detailed in previous papers [12–14]. Its main characteristics are briefly described here, along with a particular focus on experimental specificities of this work. It consists of a vertical atmospheric square combustion chamber, made of refractory (grade 310 as per European standards) stainless-steel (ss-310) and equipped with a central injector fed with methane. The latter is a straight tube, long enough to ensure a fully developed velocity profile (length-to-diameter ratio greater than 10^2), and whose internal diameter D_i and lip thickness δ are respectively 6 mm and 2 mm (Fig. 1b–c).

A first set of experiments was conducted by using exchangeable tube end pieces, tight-fitted on a same tube base, itself made of alumina (Al_2O_3). Various materials were chosen (cf. Table 1) according to their thermal conductivity λ_{burner} at ambient temperature, from copper (Cu, 395 W/(m K)) to 1250 °C-fired pyrophyllite (stumatite, 2.7 W/(m K)), including stainless steel (ss-310, 13.8 W/(m K)), material used in previous experiments [12–14]. A sheathed K-type thermocouple (sheath diameter of 0.5 mm; wire diameter of about 75 μm) is set within the lip of each burner, at the very top of the tube and centered in the middle of the lip to measure the lip temperature T_{lip}. In addition, a second thermocouple is located within the wall at 6 mm upstream measuring the temperature $T_{TC\#}$. Three additional thermocouples are implemented in the ss-310 case only, at upstream locations of 1, 3 and 10 mm, thus enabling an axial temperature gradient to be determined at the burner top. Accordingly, a conductive heat flux in the tube has been approximated under simple 1D hypothesis, $Q_{tube} = -\lambda_{burner} \times (T_{TC\#} - T_{lip})/d_{TC}$, where λ_{burner} is evaluated from literature data at a mean value over the temperature range covered and d_{TC} is the distance inter-thermocouples, 6 mm in most cases.

For each burner material, lip temperature T_{lip} was monitored over a very wide range of fuel injection velocities U_{fuel}, starting from 0.007 m/s up to the lifting velocity at about 15–17 m/s. Measurements thus cover the entire domain of attached flames, with both laminar and turbulent pipe flow regimes for the inlet fuel. Steady-state temperature values are reported here, except at lifting where $T_{lip,lifting}$ corresponds to the last value recorded while the flame was still attached. The fuel jet issues into an air coflow, whose mean flow velocity U_{ox} has been fixed here at 0.2 m/s. Note that velocities reported in this paper are all mean flow velocities (calculated from mass flow measurements and density determined from temperature measurements), and that this set of experiments was made at ambient temperature.

For each material and each U_{fuel}, 200 CH^*-chemiluminescence images were recorded by means of an ICCD camera whose resolution is 0.031 mm/pixel and exposure time is 100 ms. The camera is equipped with an interferential filter (full width at half-maximum of 5 nm) centered on 431 nm, the peak emission wavelength for CH^* radical. Location of the bottommost (attachment height H_a relatively to the burner top) and outermost (attachment radius r_a relatively to the burner axis) flame stabilization point is then extracted from image post-processing based on CH^*-intensity, as shown in Fig. 2. This paper reports mean values of H_a and r_a over each series.

Two additional burners have been employed in a second set of experiments, named here UC and BC, having the same material as ss-310 but using a whole tube made in a single piece instead of a tube end piece fitted on an alumina tube base (cf. Table 1). In this