



The role of precursors on the stabilisation of jet flames issuing into a hot environment



Paul R. Medwell^{a,*}, David L. Blunck^b, Bassam B. Dally^a

^a School of Mechanical Engineering, The University of Adelaide, SA 5005, Australia

^b Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH, USA

ARTICLE INFO

Article history:

Received 24 May 2013

Received in revised form 28 August 2013

Accepted 30 August 2013

Available online 21 September 2013

Keywords:

Lifted flames

Hot coflow

Jet in hot coflow burner

Vitiated coflow burner

ABSTRACT

This paper seeks to address unusual flame stabilisation behaviour observed in experimental jet flames which issue into a hot coflow. It has been observed that increasing the temperature and/or oxygen concentration in the coflow can lead to an increase in flame liftoff height. The paper isolates the role of chemistry, and in particular flame intermediates, on the observed phenomenon with a view to better understand how the behaviour changes over a range of conditions. A descriptive theory for this behaviour is proposed, which is based on the well-established theory that a build-up of radicals and intermediate species is responsible for autoignition of these flames. This paper systematically examines the role of these precursors with a view to better understanding of the chemical kinetics and to assess if the observed behaviour is chemistry-dominated. To this end, laminar flame calculations and ignition delay curves are presented, and the findings are validated with experiments. The results indicate that chemical effects alone are insufficient to fully explain the observations, but the calculations support the general trends noted in the experiments and highlight the importance and relative effects of some key precursors. In particular, the production and consumption of formaldehyde in a low oxygen environment supports the unusual flame behaviour observed experimentally.

© 2013 The Combustion Institute. Published by Elsevier Inc. All rights reserved.

1. Introduction

Lifted flames issuing into hot environments have received much attention over recent years because of their relevance to practical systems that incorporate recirculation of hot combustion products [1–5]. Many studies have been performed to investigate various aspects of these flames, such as autoignition (e.g., [2,3]) and developing fundamental-level understanding of the MILD (moderate or intense low oxygen dilution) combustion regime without the complex flow recirculation typically encountered in a practical system (e.g., [4,5]). The current paper reviews flame stabilisation mechanisms specifically for flames issuing into a hot environment, with a focus on the effects of temperature and oxygen level. More general review articles on lifted flames have recently been compiled by Lawn [6] and Mastorakos [7].

To replicate the conditions of a fuel jet issuing into a hot coflow, the vitiated coflow burner (VCB) was developed by Cabra et al. [2,3] for the study of lifted flames. DeVised independently of the VCB, the jet-in-hot-coflow (JHC) burner was designed by Dally et al. [4] to investigate the detailed reaction zone structure of MILD combustion. Both of these burners feature a central fuel jet which issues into a coflow of combustion products from a secondary

premixed flame. The coflow temperature and composition are controlled by the operating conditions of the secondary burner. Whilst the flames in the JHC burner experiments of Dally et al. [4,5] were attached to the jet (as evident by measurements of OH and major species) the similarity of the operating conditions with the VCB makes it ideal to compare the differences in the flame behaviour across a range of conditions. It should be noted that although MILD combustion is sometimes referred to as “flameless” combustion, the behaviour of the reacting jet is consistent with the conventional definition of a turbulent non-premixed jet flame.

Using the VCB a sensitivity of liftoff height to small changes in the coflow temperature has been observed experimentally with hydrogen/nitrogen and methane/air fuels in the jet. Analysis has revealed a build-up of radicals and intermediate species prior to ignition of these flames and indicates that autoignition is the stabilisation mechanism of these flames [8–11]. The evolution of these autoignition kernels is known to be a function of the balance between radical production and dissipation [12]. Extensive modelling activity has been conducted to replicate this phenomenon. Much of this modelling, however, has concentrated on the ability to replicate the observed trends, rather than understanding the governing physics. Notwithstanding the highly sensitive influence of small variations in coflow temperature on the liftoff height, systematic studies in the VCB have typically concentrated on a narrow range of conditions, corresponding to the experimental

* Corresponding author. Fax: +61 8 8313 4367.

E-mail address: paul.medwell@adelaide.edu.au (P.R. Medwell).

measurements. Whilst some insightful systematic studies have been performed (e.g., [12]) these have been limited to conditions very close to the two experimental studies of Cabra et al. [2,3]. In contrast, the JHC burner has been used over a much wider range of conditions, including both MILD combustion and autoignited flames [13]. However, there still exists significant gaps in understanding the flame behaviour across a range of operating conditions, which is one of the objectives of the current paper.

In experimental studies using the JHC burner by Medwell et al. [14] lifted flames were achieved in the transition to MILD conditions. These flames were seen to be very different from conventional lifted flames, including the presence of both CH_2O and OH upstream of the liftoff height. This observation led to them being referred to as “transitional” flames, where a transition in appearance is noted at the apparent liftoff height. Further investigation of these flames also revealed counter-intuitive results. Reducing the O_2 level in the coflow initially led to an increase in liftoff height (as may be expected), but further reducing the O_2 level causes the flame to re-stabilise to the jet exit plane [13]. More recently, the trend of increased liftoff with increased coflow O_2 level has been shown in numerical experiments [12,15]. Worth noting is that changes in the O_2 level of the coflow can affect the flame entrainment ratio, with a reduction in O_2 level increasing the entrainment ratio [16]. Decreasing the coflow temperature level also caused a similar trend, where the liftoff height was seen to initially increase (as may be expected) before the liftoff height starting to decrease with lower coflow temperature [13]. Although observed experimentally, a detailed description of these phenomena is not fully understood. Reaction rate analysis of hydrogen/nitrogen flames, however, indicates that the hydrogen radical (H) may play an important role in explaining the observed behaviour [12]. In the case of hydrocarbon flames in general, other radicals and intermediate species have an influential role in the stabilisation mechanism.

Imaging measurements of lifted flames in a hot coflow show a build-up of formaldehyde (CH_2O) upstream of the flame liftoff height, after which the concentration of OH rapidly increases with downstream distance [10,14]. In both the VCB and the JHC burners it is widely accepted that the presence of CH_2O and other intermediates upstream of the liftoff height is evidence of autoignition [7]. Due to the different coflow temperature and O_2 levels the appearance of the OH and CH_2O upstream of the liftoff height is quite different between the measurements of Gordon et al. [10] and Medwell et al. [14]. In the autoignitive flames in the VCB, Gordon et al. [10] show small pockets of isolated OH indicative of spontaneous ignition kernels. In contrast, in the JHC burner the flames approaching MILD combustion show continuous OH measurements upstream of a transition to the fully burning OH concentration [14]. Nonetheless, in both cases the high temperature coflow is responsible for the production of CH_2O in the lifted region of these flames. It is also noted that, despite the high temperature of the coflow ($>1100\text{ K}$), the temperature of these flames along the centreline is expected to be below $\sim 900\text{ K}$ which represents the initiation of $\text{CH}_2\text{O} \rightarrow \text{CO}$ oxidation [17], and thus any CH_2O that is formed is unlikely to oxidise in this region, leading to its accumulation. DNS results of a lifted ethylene flame support the experimental observations of precursor species (such as HO_2) upstream of the OH reaction zone [18].

The autoignition process is well-known to initiate and stabilise through the build-up of radicals [19,20]. For hydrogen flames in a hot coflow HO_2 is considered an important precursory species [21,22], and is believed to trigger autoignition [23]. The presence of intermediate species are also known to reduce the ignition delay under MILD combustion conditions [24]. In particular CH_2O is known to be very important in the hot oxidant environment [25], and is expected to aid ignition [26]. The affect of OH radicals in

the oxidant stream from a two-stage combustion processes is also expected to reduce the ignition delay [27].

Another important observation noted in the JHC burner is a reduction in apparent liftoff height with an increase in jet Reynolds number [14,28,29]. This is not seen in the autoignitive lifted flames of Cabra et al. [2,3]. It is reported that an increase in turbulence delays autoignition, but once a flame is established the increased mixing enhances the overall rate of reaction [30]. Increasing the turbulence intensity in the JHC flames reduces the apparent liftoff height, rather than increasing it, indicating that the combustion reaction had already initiated. These observations support the previous assertion that these flames are not autoignitive lifted flames, but rather MILD or transitional flames [14]. A further factor that may contribute to the observed flame behaviour is the differences in mixing due to laminarisation that can occur due to the different temperatures, both from the coflow and the reaction zone heat release [31].

In summary, flames in a hot environment may exhibit different behaviour, dependent on the properties of the coflow. It is widely accepted that autoignition is responsible for stabilisation of lifted flames in a hot coflow [12], however, with reduced O_2 levels in the coflow the flame behaviour is observed to be quite different [13]. It is postulated that the high temperature oxidant stream promotes a radical-pool build-up which assists in the stabilisation of these flames. The role of O_2 can have pronounced differences, however, on the flame stability. A descriptive process of stabilisation theory for lifted flames in a hot coflow is proposed as follows:

- With a (relatively) high coflow temperature and O_2 level lifted flames under non-MILD conditions stabilise through autoignition. (The precise definition of *relatively* high depends on the operating conditions, but loosely may be considered $\geq 10\% \text{ O}_2$ and $\geq 1400\text{ K}$.) The high temperature of the coflow initiates precursory reactions and builds a pool of radicals and minor species. The pool of precursors is expected to induce and promote rapid ignition. This is consistent with the summary provided by Gordon et al. [8–10].
- Reducing the coflow temperature and/or O_2 level of a lifted flame leads to an increase in liftoff height, as may be expected, due to a reduction in reaction rates.
- Further reducing the coflow temperature and/or O_2 level leads to flames in the MILD combustion regime. These flames typically attach to the jet exit plane, despite the lower temperature and O_2 level. This is due to O_2 penetration across the reaction zone to the fuel-rich side, which further enhances the precursor pool under these conditions, and is particularly prevalent under high strain conditions [32]. It is apparent that MILD conditions promote the production of a precursor pool leading to more stable flames that are less prone to liftoff. Increasing the jet velocity further stabilises the flame, both through increased O_2 penetration and enhanced mixing.

The aim of the present paper is to review and analyse the proposed theory regarding flame stabilisation of lifted flames in a hot coflow and assess flame behaviour across a range of conditions, highlighting the importance of minor species. Notwithstanding the important role of turbulence-chemistry interactions (which can enhance or inhibit autoignition [33–35]) and jet autoignition in heated air [36], these scenarios are beyond the scope of the present work which focuses on chemical-kinetic effects in a hot coflow at various O_2 levels. It is believed that stabilisation mechanisms in the hot coflow environments are predominately affected by the chemistry [23], supported by the observation in practical combustors employing these types of flames are only weakly dependent on operating conditions [25].

Download English Version:

<https://daneshyari.com/en/article/169015>

Download Persian Version:

<https://daneshyari.com/article/169015>

[Daneshyari.com](https://daneshyari.com)