Combustion and Flame 178 (2017) 297–310

Contents lists available at ScienceDirect

Combustion and Flame

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

Effects of oxidant stream composition on non-premixed laminar flames with heated and diluted coflows

Michael J. Evans[a,*], Paul R. Medwell[a], Zhao F. Tian[a], Jingjing Ye[a], Alessio Frassoldati[b], Alberto Cuoci[b]

[a] School of Mechanical Engineering, The University of Adelaide, South Australia 5005, Australia
[b] Dipartimento di Chimica, Materiali ed Ingegneria Chimica "G. Natta", Politecnico di Milano, 20133 Milan, Italy

ARTICLE INFO

Article history:
Received 22 June 2016
Revised 11 August 2016
Accepted 21 December 2016
Available online 7 February 2017

Keywords:
MILD combustion
Tribrachial flames
Lifted flames
JHC burner
Autoignition

ABSTRACT

The moderate or intense low oxygen dilution (MILD) combustion regime offers reductions in pollutant emissions and improvements in efficiency. The implementation of MILD combustion in non-premixed systems, however, still requires a significantly improved understanding of the effects of the oxidant stream composition in both the MILD combustion regime, and in the transition from MILD combustion to conventional spontaneous-ignition. This paper presents a numerical study of two-dimensional flames near the transition between MILD combustion and conventional spontaneous-ignition. The numerical study is performed with a detailed kinetic mechanism, using the laminarSMOKE code to provide insight into the chemical structure of flames with a hot and diluted coflow. This study is complemented by new experimental observations of laminar flames in similar coflows, which demonstrate a non-monotonic change in lift-off height with changing oxidant O_2 concentration. This change occurs in conjunction with a transition from spatially gradual ignition to well-defined flame bases, with increasing coflow O_2 level. The simulated flames are compared to a previous definition of MILD combustion in a hot coflow as an edge flame without a tribrachial flame structure. The different structures of simulated CH_4 flames are consistent with the observed experimental behaviour under similar conditions, however comparisons between experimental observations and simulations of C_2H_4 flames highlight the importance of the flow-field, even in a simple streaming flow. The simulations show that equilibrium levels of the OH radical ($<$ 10 ppm) in the oxidant stream significantly intensifies a MILD CH_4 reaction zone, by increasing CH_3 oxidation, however such levels have little effect on tribrachial, spontaneously-igniting flames. Conversely, increasing the ratio of CO_2 to H_2O in the coflow reduces the intensity of a MILD CH_4 reaction zone. Neither the inclusion of equilibrium concentrations of OH, nor the change in CO_2 to H_2O ratio, in the oxidant results in a transition between MILD reaction zones to tribrachial spontaneously-igniting flames, despite significantly affecting the temperature of reaction zones in the MILD combustion regime. The results show that the intensity of MILD combustion is strongly dependent on the different chemical species in the oxidant stream. Tribrachial spontaneously-igniting flames are, in contrast, relatively resilient against changes other than temperature and O_2 level.

1. Introduction

Requirements for improved efficiency and reduced pollutant emissions have driven research into novel combustion systems. Potential applications for new combustion technologies range from more fuel-efficient industrial furnace applications [1], to low-emissions aero-engines [2]. One aspect of research into this contemporary problem, explores combustion stabilised through exhaust gas recirculation (EGR) [1,3,4], staged combustion [2,5], or the recirculation of hot combustion products in confined burners [6–8]. Fundamentally, these systems may be described as non-premixed combustion with hot and diluted oxidants. One proposed technology to meet the targets for next-generation combustion systems, is moderate or intense low oxygen dilution (MILD) combustion [9].

The MILD combustion regime offers both reduced pollutant emissions and improved thermal efficiency over conventional combustion [1,9]. Characteristic features of MILD combustion – otherwise referred to as "flameless oxidation" or "colourless" combustion – include low peak temperatures, low luminosity, reduced

---

[*] Corresponding author.
E-mail address: m.evans@adelaide.edu.au (M.J. Evans).

http://dx.doi.org/10.1016/j.combustflame.2016.12.023

thermal gradients, and reduced soot production compared with conventional combustion [9]. The MILD combustion regime has been successfully implemented in furnaces [1,3,10], and similar combustion regimes consisting of a fuel stream issuing into a hot, low oxygen environment have been suggested for further applications [2,11–14]. Such configurations have been the foci of recent research [15–18] to better the understanding of the boundaries of MILD combustion, and the sensitivity of flame behaviour and structure to operating conditions, required for future applications of MILD combustion.

Significant experimental research into non-premixed MILD combustion has been undertaken using jet-in-hot-co-/cross-flow (JHC) burners [16–25]. These experiments have focussed on understanding the ignition and stabilisation of simple hydrocarbon fuels with combustion products used to produce hot, low oxygen environments encountered in EGR, and required for MILD combustion. These experimental studies have used different combinations of laser diagnostics, photographs and chemiluminescence imaging to reveal the structure of MILD jet flames, and have been supplemented by computational investigations [26–30].

Combustion under MILD conditions has been previously described as exhibiting gradual ignition, in both a spatial and temporal sense, without a distinct flame base [22,23,27–31]. This configuration has been specifically studied in the context of combustion of fresh fuel with a hot [oxidant], diluted oxidant (HODO) stream [32,33] providing increased initial enthalpy to the reactant mixture [34], and extending the flammability limits [35]. This is consistent with studies of combustion in porous media [36]; confined, swirl-stabilised flames [37,38] (where flames are stabilised through recirculation of hot combustion products) [8,39]; and insights into bluff-body flames [40]. Research into these combustion applications [36,40] are consistent with fundamental studies of opposed-flow flames, which suggested that CH_4 flames could not be extinguished by decreasing O_2 concentrations in HODO streams in excess of approximately 1550 K [35]. It has been concluded that laminar MILD counterflow CH_4 flames are stabilised due to partial premixing from the diffusion of O_2 from the oxidant stream into the fuel through reaction zone weakening [26]. Although this explains the presence of CH_2O near the jet centreline in flames in JHC burners [22,41], it cannot be concluded that the diffusion effects are unilateral or that the mechanism for stabilising flames in the MILD combustion regime is a direct result of the diffusion of O_2 into the fuel alone.

Conventional autoignition of non-premixed flames has, similar to MILD combustion, been studied in JHC [12,15,20,21,42–45] and vitiated coflow burner (VCB) [46–48] configurations. Although most of these experimental studies investigated non-premixed turbulent flames, laminar ‘autoignitive’ flames in hot and vitiated coflows have been observed to have distinct, lifted, tribrachial flame bases [20,21,49,50]. These tribrachial flame bases consist of three distinct ‘wings’ which “can be clearly identified with the naked eye” [50], leading to studies of flame structure based on the analysis of photographs [20,21,49]. The phenomenon of tribrachial flames has been used to describe non-premixed ‘autoignition’ in experimental studies [51–53] and has been discussed at length (with detailed figures) elsewhere [50,54,55]. This work will use the terminology ‘spontaneous-ignition’ [56] to describe the ignition of an arbitrary mixture (outside of the MILD combustion regime), which may or may not be affected by the transport of combustion precursors or products from other parts of the reaction zone.

Methane (CH_4) and ethylene (C_2H_4) have been the subject of studies of the ignition and structure of laminar [21,57] and turbulent [15–17,19,22,23,42–44,46–48,58] flames in hot and diluted (HODO) coflows. Identifying the ignition process of these fuels is critical for understanding the combustion of larger hydrocarbons under MILD combustion conditions, with C_2H_4 found in significant quantities in both rich and lean regions of more complex hydrocarbon flames, encompassing “layers” of acetylene (C_2H_2) and CH_4 [59]. Both MILD combustion and conventional spontaneous-ignition require hot environments to stabilise jet flames, generally considered to be above a pre-defined autoignition temperature [9]. Despite the similarities in the conditions for spontaneously-igniting flames and MILD combustion, the two regimes have been shown to feature very different ignition characteristics and flame structures: experimentally [18,22,23,30,60]; in zero-dimensional reactors [61]; one-dimensional flame analyses [16,28–31,62]; and direct numerical simulations of reaction zone structures in EGR configurations [63–65].

At a given oxidant temperature, increasing the concentration of coflow O_2 results in a shift from spatially gradual ignition of MILD combustion towards lifted, spontaneously-igniting flames with a well-defined flame-base [18,22,23,30]. This transition away from the MILD combustion regime, has been described both as a transition to an edge flame stabilised at a triple point in non-premixed laminar flames [20,21], and the initiation of a region of net negative heat release rate across the reaction zone [32]. This transition away from the MILD combustion regime has also been described (in homogeneous reactors) as the conditions where methyl (CH_3) oxidation becomes dominant over recombination [62].

Laser-based imaging of turbulent, lifted, C_2H_4 flames has been unable to identify any evidence of tribrachial structures, although such structures may collapse due to interactions with turbulent vortices [22]. Observations of such structures would facilitate comparisons against separate studies of laminar flames [20,21], which exhibit a transition between two distinct flame behaviours with changing coflow O_2 levels, similar to the turbulent flames [20–23]. The differences between laminar and turbulent flow regimes demonstrate the need for a systematic experimental and numerical investigation into the structure of laminar flames, without the effects of turbulence, in both the MILD and conventional spontaneous-ignition regimes.

Minor species, such as OH, are inherent in hot coflows due to the presence of combustion products. Such minor species cannot be easily controlled experimentally and are neither generally reported as boundary conditions nor taken in account during discussion of experimental observations or computational modelling. However, some previous studies of flames with hot and diluted oxidants have indicated the importance of precursor and radical species to flame stabilisation [17,41,48,66–74]. Previous studies have investigated the addition of species such as NO [66–69], N_2O [67], OH [17,75], CH_2O [17,76], H_2 [73], CO_2 [74,77] and H_2O_2 [76] on flame ignition and temperature, across a range of different configurations and conditions.

The formation of OH upstream of a visually defined flame base has previously been observed in C_2H_4 flames in a JHC burner [22]. Additionally, low concentrations of OH have been shown to significantly reduce ignition delay times when added to a premixed reactor [17]. To complement these findings, a previous investigation of equilibrium OH concentrations ($\sim$ 10 ppm) in a turbulent flame issuing into a hot coflow with 9% O_2 demonstrated negligible effects in Reynolds-averaged Navier–Stokes (RANS) simulations [75]. The small impact of equilibrium OH was in agreement with the premixed reactor simulations of CH_4 flames, which showed only slight reductions in ignition delay for oxidants with less than 10 ppm of OH [17]. The RANS study, however, did not investigate other fuel mixtures or coflows with as little as 3% O_2 (by volume) [75].

Improved understanding of MILD combustion is critical for its implementation in practical combustion systems. This study builds on the understanding of the effects of oxidant oxygen concentration and oxidant temperature in the transition to MILD combustion by further investigating the effects of coflow composition on flame stabilisation in, and the transition to, the MILD combustion regime.