Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

Experimental and numerical studies of the effects of hydrogen addition on the structure of a laminar methane–nitrogen jet in hot coflow under MILD conditions

Alexey Sepman [a,*], *Ebrahim Abtahizadeh* [b], *Anatoli Mokhov* [a], *Jeroen van Oijen* [b], *Howard Levinsky* [a,c], *Philip de Goey* [b]

[a] *Faculty of Mathematics and Natural Sciences, Energy and Sustainability Research Institute Groningen, University of Groningen, 9747 AG Groningen, The Netherlands*

[b] *Combustion Technology, Mechanical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*

[c] *KEMA Nederland B.V., P.O. Box 2029, 9704 CA Groningen, The Netherlands*

ARTICLE INFO

Article history:
Received 15 May 2013
Received in revised form
22 July 2013
Accepted 3 August 2013
Available online 2 September 2013

Keywords:
Hydrogen addition
MILD combustion
Laminar flame
Laser induced fluorescence

ABSTRACT

In this work we investigate the effects of hydrogen addition on the flame structure of MILD combustion both experimentally and numerically using a laminar-jet-in-hot-coflow (LJHC) geometry. The addition of hydrogen appreciably decreases the flame height (~25%), however only modestly affects the maximal flame temperature and the thickness of combustion zone. The NO distribution is dominated by mixing of the NO formed in the coflow with the reaction products of the diluted fuel, with negligible NO formation from the fuel in all flames studied. The numerical data are in reasonably good agreement with the measurements.

1. Introduction

MILD (moderate and intense low-oxygen-dilution) combustion is a new technology combining high efficiency and low pollutant emissions in industrial heating processes [1]. This method adopts highly preheated and diluted air and/or fuel to homogenize the temperature field and minimize NO_x emission during combustion processes. An important aspect essential for successful implementation of this combustion technology is the robustness of a practical system to variations in fuel composition; under industrial conditions, fuels may vary from natural gas to H_2/CO mixtures containing unsaturated hydrocarbons, and the combustion systems must continue to operate within the desired performance envelope. Currently, there are relatively few studies considering variations in fuel composition on MILD combustion. For example, it was shown in [2] that adding ethane or N_2 to methane both widened the operating range for MILD combustion as

* *Corresponding author*. Laboratory for High Temperature Energy Conversion Processes, University of Groningen, 9747 AG Groningen, The Netherlands. Tel.: +31 50 3634759; fax: +31 50 3634479.
E-mail address: a.v.sepman@hotmail.com (A. Sepman).

0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2013.08.015

compared to methane itself. Another study [3] found that the addition of N_2 or CO_2 to the fuel (a variety of fuel mixtures using methane, ethylene, and propane were investigated) reduced the NO_x emissions and facilitated flameless oxidation. In [4] it was reported that NO_x emissions are not sensitive to the hydrogen concentration under MILD conditions. A higher fuel jet velocity was required to achieve the transition from the conventional flame structure to MILD combustion when using a hydrogen–methane fuel [5] compared to pure methane, but a lower furnace temperature could be used. Only few studies considered the physical/chemical origins of the effects of fuel composition, in particular H_2 addition, on either the stability of the MILD regime or NO formation. For example, it was shown both computationally and experimentally in [6] that the reaction zone structure is very similar for the different fuels considered when hydrogen is added to the fuel stream. Hydrogen was found necessary for the experimental flames to stabilize. A numerical study [7] demonstrated that the hydrogen addition to methane leads to improved mixing, an increase in the turbulent kinetic energy decay along the flame axis and flame entrainment, higher reaction intensities, improved mixture ignitability and enhanced rate of heat release. Numerical and experimental investigations of burners operating in MILD combustion regime and fed with methane and methane–hydrogen mixtures showed the need of a detailed chemistry approach [8] and the need of a proper turbulence/chemistry interaction treatment [9] to capture the volumetric features of MILD combustion. The effect of the composition of methane/hydrogen mixture on mild flameless combustion was studied in [10] on a laboratory-scale facility. In [11] it was shown that hydrogen oxidation kinetic significantly interacts with methane Mild Combustion process. See also [12] for more references on the flameless oxidation of various fuels. We note that all above mentioned work was done in turbulent flames. To our knowledge there are no combined experimental and numerical studies of the effects of fuel composition on MILD flames in good defined conditions where chemical models can be tested.

In this work we investigate the effects of hydrogen addition on both spatial structure and the NO formation of a MILD flame burning using an axisymmetric laminar-jet-in-hot-coflow (LJHC) burner both experimentally and numerically. Towards this end, we expand our previous studies performed on the MILD flame with methane as a basis fuel (this base flame was investigated by the authors in [13–15]) by adding hydrogen to the fuel. The distributions of temperature and fractions of major species and NO are measured using spontaneous Raman scattering and laser-induced fluorescence (LIF).

2. Experimental

A schematic of the LJHC burner is shown in Fig. 1. An upright ceramic fuel tube (i.d. of 7 mm, wall thickness of 1.5 mm) was surrounded by a coflow annulus (a perforated ceramic tile with an overall diameter of 58 mm). The experimental conditions (the exit velocity, temperature and composition) for the fuel and oxidizer are reported in Table 1 for two Cases studied. The hot oxidizer stream was formed by the combustion products of a nearly one-dimensional flame of a fuel-lean $N_2/CH_4/O_2$ mixture, see [14,15] for more details on the operation of the burner. The experimental and numerical results for Case M were reported and thoroughly described in our previous works [13–15]. Here we study the effects of the H_2 addition to the fuel on the spatial structure of the MILD flame (Case M). Methane and hydrogen were mixed while keeping the total flow rate of the fuel constant. The flows of all gases were measured using calibrated mass flow meters (Bronkhorst). The velocities reported in Table 1 are the flows of coflow and fuel (measured at standard conditions) normalized by the corresponding exit areas. The profiles of temperature and species fractions were obtained by moving the burner axially and radially (vertically and horizontally, respectively) by a precision positioner (Parker, positioning uncertainty less than 0.1 mm).

The flame temperature, major species (CO, CO_2, N_2, H_2, H_2O, CH_4 and O_2) and NO fractions were measured using spontaneous Raman scattering and Laser induced Fluorescence, respectively. The optical scheme for the spontaneous Raman measurements is essentially identical to that described in [16]. At the exit plane of an f/4 Acton Research Spectra Pro 2300i spectrometer, a PI-Max intensified 1024 × 1024 pixel CCD camera (Princeton Instruments, 13 μm pixel size) was mounted. In the present study, 40 pixels were binned along the axis of the laser beam, integrating the signal over distances of roughly 1 mm, yielding the radial spatial resolution of the experiment. The temperature measurements were performed using moderately resolved Raman spectra of N_2, the concentration measurements using low-resolution Raman spectra which included the spectral features of all

Table 1 – The experimental conditions.

Case	Coflow							Fuel				
	v^a (cm/s)	$O_2{}^b$	N_2	H_2O	CO_2	NO (ppm)	T^c (K)	v^a (cm/s)	CH_4	H_2	N_2	T^d (K)
M	15.5	0.036	0.732	0.145	0.087	10	1530	5.8	0.18		0.82	1150
H	15.5	0.036	0.732	0.145	0.087	10	1530	5.8	0.09	0.09	0.82	1185

a The exit velocities are reported at Standard conditions ($T = 273$ K, $P = 1$ atm).
b The composition of gases is given by volume %.
c Coflow temperature in the exit plane of the fuel tube.
d Fuel temperature at 3 mm above the exit plane of the fuel tube.