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Effects of oxygen index on soot production and temperature in an ethylene inverse diffusion flame

F. Escudero [a,b], A. Fuentes [a,*], R. Demarco [a], J.-L. Consalvi [c], F. Liu [d], J.C. Elicer-Cortés [b], C. Fernandez-Pello [e]

[a] Departamento de Industrias, Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso, Chile
[b] Departamento de Ingeniería Mecánica, Universidad de Chile, Av. Beauchef 851, Santiago, Chile
[c] Aix-Marseille Université, IUSTI/UMR CNRS 7343, 5 rue E. Fermi, 13453 Marseille Cedex 13, France
[d] Black Carbon Metrology, Measurement Science and Standards, National Research Council of Canada, 1200 Montreal Road, Ottawa, Ontario K1A 0R6, Canada
[e] Department of Mechanical Engineering, University of California, Berkeley, CA 94720, USA

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ABSTRACT

An experimental study was conducted to investigate the effects of the Oxygen Index (OI) in an ethylene laminar inverse diffusion flame (IDF). The OI was varied from 21% to 37% and its influence was measured in terms of the flame height, soot volume fraction, soot temperature and radiant fraction. The stoichiometric flame height was measured by the spontaneous emission of CH^* radicals and was found to decrease when the OI increases. In contrast, the luminous flame height increases with OI because soot can still form and grow beyond the reaction zone. Radial profiles of soot volume fraction and soot temperature were obtained by means of a Modulated Absorption/Emission (MAE) technique. The line-of-sight intensities, integrated along the optical path and captured by ECCD camera at two wavelengths were inverted using deconvolution and regularization techniques in order to obtain radial profiles of soot volume fraction and temperature. The increase in OI enhances soot volume fraction due to higher temperatures and soot formation rates. Both the local and integrated soot quantities increase with OI. The radiant fraction of IDF increases with the OI in a similar way to the integrated soot volume fraction.
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1. Introduction

Combustion is a very complex phenomenon and has been studied for many decades. However, complete understanding of combustion processes in turbulent flames remains a challenge due to the large number of simultaneous processes involved. The axisymmetric laminar diffusion flame configuration has often been used as a valuable model to gain fundamental insights into the complex phenomena occurring in turbulent flames. These laminar flames are of great interest because they are sufficiently stable and repeatable to allow non-simultaneous measurements of various quantities, such as velocity, temperature, and species concentrations, to probe the effects of various parameters on flame properties, including but not restricted to the fuel and oxidizer stream velocities, fuel dilution, and oxidizer compositions. Depending on the flame characteristics, soot may or may not be completely consumed within the flame. Emissions of soot from flames and combustion systems have been identified harmful to human health and the environment [1]. It is interesting to mention that in some industrial applications, in which the direct flame radiation is used to heat the secondary fluid, it is often desirable to enhance soot formation in flames to maximize radiation heat transfer from flames yet to avoid emissions of soot from such combustion devices. The amount of released soot depends on the competition between soot formation and soot oxidation processes within the flame.

Despite the significant progress in the last few decades towards soot formation processes, the key steps in soot inception remain elusive [2]. The inverse diffusion flame (IDF) is an interesting flame configuration to investigate particularly the soot inception process. IDFs are similar to normal diffusion flames (NDFs) in terms of the flame structure, but the roles of fuel and oxidizer are exchanged: an oxidizer flow is surrounded by a fuel flow in an IDF and soot escapes from the reaction zone un-oxidized allowing its study in the early stages of formation [3]. The combustion process in an IDF resembles that in an under-ventilated NDF and is highly relevant to flames or fires under fuel rich conditions.

There have been extensive studies of NDFs. However, only few works have been reported in the literature concerning IDFs. The concept of the inverse diffusion flame was introduced vaguely by Friend [4] in the early 20s in a single sentence. Burke and

* Corresponding author. Tel.: +56 32 2654650.
E-mail address: andres.fuentes@usm.cl (A. Fuentes).

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Nomenclature

a	buoyancy acceleration of a fluid parcel within the flame ($m\ s^{-2}$)
C_2	second constant of Planck's equation (m K)
C_λ	absorption function (–)
Fr	Froude number (–)
f_s	soot volume fraction (ppm)
HAB	height above the burner (m)
h_f	flame height (m)
HRR	heat release rate (W)
I_λ	spectral radiation intensity of the flame ($W\ sr^{-1}\ m^{-3}$)
I_λ^{bb}	blackbody spectral radiation intensity of the flame ($W\ sr^{-1}\ m^{-3}$)
J_λ	local emission of the flame ($W\ sr^{-1}\ m^{-4}$)
l	local position along the line-of-sight within the flame (m)
l_0	beginning of the line-of-sight of the flame (m)
l_1	end of the line-of-sight of the flame (m)
N	number of annular elements of the discretized flame (–)
Q	volumetric flow rate ($m^3\ s^{-1}$)
q''	vertical distribution of heat flux measured by the radiometer ($W\ m^{-2}$)
R	distance between the radiometer and the axis of the flame (m)
r	radial position from the flame axis (m)
R_f	flame radius (m)
T_{ad}	adiabatic temperature of the flame (K)
t_{res}	residence time of a fluid parcel to reach the flame height (s)
V_f	fuel velocity at the burner exit ($m\ s^{-1}$)
y	abscissas coordinate of the projected data (m)
z	vertical distance from the burner exit surface (m)

Greek symbols

β	integrated soot volume fraction ($ppm\ m^2$)
κ_λ	spectral absorption coefficient (m^{-1})
λ	wavelength (m)
τ_λ	fraction of transmitted light (–)
$\Phi_{overall}$	overall equivalence ratio, defined as the fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio at the burner exit (–)
χ_r	radiant fraction (–)

Acronyms

FWHM	full width at half maximum
IDF	inverse diffusion flame
LOSA	line-of-sight attenuation
MAE	Modulated Absorption/Emission
NDF	normal diffusion flame
OI	oxygen index
OP	Onion-Peeling
PAH	polycyclic aromatic hydrocarbons

Schumann [5] reported the measured heights of some IDFs but without specific details. More recently, there have been more studies about this type of flames. Wu and Essenhigh [6] mapped inverse methane flames by varying the air and fuel velocities and identified six different regimes with stable and unstable flames and emitting more or less soot depending the flow conditions. Lee et al. [7] identified a similar kind of map for ethylene flames adding three more kind of regimes. They also identified the reaction zone, soot particles and the degree of soot maturation by means of carbon to hydrogen ratio (C/H ratio) and morphology of soot samples. Kaplan and Kailasanath [8] made direct numerical simulations for different quotients between air and fuel velocities for NDFs and then compared them with IDFs with the same velocities. They found that under the same conditions IDFs produce much less soot than NDFs because the surface growth rate is lower in IDFs due to the unfavorable temperature and stoichiometric conditions for soot inception. Blevins et al. [9] confirmed the hypothesis that soot of IDFs is similar to the one of NDFs by collecting samples of exhaust soot and analyzing its morphology. Mikofski et al. [10,11] analyzed the structure and heights of methane and ethylene flames varying the air flow rate. They studied quantitatively the temperature of flames and qualitatively the concentrations of soot, PAH and OH^* radicals to understand the soot formation mechanisms in these flames, which were found similar to the mechanisms in NDFs. They also found that heights of reaction zone of the flames follow the theory of Roper for circular port burners. Macko et al. [12] made extinction measurements to obtain soot concentrations and found that they were about an order of magnitude lower than those in NDFs. Demarco et al. [13] studied numerically IDFs with OI of 21% focusing on radiative heat transfer. They showed that radiant fractions are much lower than those observed in NDFs and the contribution of soot to radiation is lower than the contribution of gaseous radiant species.

An effective way to alter the relative importance of soot production and oxidation mechanisms, and therefore the radiative properties of a flame, is to vary the oxygen index (OI) defined as the mole concentration of oxygen in the oxidizer stream containing a mixture of oxygen and nitrogen. Recently, Jung et al. [14] studied the effects of OI in ethylene IDFs. They measured the heights and temperature of the flame and the concentrations of PAHs and soot. They also measured the C/H ratio to evaluate the degree of carbonization. In this study new experimental data are obtained as a function of OI, from 21% to 37%, in a standard inverse flame burner. Non-intrusive diagnostics were carried out in order to obtain radially resolved profiles of soot temperature and soot volume fraction, the radiant fraction and the height of the reaction zone. These results are valuable addition to the existing experimental results obtained in similar NDFs conditions for validation of numerical models of soot formation and growth.

2. Experimental methodology

In the following section the experimental setup and conditions used in the study are presented. Also the experimental procedure to obtain soot volume fraction, soot temperature, flame height and radiation heat flux is described.

2.1. Inverse flame burner and experimental conditions

The IDF investigated in this study was produced with a similar co-annular inverse flame burner used previously in other studies by Blevins et al. [9], Mikofski et al. [10,11] and Macko et al. [12]. Basically, the inverse flame burner consists of three concentric tubes. The inner diameters of the tubes were 10, 30 and 64 mm for the oxidizer, fuel, and inert flows, respectively. The fuel tube and the inert annulus contain a honeycomb structure to smooth the flow. The fuel used was pure ethylene and the inert gas was nitrogen to prevent secondary flames from forming between the fuel and the ambient air. For OIs lower than 21% the flame became

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