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Experimental and numerical study of the effects of the oxygen index on the radiation characteristics of laminar coflow diffusion flames

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ABSTRACT

The oxygen concentration in the oxidizer stream ($O_2 + N_2$) of laminar coflow ethylene diffusion flames is varied from 17% to 35% in order to study its influence on the flame height, the soot formation/oxidation processes, the smoke point characteristics, and the vertical distributions of radiative flux at a distance of 6.85 cm from the flame axis. Measured values for all the investigated parameters are compared with the predictions provided by a numerical model based on a two-equation semiempirical acetylene-based soot model and on the statistical narrow-band correlated-*k* model to compute thermal radiation. Predictions are in overall reasonable agreement with the experiments for oxygen indices in the range 19–35%, whereas all the investigated parameters are significantly underestimated for an oxygen index of 17%. Measured flame heights based on CH* emission below, at, or slightly above the smoke point, as well as predicted stoichiometric flame heights, are found to be proportional to $\zeta = \dot{V}_f[D_\infty \ln(1+1/S)]^{-1}(T_\infty/T_{ad})^{0.67}$, where $\dot{V}_f$, D_∞, S, and T_{ad} are the volumetric flow rate of ethylene, the diffusion coefficient at ambient temperature, the stoichiometric molecular air-to-fuel ratio, and the adiabatic flame temperature. Soot formation processes are found to increase with the oxygen index, leading to higher values of the maximum soot volume fraction and the peak integrated soot volume fraction. In addition, the latter is reached at a nondimensional height (normalized by ζ of approximately 0.05, regardless of the oxygen index within the investigated range. Two regimes are evidenced: The first regime, occurring for oxygen indices lower than 25%, is dominated by soot oxidation and is characterized by an enhancement in both the maximum soot volume fraction and the fuel flow rate at the smoke point with the oxygen index. The second regime, occurring for oxygen indices higher than 25%, is dominated by soot formation; the rate of increase in the maximum soot volume fraction with the oxygen concentration is lower than in the first regime, whereas the fuel flow rate at the smoke point decreases. Finally, the peak of radiative flux increases with the oxygen index, but its rate of increase is also found to be considerably reduced for oxygen indices greater than 25%.

1. Introduction

Mass burning, flame spread, and fire growth at hazardous scales are driven by thermal radiation from soot and combustion gases, with the continuum thermal radiation from soot usually accounting for the majority of flame radiation. Real fire generally occurs under vitiated conditions. On the other hand, diffusion flames in oxygen-enriched environments have direct applications in fire safety for spacecraft and planetary surface bases [1]. In addition, enhanced ambient oxygen may be used in bench-scale testing to reach radiative fluxes as severe as those encountered in large-scale well-ventilated fires [2]. As a consequence, how the radiative properties of diffusion flames are affected by varying the oxygen concentration in the oxidizer flow (called the oxygen index and referred to as the OI hereafter) of nonpremixed flames is a crucial issue for fire safety. This question is also of practical interest in the design of oxy-fuel burners, applied to a variety of industrial processes to improve efficiency and pollution characteristics, where the generation of intermediate soot is desirable for increasing radiant heat transfer [3].

Well-defined laminar flames were used in previous works to investigate the influence of varying the OI on soot production. Laminar flames offer more tractable configurations for analysis and experiments [4–6] than the practical turbulent diffusion flames involved in combustion systems and fires. Moreover, their use is justified by the similarities between laminar and turbulent diffusion flames, and the results can be extrapolated to turbulent flames through approximate approaches like the laminar flamelet concept [4–6]. Experimental studies of counterflow diffusion

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Nomenclature

A_{OP}	coefficient matrix of the Onion–Peeling deconvolution (m)
A_S	soot surface area (m^{-1})
C_a	agglomeration rate constant
d_S	soot particle diameter (m)
D	diffusion coefficient ($m^2\,s^{-1}$)
$f(r)$	field variable (m^{-1})
f_S	soot volume fraction (–)
h_f	flame height (m)
k_B	Boltzmann constant (J kg^{-1})
k_S	absorptive index of the soot (–)
$k_{S,n}$	soot nucleation Arrhenius reaction rate (s^{-1})
$k_{S,sg}$	soot surface growth Arrhenius reaction rate (m s^{-1})
m_S	complex index of refraction of the soot ($m_S = n_S - ik_S$) (–)
N	number of discrete field variables, projection location (–) Avogadro number (particle·mol^{-1})
NC_{min}	number of carbon atoms in the incipient soot particle (–)
n_S	refractive index of the soot (–)
N_S	soot number density per unit mass of mixture (particle·kg^{-1})
OI	OI oxygen index (–)
$P(y)$	projected area (m^2)
p_i	partial pressure of species i (atm)
$\dot{q}''_R$	radiative flux (W m^{-2})
R_f	flame radius (m)
r	radial coordinate (m)
S	stoichiometric air–fuel molar ratio (–)
T	temperature (K)
$\dot{V}_f$	volumetric flow rate of fuel ($m^3\,s^{-1}$)
v_z	axial velocity (m s^{-1})
W_i	molecular weight of the species i (kg mol^{-1})
x_i	mole fraction of species i (–)
y	axial location
Y_S	soot mass fraction (–)
z	axial coordinate (m)
α_0	zero order regularization parameter
$\kappa_{S,\lambda}$	spectral absorption coefficient for soot (m^{-1})
λ	wavelength (m)
ρ	density (kg m^{-3})
$\phi_\imath$	collision efficiency factor of species i (–)
$\dot{\omega}_n$	reaction rate for the soot nucleation process (mol $m^{-3}\,s^{-1}$)
$\dot{\omega}_{sg}$	reaction rate for the soot surface growth process (mol $m^{-3}\,s^{-1}$)
$\dot{\omega}_{N_s}$	reaction rate for the soot number density (particle·$m^{-3}\,s^{-1}$)
$\dot{\omega}_{O_2}$	reaction rate for the soot oxidation process by O_2 (kg $m^{-3}\,s^{-1}$)
$\dot{\omega}_{OH}$	reaction rate for the soot oxidation process by OH (kg $m^{-3}\,s^{-1}$)
$\dot{\omega}_{Y_s}$	source term for the soot mass fraction (kg $m^{-3}\,s^{-1}$)

Subscripts

∞	ambient condition
ad	adiabatic
ag	agglomeration
f	formation
n	nucleation
OP	Onion–Peeling
ox	oxidation
R	radiation
sg	surface growth
S	soot
SP	smoke point
u	unburnt

flames showed that soot production was enhanced with increasing OI [7–11], thermal effects being the main cause for this enhancement [9,11]. Encouraging numerical predictions of flame structure and soot concentrations were also reported in oxygen-enriched counterflow configurations using either a detailed soot formation model [9] or two-equation semiempirical soot models [10,12,13].

Axisymmetric laminar diffusion flames were also experimentally and numerically investigated [3,14–16]. Bennett et al. [14] provided accurate predictions of oxygen-enhanced axisymmetric laminar methane flames by considering a fully coupled fluid flow/detailed chemistry numerical model. However, soot formation was ignored. Glassman and Yaccarino [15] investigated the influence of the OI on smoke point characteristics in ethylene diffusion flames experimentally. They found that the ethylene flow rate at the smoke point reached a maximum for an OI of 24%. Lee et al. [16] considered a well-characterized methane flame, and two other methane diffusion flames with the same volumetric flow rate of fuel and with oxygen enrichments of 50% and 100%, respectively. A reduction in the mass of soot particles within the flame in both enrichment conditions was observed, with larger reduction for the methane/100% oxygen flame. On the other hand, they found that the peak of soot volume fraction followed a non-monotonic evolution with the OI with a maximum for the methane/50% oxygen flame. Zelepouga et al. [3] used the same methane/air flame as Lee et al. [16] as a reference flame to study the influence of the addition of acetylene and polycyclic aromatic hydrocarbons (PAHs) on soot formation. Oxygen concentrations of 35%, 50%, and 100% were also considered. The authors also observed a reduction in the overall mass of soot particles in the three cases, whereas the peak of radially integrated soot volume fraction was found to increase between 21% and 35% and to decrease for OIs greater than 35%.

The aim of this paper is twofold: (i) To provide experimental measurements and analysis of flame height, soot volume fraction, smoke point characteristics, and radiative flux in laminar coflow ethylene diffusion flames by varying the OI from 17% to 35%. To the authors' best knowledge, such a comprehensive study concerning the effects of varying oxygen index on laminar coflow diffusion flames has not been reported in the past. The experimental conditions differ from those involved in [16] by considering a refined range of OI between 21% and 35% and extend them by dealing with underventilated configurations (OI in the range 17–21%). (ii) To assess the capability of a numerical model based on direct coupling between fluid flow and detailed gas-phase chemistry, a semiempirical two-equation acetylene-based soot model, and a state-of-the-art radiation model to predict flame structure, soot formation, and radiative flux in such configurations. The choice of a semiempirical two-equation model is justified by the fact that advanced PAH soot models involving detailed modeling of soot aerosol dynamics (see [17] as an example) remains probably too computationally expensive to be implemented in turbulent combustion codes in view of application to real fire situations and industrial problems. The experimental conditions present a severe test for the soot model, since soot production is modeled over a wide range of flame