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Experimental investigation of the flame extinction processes of nonpremixed methane flames inside an air coflow diluted with CO_2, N_2, or Ar

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The flame extinction processes and lifted flame stabilization features of nonpremixed flames issuing in diluted coflowing air were systematically examined under a wide range of aerodynamic conditions in order to reveal the competition between aerodynamics and dilution. Four diluents (CO_2, N_2, Ar, and CO_2 + Ar) were used in preparation for discriminating between the effects, namely, dilution, thermal action, and chemistry, induced by diluent addition. Flame extinction limits, ignition diagrams, liftoff height, and its associated apparent radius were investigated to provide key elements involved in lifted flame stabilization and extinction mechanisms with a diluted air stream. Flame extinction limits have been expressed as a 3D surface $E_{extinction}$ in the physical space $(Q_{diluent}/Q_{air}, U_{air}, U_{CH4})$. This surface is composed of two parts, a pure extinction surface where flame extinction is necessarily attained from lifted flames, and a common surface between flame lifting and extinction where flame extinction is achieved directly from attached flames. This distinct behavior is due to the presence of the semithick burner rim that protects the flame base. The flame ignition diagrams confirm that the pure extinction surface is independent of U_{CH4} for flames initially lifted without dilution. Furthermore, $(Q_{diluent}/Q_{air})/K_{diluent}$, where $K_{diluent}$ characterizes the capacity of a diluent to act on the flame destabilization process, has proved to be the affine parameter leading to a unified extinction surface for the tested chemically weak diluents. Moreover, by using $(Q_{diluent}/Q_{air})/K_{diluent}$, liftoff height H_L/H_L° and flame radius R_P/R_P° reduced by the no-dilution measures merge to unique self-similar curves whatever the diluents and aerodynamic conditions. The key element is the flame leading-edge burning velocity, which was found to be identical for diluted flames when the diluents were added into the air stream in the relative proportions given by $K_{diluent}$. In this way, it is possible to estimate flame behavior based on the results for CO_2, once $K_{diluent}$ is known.

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1. Introduction

Diluted combustion systems are widely used nowadays in (i) combustion systems using exhaust gas recirculation, which has proved to be an effective way of improving combustion efficiency and reducing emissions of pollutants such as NO_x; (ii) fire extinction. In our previous papers [1–3], the influence of air-side dilution on the attached flame stabilization mechanism, especially on its transition from attachment to liftoff, was studied carefully. Flame stability was shown to be greatly reduced by diluent addition through three main effects: pure dilution, thermal action, and chemistry. The present experimental study extends the preceding work by investigating experimentally the air-side dilution impact on the lifted flame stabilization and flame extinction processes.

Generally, lifted flame stabilization and flame extinction limits are of great importance, since they are involved in many industrial applications, such as burners in commercial boilers, where thermal damage to nozzle material is reduced by keeping flames away from the nozzle. Therefore, much research have been devoted to the stabilization of nonpremixed lifted flames. The review articles of Lyons [4], Lawn [5], and Aggarwal [6] summarize the main theoretical, numerical, and experimental work concerning lifted flames existing in different flow configurations such as free jets, coflow jets, and even inverse coflow jets. These research works also cover a wide range of flow velocities, and can be classified into three categories: laminar jets [7–9], organized jets [10,11], and turbulent jets [12–14]. Lifted flames are commonly described as partially premixed flames sustained by imperfect mixing between fuel and air flows above the burner exit [15]. They stabilize on the mean stoichiometric mixture contour where the local flow velocity matches the relevant flame burning velocity [13,16]. Various features of lifted flames, such as their responses to partial premixing or to jet instabilities, the dynamics of their leading edge (triple flame, propagation kernel, etc.), and the competition between the propagation edge and the trailing diffusion flame, have been

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thoroughly investigated to characterize stabilization of laminar [8,9,17] and turbulent flames [18–20]. Simultaneous PIV and CH-PLIF experiments have been performed to capture the velocity field at the flame base and the flame surface location. Among these authors, Muniz and Mungal [12] found that the instantaneous flame base is anchored primarily in a low-velocity region with a high gradient. It was shown that the secondary vortical jet structures contribute to the flame stabilization control [10,11]. For well-ordered jets in the transitional regime (from the laminar to a fully turbulent regime), the presence of a hysteresis zone where a flame can be either attached to or lifted above the burner leads to a less rapid liftoff height increase than in the fully developed turbulent region [10,11,21]. Flame liftoff height, H_L, considered as one of the main characteristic parameters qualifying flame stabilization, was found by Kalghatgi [22], in a free-jet configuration, to vary linearly with the exit jet velocity and to be independent of the burner diameter for a given gas. By plotting liftoff height measurements expressed by the nondimensional parameter $H_L S_L/\nu_{CH4}$ as a function of the nondimensional velocity $(\rho_{CH4}/\rho_{oxidant})^{1.5} U_{CH4}/S_L$, all the data obtained with several fuels were shown to merge on a single curve. S_L is the laminar flame burning velocity for the stoichiometric fuel–oxidant mixture. The experimental work of Cessou et al. [14] provided a large database of flame liftoff locations and their associated radii for different fuels and nozzle diameters measured by planar laser-induced fluorescence of OH radicals (PLIF-OH). Liftoff height and radius increased nonlinearly with exit jet velocity, but flame radius evolved linearly with liftoff height.

Once the mean flow velocity is too high to match the flame burning velocity, flame extinction occurs. Extinction can also occur through lack of fuel, a lean-limit phenomenon. Moore et al. [23] concluded that lifted flame blowout occurred when the leading edge of the reaction zone moved to a downstream region where the local fuel concentration was lower than the lean flammability limit. In practice, correct estimation of the lifted flame blowout limit is of great importance to prevent burner dysfunction. Kalghatgi [24] investigated the blowout limit, expressed as the critical fuel velocity at which extinction occurs, for nonpremixed jet flames developing in still air without confinement. Based on numerous data for several fuel types and a wide range of velocities, an empirical nondimensional formula giving the critical blowout velocity was proposed as a function of fuel and air densities, flame burning velocity S_L, injection fuel velocity, and distance along the burner axis where the mean fuel concentration fell to the stoichiometric level. Later, the influence of an air coflow was examined by Mungal and other researchers [12,13], who conducted flame extinction experiments inside a large vertical atmospheric furnace for various fuel and coflow air velocities. The blowout velocity was found to be greatly decreased when air velocity increased. Lifted flames blew out at nearly the same height (~190 mm) for the whole range of aerodynamic conditions ($U_{air} \leqslant 1.85$ m/s, $U_{CH4} \leqslant 50$ m/s). They presented a phenomenological blowout mechanism that relied on the flame leading edge stabilization mechanism such that the entire flame blew out if the specific axial velocity at the stoichiometric contour, a measure of the mixing between the jet and the surrounding field, was not sustainable by the flame base. Since the stoichiometric mixture fraction for most hydrocarbon fuels is small, the stoichiometric velocity is highly weighted to the coflow speed.

Dahm, with other researchers [25,26], chose a different approach to describe the extinction mechanism occurring in the far field, in which the physical properties of the initial fuel jet should not be taken into account, whereas ambient or coflow fluid physical properties should be involved. They proposed that the molecular mixing rate, expressed in terms of the associated far-field scaling laws, controlled the blowout characteristics of turbulent diffusion flames. For that purpose, they introduced a blowout parameter ε, equivalent to a Damköhler number, defined as the ratio of the local mixing time t_m over the chemistry time t_c able to determine the flame extinction limit when ε fell below a critical value.

Furthermore, studies on the impact of diluent additions have been strongly motivated by new combustion technologies where fuel-side or air-side dilution is involved. Most of these studies have focused on fuel-side dilution, in preparation for the use of biogas. For this purpose, Broadwell et al. [16] established a semiempirical formula to predict the modified extinction velocity of fuel-diluted flames by comparing their analytical results with data found in Kalghatgi's work [22]. These authors highlighted the important role played by the flame burning velocity S_L, which was decreased by fuel-side dilution, reducing the blowout limit. This was confirmed again through experimental work with hydrogen flames diluted by propane or by carbon dioxide.

As for the air-side dilution, which is widely involved in exhaust gas recirculation furnaces and in fire extinction, most of the research found in the literature limits investigation to a specified velocity condition, a high gas velocity in the case of industrial combustion furnaces or a low gas velocity in the case of fire safety. From a physical point of view, the main effects due to the addition of a chemically weak diluent can be classified into three families: pure dilution, thermal action, and chemistry [2,27]. A chemically weak diluent refers to a diluent that influences flame stability mainly by physical actions, such as dilution and thermal processes, or even by indirect and limited chemical effects (balance in some chemical equations is modified), which leads finally to reduced flame temperature (for details see [2]). On the other hand, a chemically active diluent refers to a diluent driven essentially by chemical aspects; it extinguishes flame through active reduction of reactive radicals, such as OH and CH, by means of their chemical neutralizations [28]. This weakens flame stability considerably. Takahashi et al. [29] compared the effectiveness of several diluents in extinguishing attached flames developing in very low-velocity configurations ($U_{air} = 0.1$ m/s and $U_{CH4} = 0.0092$ m/s). They concluded that the relative effectiveness between diluents is controlled by thermal aspects, characterized by the molar heat capacity C_p of the diluted oxidants. Again, in a low-velocity configuration ($U_{air} = 0.5$ m/s and $U_{CH4} = 0.5$ m/s), Lock et al. [30] noted that air-side dilution by CO_2 was much more effective than fuel-side dilution in extinguishing flames and also in increasing their liftoff height, since oxygen was the deficient reactant in their experimental configuration. Simulations by Briones et al. [31] revealed that as the diluent concentration was increased, the flame became weaker due to a reduced reaction rate at the leading edge; it moved downstream along the stoichiometric mixture fraction line. Guo et al. [2] emphasized the chemical effect on flame stabilization induced by the addition of CO_2, even though the effect is still less than that of pure dilution and thermal effects.

However, there is still a real lack of work dedicated to the combined effects of aerodynamics and air-side dilution, in particular, to highlight how flame stability (flame stabilization and extinction) is modified when the convection regime is driven from a natural regime (fire safety) to a forced one (industrial furnaces).

Based on our previous work concerning attached flames and lifting processes by air-side dilution, the present study deals with the influence of air-side dilution on flame extinction processes and lifted flame stabilization within a wide range of aerodynamic conditions. Here the methodology relies on the one implemented in [1]. CO_2 is chosen as the main diluent since its impact is crucial in industrial systems in which exhaust gas recirculation is involved, as well as in fire safety. Three other diluents are used for their complementary properties. They are helpful to interpret results: nitrogen (N_2), a thermally and chemically inert species, ar-

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