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Liftoff and extinction characteristics of fuel- and air-stream-diluted methane–air flames

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Abstract

Partial premixing of fuel and oxidizer is of common occurrence in fires. However, most previous studies dealing with flame extinction have focused on nonpremixed flames. In this experimental–numerical study, we examine the effectiveness of fuel-stream versus air-stream dilution for extinguishing laminar methane–air partially premixed (PPFs) and nonpremixed flames (NPF) using the chemically inert fire suppressant CO_2. Experimental measurements were made in lifted methane–air coflow flames, while both counterflow and coflow flames were simulated using a time-accurate implicit algorithm that incorporates detailed chemistry and includes radiation effects. Both measurements and simulations show that with fuel-stream dilution, PPFs stabilize at a higher liftoff height and blow out at a lower CO_2 dilution than NPFs. In contrast, with air-stream dilution, NPFs move to a higher liftoff height and blow out at a lower CO_2 dilution than PPFs. Despite different configurations, there is remarkable similarity in the extinction characteristics of coflow and counterflow flames with regard to the level of partial premixing and air- and fuel-stream dilution. The critical fuel-stream CO_2 mole fraction required for the extinction of both counterflow and coflow flames increases as ϕ is increased, i.e., as the level of partial premixing is reduced. Conversely, the critical air-stream CO_2 mole fraction decreases as ϕ is increased. Results also indicate a crossover value of $\phi \approx 2.0$, corresponding to the stoichiometric mixture fraction of $f_S = 0.5$, such that flames (including NPFs) with $f_S < 0.5$ are more difficult to extinguish with fuel-stream dilution, since oxygen is the deficient reactant, whereas flames with $f_S > 0.5$ are more difficult to extinguish with air-stream dilution, since fuel is the deficient reactant for these flames.

Keywords: Liftoff; Blowout; Extinction; Partially premixed; Laminar methane flames

1. Introduction

Flame extinction is important from both fundamental and practical considerations. Therefore, several analytical, numerical, and experimental investi-

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gations have focused on the strain-induced extinction of counterflow nonpremixed (NPFs) and partially premixed flames (PPFs) [1,2]. The counterflow geometry is useful since it affords control over both the strain rate and the flame position [3]. In this context, the agent concentration requirements for the suppression of counterflow flames at low strain rates are also of interest, because they may correspond to the corresponding requirements for axisymmetric cup burner flames [4] that more closely represent real fire scenarios. However, most previous studies concerning flame extinction have characterized the air-stream agent requirements for the suppression of NPFs. There have been relatively few investigations on the fuel-stream agent requirements for the suppression of NPFs and PPFs, especially in a cup burner or coflow configuration.

Bundy et al. [5] investigated the fuel- and air-stream agent (N_2, CO_2, and CF_3Br) requirements for the suppression of low-strain-rate counterflow NPFs and observed that the air-stream-diluted NPFs extinguish at lower dilution than the corresponding fuel-stream diluted NPFs. Trees et al. [6] investigated the extinction of NPFs using a chemical agent, CF_3Br (Halon-1301), and surmised that the difference between the fuel- and air-stream effectiveness of a diluent could be attributed to preferential diffusion effects. Since their diluent was not chemically inert, it is not clear if the difference between the fuel- and air-stream effectiveness of inert agents (such as N_2 and CO_2) could also be attributed to such effects.

Flame extinction generally occurs due to three effects [7], namely, by reducing the (1) deficient reactant concentration so as to affect the reaction rates (dilution effect); (2) flame temperature (thermal effect), which decreases the radical pool; or (3) free radical concentration and thus interrupting the flame chemistry (chemical effect) by adding a chemical agent, such as halon. In this context, CO_2, which is essentially chemically inert [8], can extinguish flames through both dilution and thermal effects. Halons have been successfully used as chemically active fire-suppression agents but have significant ozone depletion potential [9]. In addition, chemically active agents often generate substances in flames that prevent their use in occupied confined spaces. Therefore, CO_2 is considered in this investigation. It is also used as a fire-suppressant agent in the U.S. modules of the International Space Station.

There is a likelihood that unwanted fires can originate in a partially premixed mode when a pyrolyzed or evaporated fuel forms an initial fuel-rich mixture with the ambient air. It is often difficult to categorize such fires in terms of premixed flames or NPFs. In addition, catastrophic phenomena such as backdraft in building fires, which can have fatal consequences [10–12], are also promoted by partially premixed combustion [13]. Hence, partially premixed combustion is an important consideration in the context of fire safety [14]. Moreover, previous studies have shown that the structure of PPFs can be modified significantly by changing the level of partial premixing [15]. Consequently, it is important to characterize the effectiveness of fuel-stream dilution versus air-stream dilution in extinguishing flames that are established at different levels of partial premixing. There is, however, relatively little fundamental information available in the literature on the extinction characteristics of PPFs, since most previous investigations have focused on the extinction of NPFs. Moreover, previous studies, except for one reported by Seiser et al. [16], have not examined the effectiveness of fuel-stream dilution versus air-stream dilution in extinguishing flames, especially in the context of PPFs.

Motivated by the above considerations, we report herein on an experimental and numerical investigation that examines the effectiveness of air-stream versus fuel-stream dilution in extinguishing nonpremixed and partially premixed flames. Lifted, laminar methane–air flames were established in axisymmetric coflowing jets, and the chemically inert diluent, CO_2, was added either to the fuel stream or to the air stream. The diluent concentration was slowly increased until the lifted flame was extinguished (through blowout). For both air-stream and fuel-stream dilutions, the flame liftoff and blowout conditions were characterized for various levels of partial premixing in terms of the flame topology, liftoff height, and critical CO_2 mole fraction required for flame blowout. The CO_2-diluted axisymmetric NPFs and PPFs were also simulated using a time-accurate, implicit algorithm that uses detailed descriptions of chemistry and transport. The computed flame topology, liftoff height, and critical CO_2 mole fractions when flame blowout occurred were compared with measurements. In addition, CO_2-diluted NPFs and PPFs were simulated in a counterflow configuration and their extinction characteristics were investigated using various amounts of fuel- and air-stream dilutions. Here, our objective was to examine the similarity between the structures of coflow and counterflow flames at different dilution levels and the effect of geometry on their extinction characteristics.

It is important to distinguish between our study and that of Seiser et al. [16]. The cited study focused on the strain-induced extinction of PPFs in a counterflow configuration. In their case, the strain rate was continuously increased while keeping the equivalence ratio (ϕ) in one or both the streams fixed until the flame was extinguished. In contrast, we considered the dilution-induced extinction of lifted NPFs and PPFs in both coflow and counterflow configura-