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Lifted methane–air jet flames in a vitiated coflow

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Abstract

The present vitiated coflow flame consists of a lifted jet flame formed by a fuel jet issuing from a central nozzle into a large coaxial flow of hot combustion products from a lean premixed H_2/air flame. The fuel stream consists of CH_4 mixed with air. Detailed multiscalar point measurements from combined Raman–Rayleigh–LIF experiments are obtained for a single base-case condition. The experimental data are presented and then compared to numerical results from probability density function (PDF) calculations incorporating various mixing models. The experimental results reveal broadened bimodal distributions of reactive scalars when the probe volume is in the flame stabilization region. The bimodal distribution is attributed to fluctuation of the instantaneous lifted flame position relative to the probe volume. The PDF calculation using the modified Curl mixing model predicts well several but not all features of the instantaneous temperature and composition distributions, time-averaged scalar profiles, and conditional statistics from the multiscalar experiments. A complementary series of parametric experiments is used to determine the sensitivity of flame liftoff height to jet velocity, coflow velocity, and coflow temperature. The liftoff height is found to be approximately linearly related to each parameter within the ranges tested, and it is most sensitive to coflow temperature. The PDF model predictions for the corresponding conditions show that the sensitivity of flame liftoff height to jet velocity and coflow temperature is reasonably captured, while the sensitivity to coflow velocity is underpredicted.

Keywords: Laser spectroscopy; Multiscalar measurements; Computational modeling; Reactions in flames; Vitiated flow

1. Introduction

In practical combustion systems hot combustion products are often recirculated to enhance flame stability. Prediction of turbulent flames with complex recirculating flows can be a significant challenge for current combustion models. The vitiated coflow flame is a turbulent reacting flow within a hot environment but with a simplified geometry. It consists of a fuel jet issuing into a coflow of hot combustion products from a lean premixed flame. The coflow diameter is much larger than the central jet diameter. This large diameter isolates the central fuel jet from ambient air for a sufficiently long distance so that the computational problem may be cast as a two-stream flow. Therefore, the vitiated coflow burner allows detailed experimental and computational investigation of turbulent

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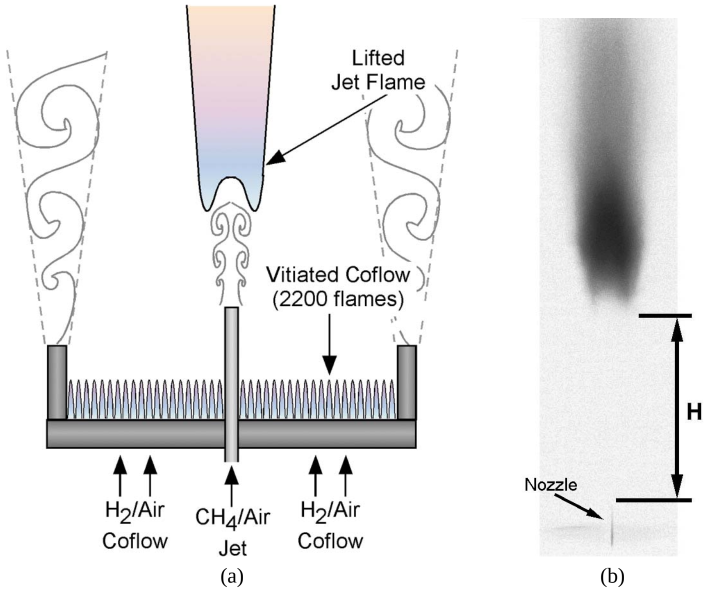

Fig. 1. (a) Burner schematic and (b) luminosity image (negative) of a lifted CH_4/air jet flame in vitiated coflow.

mixing and flame stabilization for a fuel flow in hot combustion products, while avoiding the additional complexities of recirculating fluid dynamics found in practical combustors or laboratory-scale swirl burners.

The present investigation of lifted CH_4/air jet flames is an extension of previous experimental and computational work on a lifted H_2/N_2 jet flame in vitiated coflow [1]. The H_2/N_2 and CH_4/air flames were selected to provide complementary experimental data to be used for evaluation of combustion models, with these methane cases following the kinetically simpler hydrogen case. As discussed in [1] and in recent computational studies of the H_2/N_2 case by Masri et al. [2] and Goldin [3], the vitiated coflow introduces autoignition as an additional possible mechanism of lifted flame stabilization. The liftoff height, which nominally corresponds to an average stabilization position of the flame, is sensitive to several flow and flame parameters, especially the coflow temperature as illustrated by a recent numerical study [4]. Therefore, the measured sensitivity of liftoff height to selected parameters is a useful basis for evaluation of combustion models, and this approach is used in the present work to test the probability density function (PDF) method of combustion modeling. Some features of the scalar structure of the H_2/N_2 flame are compared to those of the CH_4/air flame in the present paper.

Within PDF methods the mixing submodel remains an area in need of improvement (e.g., Pope [5] and Fox [6]). Past studies have examined the performance of available mixing models. For example, the modified Curl (M-Curl) mixing model [7] has performed well for turbulent jet flames of H_2 [8] and natural gas [9], as well as the H_2/N_2 lifted flame in vitiated coflow [1,2]. Subramaniam and Pope [10] found that the Euclidean Minimum Spanning Tree (EMST) model [11] outperformed the Interaction by Exchange with the Mean (IEM) model [11] for a flow with periodic reaction zones. Additionally, both the EMST [13] and the M-Curl [14] mixing models successfully predicted the piloted turbulent nonpremixed flames reported by Barlow and Frank [15]. The present study compares the performance of several mixing models in an environment that exhibits important similarities to practical combustor designs, in that there is mixing and flame stabilization of a turbulent fuel flow surrounded by lean combustion products. The CH_4/air jet flame is modeled by the joint scalar PDF approach using a series of mixing models, and experimental results are used to evaluate their relative performance.

2. Experimental methods

The vitiated coflow burner is shown schematically in Fig. 1a. The vitiated coflow was produced using a perforated plate (brass, 210-mm diameter and 12.7-mm thickness) as a premixed flame holder. A flow blockage of 87% was achieved by drilling 2200 holes (1.58-mm diameter) through the plate. Premixed H_2/air jet flames were stabilized on each hole, and their products mixed to form the vitiated coflow. An exit collar surrounded the coflow and served as a barrier that delayed entrainment of ambi-