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A unified view of pilot stabilized turbulent jet flames for model assessment across different combustion regimes

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Abstract

Single-regime turbulent combustion has been the main focus in previous studies. Significant limitations exist in those studies since most practical combustion applications involve multi-regime combustion. Developing and validating multi-regime turbulent combustion models are expected to be an emerging area with significant challenges. To facilitate model assessment across different combustion regimes, we develop a model validation framework by unifying several existing pilot stabilized turbulent jet flames in different combustion regimes. The characteristic similarity and difference of the employed piloted flames are examined, including the Sydney piloted flames L, B, and M, the Sandia piloted flames D, E, and F, a series of piloted premixed Bunsen flames, and the Sydney/Sandia inhomogeneous inlet piloted jet flames. Proper parameterization and a regime diagram are introduced to characterize the pilot stabilized flames covering non-premixed, partially premixed, and premixed flames. A preliminary model assessment is carried out to examine the simultaneous model performance of the large-eddy simulations (LES)/probability density function (PDF) method for the piloted jet flames across different combustion regimes.

Keywords: Multi-regime combustion; Piloted jet flames; Regime diagram; Model assessment; LES/PDF

1. Introduction

Most studies of turbulent combustion in the past have focused on a problem that is dominated by one regime of combustion. Practical combustion problems, however, are typically not in a single regime, and different regimes of combustion can occur simultaneously in the same combustion field. It is imperative to study multi-regime combustion to provide a detailed understanding of combustion processes that are of practical interest.

Past modeling studies of turbulent combustion have primarily focused on developing and validating models for a specific combustion regime. Typically a model that is suitable for one combustion regime cannot be used directly in another regime without significant modifications. The mixture fraction based models such as flamelet [1] and conditional moment closure (CMC) [2] are applicable to turbulent non-premixed combustion, although the idea of the modeling concept in flamelet

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and CMC can be borrowed for developing premixed combustion models [3,4]. The transported probability density function (PDF) model [5] does not embed strong assumptions about combustion regimes in the model when compared to other models such as flamelet, and in theory the model is potentially applicable to all combustion regimes although the current PDF model has been only tested in single regime combustion and some mixing models such as Euclidean Minimum Spanning Tree (EMST) [6] are originally developed for non-premixed flames.

The goal of this work is to establish a systematic framework for validating turbulent combustion models across different combustion regimes. The idea behind this work is largely based on the outcomes of the TNF workshop [7], and it is built upon the seminal work of the pilot stabilized jet flames. The piloted jet flames originate from the early work by Masri and Bilger [8], Masri et al. [9]. The Sydney piloted jet flames L, B, and M [9,10] are examples of early work. Later, the Sydney burner is used in the Sandia piloted flames D, E, and F [11] which received unprecedented attention from modelers. A similar burner is also used in the study of turbulent premixed Bunsen flames, the flames F1, F2, and F3 [12]. Recently, a series of new flames with inhomogeneous fuel jet inlet [13–15] is developed by introducing another tube that is retractable inside the Sydney pilot burner to produce variable fuel jet inlet conditions. Various combustion regimes can be produced from this series of new flames, ranging from non-premixed to partially premixed flames. The pilot used in the Sydney burner also appears in many other flames, such as the piloted premixed jet burner (PPJB) [16] and the Darmstadt stratified burner [17,18], which are not covered in the current work. In the present paper, the considered burners are limited to those which have methane as fuel issuing from the central fuel jet and cold air as the coflow.

In this work, we examine the similarity of these existing pilot stabilized turbulent jet flames and characterize this similarity through a set of parameters so that all the considered piloted jet flames can be viewed as flames in the same series. By doing so, we expect to be able to provide an innovative framework for validating turbulent combustion models across different combustion regimes. The specific objectives of the work are two folds: to provide a unified view of pilot stabilized turbulent jet flames across different combustion regimes, and to conduct a preliminary assessment of the LES/PDF method [19] in the unified piloted turbulent jet flames.

2. A unified view of piloted turbulent jet flames

Four cases of piloted turbulent jet flames are considered, including the Sydney piloted flames L, B, and M [9,10], the Sandia piloted flames D, E, and F [11], the piloted premixed Bunsen flames F1, F2, and F3 [12] , and the Sydney/Sandia inhomogeneous inlet jet flames [13–15].

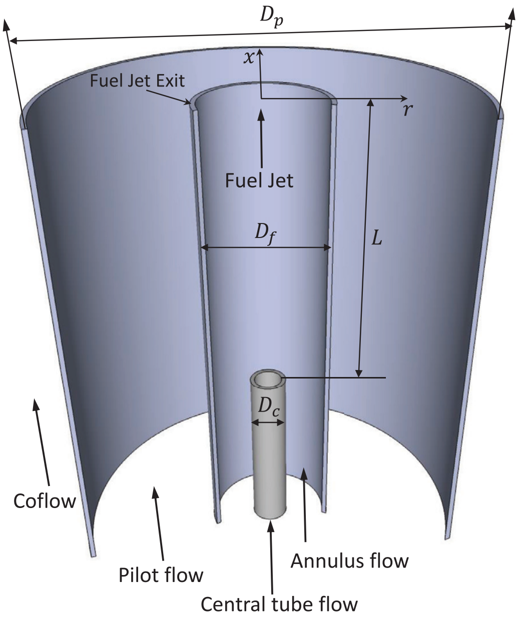

Fig. 1. The Sydney pilot flame burner [8,9]. Two concentric tubes are used, the fuel jet tube (D_f) and the pilot tube (D_p), to separate the fuel jet, the hot pilot flow, and the coflow air. The central tube (D_c) is a recent addition to the burner [13–15] to produce different stratifications in composition at the fuel jet exit with varying recession distance L. More information about the geometric parameters can be found in Tables 1 and 2.

2.1. Global characterization of piloted turbulent jet flames

A sketch of the pilot burner is shown in Fig. 1. For the four cases of piloted turbulent jet flames, Table 1 summarizes the dimension of the burner (D_f: the fuel jet pipe diameter; D_p: the pilot pipe diameter) and the Reynolds number based on the fuel jet bulk velocity, $Re_{f,b}$. The flames I1, I2, I3, and I4 denote the Sydney/Sandia inhomogeneous inlet jet flames [13–15] with their additional information summarized in Table 2. In these flames, the central tube in Fig. 1 is used, and it is retractable so that different recession distance L can be achieved. The central tube supplies CH_4, and the annulus supplies air in flames I1–I4. The retraction mechanism provides an adjustable level of partial mixing between CH_4 and air. The bulk velocities of the central tube $u_{c,b}$, of the annulus $u_{a,b}$, and of the fuel jet $u_{f,b}$ in flames I1–I4 are shown in Table 2.

The above four cases of flames on a pilot burner are from independent studies. In this work we draw the similarity of these different flames and provide