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Proceedings of the Combustion Institute 35 (2015) 1385–1392

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Impact of heat loss and hydrogen enrichment on the shape of confined swirling flames

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Available online 27 June 2014

Abstract

Shape transitions of swirling flames are often observed in combustion chambers operated at steady flow injection conditions. These transitions may alter pollutant emissions, heat fluxes to the chamber walls or the system stability. In adiabatic combustors, transitions between V and M shapes of swirling flames are controlled by the dynamics of stretched flame elements propagating through the reactants diluted by the burnt products in the outer shear layer of the swirling combustible jet in contact with the hot outer recirculation zone. The impact of H_2 concentration in the fuel and of heat loss at the chamber walls modifying the temperature in the outer recirculation zone are analyzed in this study for lean premixed CH_4/H_2/air flames. Laser induced OH fluorescence in different planes and particle imaging velocimetry are used to determine the probability of V to M shape transitions when the hydrogen concentration or the temperature of the combustor walls are modified. The wall temperatures are determined by laser induced phosphorescence and the temperature in the outer recirculation zone is inferred from thermocouple measurements. It is found that the probability of stabilizing a M flame increases with the H_2 concentration in the combustible mixture.. For the same laminar burning velocity, the flame featuring a higher extinction limit to strain rate has a higher probability to take a M shape. When combustion is initiated with cold chamber walls, the V to M flame transition probability is reduced compared to a situation with hot walls. During thermal transient and at steady state, it is shown that the temperature of the combustion chamber walls is an important factor controlling these shape transitions due to its impact on the temperature of the burnt gases in the outer recirculation zone. This study confirms that the topology of swirling flames is highly sensitive to heat transfer to the combustion chamber walls.

Keywords: Swirling flames; Non-adiabatic combustion; Flame shape transition; Thermographic phosphors; H_2 enrichment

1. Introduction

The shape taken by the flame in a steady operating combustor is an important feature that controls the uniformity of the temperature field in the

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http://dx.doi.org/10.1016/j.proci.2014.06.016
1540-7489/

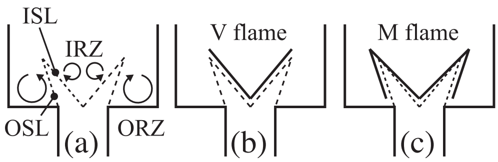

Fig. 1. (a) Schematic of a swirling jet flow in a combustion chamber with its inner (ISL) and outer (OSL) shear layers and the inner (IRZ) and outer (ORZ) recirculation zones. (b) V flame. (c) M flame.

burnt gases at the combustor outlet, pollutant emissions, heat fluxes to the combustor walls and to the injector, and that may alter the combustor stability with respect to thermo-acoustic oscillations. In technically premixed combustors with swirl injectors, flames generally have a V shape if the combustion reaction only takes place at the boundaries of the internal shear layer (ISL) of the swirling jet of reactants in contact with the hot internal recirculation zone (IRZ) of burnt products (Fig. 1a and b). If combustion also takes place between the outer shear layer (OSL) of the jet and the external recirculation zone (ORZ) of burnt gases, the flame stabilizes with a M shape (Fig. 1a–c). It is not unusual to observe flame shape transitions during operation of the combustor when the injection conditions are modified or after ignition of combustion during the warm-up phase even without changes of the flow injection conditions.

Experimental characterizations of these transitions are scarce mainly due to the difficulty to gather simultaneously quantitative information on the flow field and flame shape together with the proper thermal boundary conditions of the combustor. The objective of this study is to document such a flame topology transition in a well instrumented generic swirled combustor and analyze the impact of the chamber wall temperatures on this transition. It is shown that these data are needed to reproduce the correct behavior of flame stabilization during the warm-up phase of the combustor and that heat loss to the walls is an important mechanism controlling the flame shape for steady flow injection conditions.

It is now worth examining previous studies considering the stabilization of V and M flames. The shape taken by a laminar premixed flame stabilized in the wake of a solid surface results from a competition between the local flow velocity, the stretched flame speed and heat loss to the burner. Many studies have focused on the stabilization of V flames [1–5]. Simultaneous analyses of the stabilization of laminar V and M flames are more seldom [3,6]. It was found that these different shapes can be obtained by modifying the ignition location for the same flow conditions [7]. Kawamura et al. [3] and Mallens et al. [6] studied experimentally and numerically V and M flame shape transitions on a laminar unconfined burner. By increasing the flow velocity they found that the M to V shape transition is reached for a critical velocity gradient in the jet flow lower than the value necessary to reach the V flame blow-off limit.

In turbulent configurations, unconfined flames are mainly stabilized by a bluff body [8] or by imparting swirl to the flow [9,10] to create an IRZ that continuously provides hot burnt gases to the flame root and help stabilizing the reaction. Unconfined turbulent flames generally have a V shape and it is difficult to identify situations with unconfined turbulent M flames fed by hydrocarbon combustible mixtures. For high injection Reynolds numbers, the strain rate in the OSL and ambient air entrainment diluting the reactive stream of gases are generally too important to stabilize a reaction layer in this region [8,11,12], even in strongly swirling flows [13].

By confining the flame, the ORZ of hot burnt gases generated in the corners of the injection plane and chamber walls helps stabilizing the flame. Swirling V flames are only stabilized in the ISL formed by the jet flow and the IRZ (Fig. 1b). A flame with a root in the IRZ and featuring a tip protruding in the ORZ is called a M flame (Fig. 1c). This supplemental flame front may eventually reach the injector lip [14]. In this study a M flame is defined as a swirling flame stabilized in the two shear layers comprised between the IRZ and ORZ. Hence, a V-shaped flame does not interact with the OSL formed between the swirling jet and the ORZ.

Transitions between these shapes are often observed as the flow operating conditions of the combustor are modified [15], but the governing mechanisms are not well understood. In partially premixed system, Kim and Hochgreb [16] found that fuel stratification has a strong influence on the flame topology for the same fuel mass flowrate injected. Kim et al. [14] showed that hydrogen addition to a hydrocarbon/air swirling flame modifies the propensity of the flame to switch from a V to a M shape. They indicate that this bifurcation is partly controlled by the flame speed increase resulting from hydrogen addition. By increasing the inlet combustible mixture temperature in their simulations, Huang and Yang [17] identified a V to M flame transition triggered by flashback in the boundary layer along the combustor wall. Guiberti et al. [18] showed the influence of the Lewis and swirl numbers on this type of transition. It was also found that this mechanism ceases when the V flame tip lies far away from the solid chamber walls. Tay Wo Chong et al. [19] analyzed numerically effects of strain and heat loss on flame stabilization in a non-adiabatic combustor. They had to take into account heat loss and stretch effects in their simulations to reproduce the correct V shape