Fuel 160 (2015) 366–374

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Numerical study of the effects of the channel and nozzle wall on the transition behavior of a methane tribrachial flame in a confined flow

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HIGHLIGHTS

- The effects of the channel and nozzle wall are studied for a CH_4 tribrachial flame.
- The flow boundary layer of the nozzle wall contributes to the flame's instability.
- The hot channel heated by the flame causes extra flow redirection upstream.
- The flame location depends on the tradeoff between the trends induced by the channel.
- The boosted production of H accounts for the intensification of combustion.

ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form 14 July 2015
Accepted 31 July 2015
Available online 6 August 2015

Keywords:
Partially premixed combustion
Tribrachial flame
Methane
Transition behavior
Fluid solid coupling

ABSTRACT

In a confined combusting flow, the solid wall is heated by the flame, which in turn affects both the hydrodynamic and chemical characteristics of the flow, and hence the behavior of the flame. In this study, the transition behavior of a methane air tribrachial flame in a confined flow is numerically studied on the basis of fluid solid coupling and multi-step mechanism. The effects of the channel and nozzle wall on both the cold and reacting flows are investigated. The obtained results show that the boundary layer of the nozzle wall causes a velocity variation. This variation accounts for the jump in the final axial location of the triple point between the attached and lifted states. In a sufficiently narrow channel, the following may be concluded. (1) The influences of the incoming velocity and premixing of the center jet on the stoichiometric contour become remarkable. (2) The thermal expansion of the unburned mixture caused by heat transfer from the hot channel wall and the nozzle's flow boundary layer results in extra flow redirection upstream from the flame front. (3) The channel wall heated by the flame accelerates the unburned mixture, which causes the flame to propagate downstream, and intensifies the combustion in the nearby region to help the flame propagate upstream. The final location of the flame front depends on the tradeoff between these two factors. (4) The production of H is remarkably boosted in every major route, resulting in the intensification of elementary reactions that consume fuel and oxygen, including the key chain branching reaction R35 ($H + O_2 \rightarrow O + OH$).

1. Introduction

Partially premixed combustion has been widely researched in laboratorial [1] and industrial combustors [2]. Even in typical premixed or diffusion combustors, a certain extent of partially premixed flames is inevitable, such as the autoignition fronts in internal combustion engines [3]. Owing to its widespread application, considerable research has focused on the partially premixed flame from both environmental protection and engineering perspectives, covering flame behaviors in furnaces [4], porous media [5], and direct injection spark ignition (DISI) engines [6].

In contrast to premixed or diffusion flames that contain a single reaction zone, the partially premixed flame is a hybrid flame characterized by "multiple reaction zones." As shown in Fig. 1, the tribrachial (or triple) flame is a typical type of partially premixed flame consisting of fuel-lean and fuel-rich premixed branches and a trailing diffusion flame located at the "tribrachial (or triple) point" where the three branches combine. These premixed and diffusion flame branches are separated and can be easily distinguished. However, they are synergistically coupled through hydrodynamic and chemical interactions. The disappearance or

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http://dx.doi.org/10.1016/j.fuel.2015.07.109
0016-2361/

Nomenclature

D	inner diameter of the channel	Φ_{jet}	equivalence ratio of the center jet
d_{jet}	inner diameter of the center-jet nozzle	V_0	incoming velocity of the mixture
Φ_{co}	equivalence ratio of the coflow		

appearance of a certain branch significantly influences the macroscopic properties of a tribrachial flame.

For the case of a stoichiometric laminar premixed flame, as the fuel concentration gradient increases, the flame front curves and becomes tribrachial, accompanied an increase in the propagation velocity [7]. With the additional increase in the fuel concentration gradient, the flame shape evolves asymmetrically, becoming bibrachial [8] and monobrachial finally [9]. The flame propagation velocity decreases along with that transition. In Kim's study [10], the fuel concentration gradient peaks the propagation velocity was suggested to be a criterion of transition between premixed flames and triple flames. Aside from the premixing condition, the transition of a partially premixed flame can also be attributed to the vortex [11], fuel type [12], inertial dilution [13], buoyancy [14], etc.

To the best of our knowledge, detailed studies on the characteristics of tribrachial flames have been conducted, as reviewed by Buckmaster [15], Chung [16], Lyons [17], and Aggarwal [18]. However, few studies have investigated the transition behavior of the tribrachial flame in a confined flow. In a confined flow, the interaction between the flame and the channel wall becomes significant. Miesse et al. [19,20] experimentally studied the flame cells in a microscale combustor and observed a tribrachial structure with a very short diffusion tail near the top of the burner. They argued that the main cause of that structure was that the lead-edge of tribrachial flame was more able to withstand the heat loss to the wall than the trailing diffusion flame. By changing the flow rate in a mesoscale channel, Xu and Ju [21] discovered a transition between an unsteady bimodal flame regime and a tribrachial flame street regime. They suggested that a series factors of heat loss, curvature, diffusion and dilution effect contributed to that transition. In addition to the development of microscale and mesoscale combustors, studies of tribrachial flames in laboratory-scale burners involving a confined channel offer an alternative way to understand the characteristics of non-premixed flames under different flow conditions. Lee and Kim [22] investigated the stabilization of a methane air tribrachial flame in a confined flow and indicated that the applicability of the edge-flame theory in open space to confined case was acceptable and would be improved by considering the effects of heat loss, shear stress and dead space near the wall. In Cho's study [23], the transition in tribrachial flame structure accompanied with change in propagation velocity in confined condition was experimentally investigated. The results showed that the coupling effect mechanism between heat loss and flow redirection played a key role in the variation of the flame behavior. Mulla and Chakravarthy [24] reported the variation in the curvature of a tribrachial flame stabilized in a confined splitter plate burner as the flame structure transitioned form that of a nearly diffusion to a nearly premixed flame. During the transition, the peak flame speed was primarily dictated by the effect of the non-premixed branch heating the leading edge. By adopting adiabatic wall condition in a numerically research, Dobrego et al. [25] focused on the role of the channel width in the tribrachial flame propagation. The results showed that the flame velocity increased with the channel width and came to saturation at a critical width which could be expressed by a function of flame front width and mixing degree. According to Lee and Chung [26], the lift-off of a free jet flame using fuel with a Schmidt number in the range of 0.5 to 1, such as methane or ethane, was physically unrealistic. Hence, the influence of the nozzle wall could not be ignored in the case of an attached flame and worth further investigation. It has been reported that the tribrachial flame stability depended strongly on the burner geometry, such as the jet spacing of counter-flow burner [27] and nozzle diameter of jet burner [28].

To extend our understanding of the transition behavior of a methane air tribrachial flame in a confined flow, a numerical investigation of the effects of the channel and nozzle wall on the physical and chemical aspects of the tribrachial flame is carried out in this study under various conditions of flow field velocities and equivalence ratios based on the fluid solid coupling.

2. Numerical model

The results in this work are obtained by solving the governing equations for steady state in FLUENT. A schematic of the computational domain and the boundary conditions are illustrated in Fig. 2. The dimensions are between 25.5 mm (r) × 25 mm (x) and 15.5 mm (r) × 50 mm (x) for different flow field scales. The rich and lean premixed methane air mixtures enter the flow field through a central tube and coflow annular region, respectively.

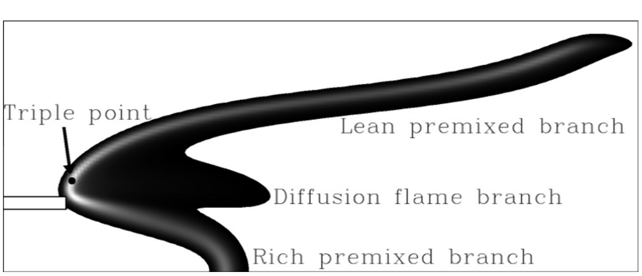

Fig. 1. Structure of a tribrachial flame.

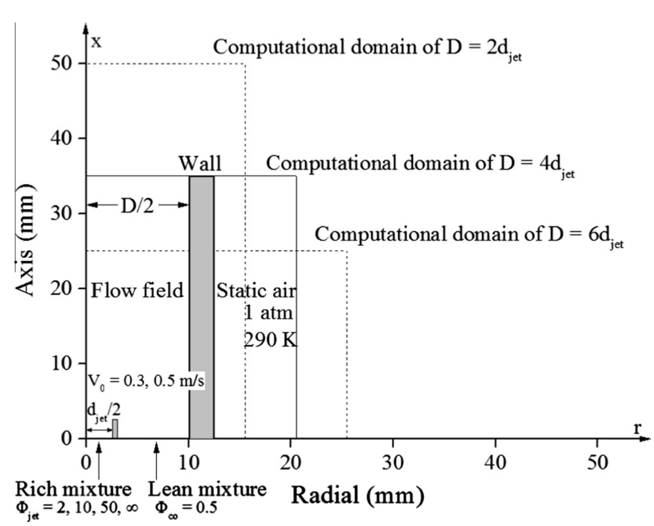

Fig. 2. Computational domain and boundary conditions.