International Journal of Heat and Mass Transfer 102 (2016) 219–225

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental study of bluff body stabilized laminar reactive boundary layers

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ARTICLE INFO

Article history:
Received 19 March 2016
Received in revised form 13 May 2016
Accepted 10 June 2016

Keywords:
Non-premixed flames
Bluff body stabilization
Flame stability map
Hysteresis effect
Hydrogen

ABSTRACT

Experiments have been carried out to analyze the characteristics of laminar cross-flow methane–air diffusion flames in the presence of bluff bodies. The stable operating regime having steady and oscillating flames, and unstable operating regime that includes flame blow-out and extinction, are identified by varying the air and fuel flow rates systematically. Detailed stability maps indicating these regimes have been proposed for bluff bodies having rectangular, isosceles triangular and semicircular shapes. Three types of flames, namely plate stabilized, bluff body stabilized and separated flames, have been captured using a high-definition digital camera. The flame anchoring locations, flame shapes and transitions between different regimes of stabilization have been analyzed thoroughly. Hysteresis effects in the transition between the regimes, when the air flow rate is systematically increased or decreased, are also presented in the stability maps. The interesting features of the semicircular cylinder bluff body have been discussed in comparison to other two bluff bodies. Additionally, the effect of addition of hydrogen in small quantities to methane has also been envisaged. When 10% hydrogen by volume is added to methane, the plate stabilized regime is seen to be widened. Also, the hysteresis effect is seen to reduce with the injection of hydrogen.

1. Introduction

Flame stability for a wide range of operating conditions is the primary requirement for a non-premixed burner. The mixing of fuel with oxidizer and the flow residence time can be enhanced by using bluff bodies that create recirculation zones in the flow field. Even under laminar flow conditions, for a cross-flow diffusion flame, a bluff body is seen to increase the stable operating regime and control flame oscillations. Therefore, a thorough knowledge of flame stability regimes in the presence of cylindrical bluff bodies of various shapes and dimensions is essential in the design of combustion chambers, which employ non-premixed mode of combustion. Experimental studies can be more convenient and reliable in generating such detailed flame stability maps.

The earliest study reporting cross-flow diffusion flame is the similarity solution for the two-dimensional reactive boundary layer over a flat plate by Emmons [1]. This work inspired many experimental and theoretical studies on laminar cross-flow diffusion flames (Mori [2]; Sparrow and Minkowycz [3]; Lavid and Berlad [4]; Torero et al. [5]; Ha et al. [6]). Investigation on the stability limits for the bluff body flame holders was reported by Filippi and Mazza [7]. Experiments were conducted over a wide range of fuel flow rates and equivalence ratios to analyze blow-out limits. Sergeev et al. [8] conducted theoretical and experimental studies on evaporation and reaction with liquid fuel injected to an external oxygen stream considering multi-component diffusion. A mathematical model for studying flows around bluff body flame holders was proposed by Kundu et al. [9]. Velocity and stream function distribution around three bluff bodies, a plate, a cylinder and a wedge, were studied. Hirano and Kanno [10] conducted experiments on cross-flow diffusion flames by injecting a gaseous fuel through a horizontal porous plate kept parallel to an almost uniform air stream. Significant acceleration of the gas stream around the flame zone was observed inside the laminar, two-dimensional, reacting boundary layer. Velocity and temperature profiles were measured and the pressure distribution was calculated. Gravitational effects on boundary flows over a horizontal flat plate were clarified theoretically by Lavid and Berlad [4] and experimentally by Ueda et al. [11].

Several aspects of bluff body stabilized flames have been extensively investigated by several other researchers. Early experimental (Nicholson and Field [12]; Williams and Shipman [13]; Williams et al. [14]; Zukoski and Marble [15]; Maxworthy [16])

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.028
0017-9310/

and theoretical (Cheng and Kovitz [17]; Kovitz and Fu [18]) studies paved the foundation for future investigations in bluff body flame stabilization. Stability limits and flame anchoring positions for different bluff body flame holders were reported in these works. Importance of the composition of the mixture in the wake region of bluff body and the nature of the recirculation zone were systematically established in the experimental studies. Nicholson and Field [12] investigated flame stabilization in the wake of a bluff body using high speed schlieren and shadowgraph images and revealed the dynamics of the flame front during ignition and blow-off. This inspired further experimental and theoretical investigations of flow-flame interactions. Williams and Shipman [13] carried out experimental studies on rod stabilized flames. The flame stability was shown to depend on the nature of recirculation zones. Not surprisingly, the shape of the bluff body placed in the flow was observed to play a major role in the flame stabilization. Further studies of the stability characteristics of bluff body flame holders were carried out by Williams et al. [14]. Fan et al. [19] used a bluff body to extend blow-off limit in a micro combustor. The effect of flow, heat transfer and their interactions with flame were revealed by their experimental and numerical studies.

Experimental studies were carried out by Rohmat et al. [20] using different obstacles (backward facing step and rectangular cylinders) of different dimensions, positioned at different locations upstream of the horizontal fuel injector, injecting fuel perpendicular to the air stream. The regimes of flame stabilization were explained using stability maps plotted with air and fuel flow velocities as the coordinate axes. Following Rohmat et al. [20], numerical investigations of three types of flames behind a rectangular cylinder have been reported by Shijin et al. [21] to explain the physics of flame stabilization in different regimes.

Combustion characteristics of lean premixed hydrogen/air flame in a micro-combustor with a triangular bluff body were analyzed by Wan et al. [22]. Following them, Fan et al. [23,24] numerically investigated the effect of bluff body shape on the flame blow-off limit using triangular and semicircular bluff bodies placed in a planar micro combustor. Significant improvement in the blow-off limit was observed with the introduction of bluff-bodies. The effect of blockage ratio was also analyzed in their CFD simulation.

Even though flame stability maps have been reported earlier (Rohmat et al. [20]), the effect of the shape of the bluff body on flame stabilization and the hysteresis effect observed during transition from one stability regime to another due to increasing or decreasing flow rates, have not been reported in literature. This provides the motivation to carry out experimental studies to reveal different regimes of stabilization in the presence of bluff bodies having different shapes. A semicircular bluff body, which does not have any sharp edge or fixed vortex shedding location, is considered in the present study, in addition to rectangular and triangular bluff bodies. A suitable bluff body height and position are identified based on the experimental results of Rohmat et al. [20] for similar combustor geometry. Additionally, the effect of addition of a small quantity of highly reactive fuel such as hydrogen on stabilization is also studied.

2. Problem description and methodology

An experimental setup is designed and fabricated with a settling chamber, a test section, air and fuel supply systems as shown in Fig. 1. The design of the test section is based on that of Rohmat et al. [20]. A porous plate made of 99.8% alumina, having mean pore size of 35–50 microns and, with dimensions 70 mm × 19 mm × 10 mm, is placed in the slot for fuel injection. The side walls are fitted with quartz windows to visualize the flame. Methane gas, with a purity of 99.97%, is supplied normal to the air stream. A calibrated digital mass flow controller is used to regulate the flow rate of methane. The average air and fuel flow

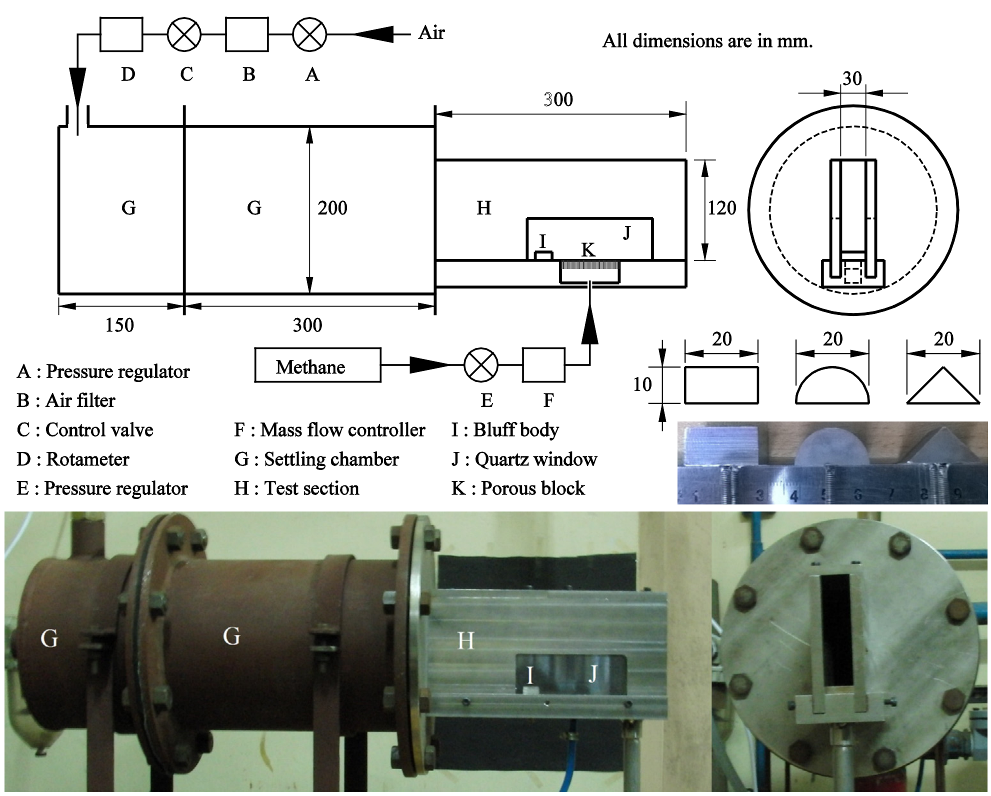

Fig. 1. Schematic (top) and photograph (bottom) of the experimental set-up. Scaled front views of the bluff bodies are also shown.