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Full Length Article

Experimental study of flame characteristics and stability regimes of biogas – Air cross flow non-premixed flames

A. Harish[a], H.R. Rakesh Ranga[a], Aravindh Babu[b], Vasudevan Raghavan[a,*]

[a] Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[b] Department of Mechanical Engineering, National Institute of Technology, Trichy, India

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ABSTRACT

Biogas is an alternative fuel that typically contains around 45% carbon-dioxide by volume, besides methane. Due to the inherent content of carbon-dioxide, it is necessary to study the flame characteristics and stability limits in cross-flow non-premixed burners. In this study, cross-flow non-premixed flames, where biogas is injected through a horizontal porous plate and air is blown parallel to the fuel injector, are studied systematically. In order to increase the stable operating regime, devices such as backward facing steps and cylindrical bluff-bodies are commonly employed. Different step-heights and locations from leading edge of the fuel injector are considered for the cases with backward facing steps. A rectangular cylindrical bluff-body is also used as a flame stabilizing obstacle. Baseline cases are studied without any backward facing step or cylindrical bluff-body. Volume flow rate of biogas is varied from 36 liter per hour to 360 liter per hour. Air velocity is varied in the range of 0.2 m/s to 3.0 m/s. For a given fuel velocity, air velocity is gradually increased in order to record the transition of flame from one regime to another. Flame stabilization is carefully assessed by monitoring the high definition direct flame photographs captured from front and top views, for all the cases. The cases are repeated at least three times to ensure repeatability. Stability maps are plotted as a function of fuel velocity and air velocity for all the cases. For cases with backward facing steps, both step height and its location play an important role in delineating the boundaries of the flame regimes. Parametric variations show interesting features. Bluff-body flames become quite oscillatory and three dimensional at higher air velocities. For this case, stability maps of flames from biogas and pure methane are compared.

1. Introduction

Non-premixed flames are safer and easier to handle. However, proper methodologies are necessary to ensure mixing of fuel and air and provide flame anchor region. These vary with the type of the burner. Cross-flow configuration, where fuel and air are injected perpendicular to each other, is used in several industrial furnaces and boilers. This configuration is popular due to the presence of a simple boundary layer type reacting layer. Based on the air and fuel feed rates, different regimes of flames are obtained and at a certain range of air and fuel flow rates, flames become unstable and even blow off.

Biogas is an alternative fuel that mostly constituted by around 45% carbon-dioxide and 55% methane. Other species like nitrogen, hydrogen sulfide, hydrogen, oxygen, carbon monoxide are present in trace amounts. The percentages of major constituents of biogas, methane and carbon dioxide, depend on the source from which biogas is produced. Biogas obtained from landfills has 45%–62% methane and 24%–50% carbon-dioxide, biogas obtained from sewage digesters have 58%–65% methane and 33%–40% carbon-dioxide and biogas obtained from organic waste digesters typically have 60%–70% methane and 30%–40% carbon-dioxide [1]. In India, it is produced from animal wastes such as cow dung and typically contains around 45% carbon-dioxide and 55% methane. It is used for domestic cooking in rural areas. Due to the inherent content of carbon-dioxide, which is generally an inert with a high specific heat, and also a radiation absorbing gas, it is necessary to study its flame characteristics and stability limits. In this study, cross-flow non-premixed biogas – air flames are studied systematically. In order to increase the stable operating regime, devices such as backward facing steps and cylindrical bluff-bodies are commonly employed. Such devices are used to study how they improve the stability limits and increase the operating range (turn-down ratio).

Mori [2] presented one of the earliest studies in laminar convective flow over a horizontal flat plate and it was followed up by Sparrow and Mincowycz [3]. They predicted the roles of the Grashoff, Reynolds and Prandtl numbers in laminar flow over a flat plate. Lavid and Berlad [4] explored the area further with their mathematical model of a reacting

* Corresponding author.
E-mail address: raghavan@iitm.ac.in (V. Raghavan).

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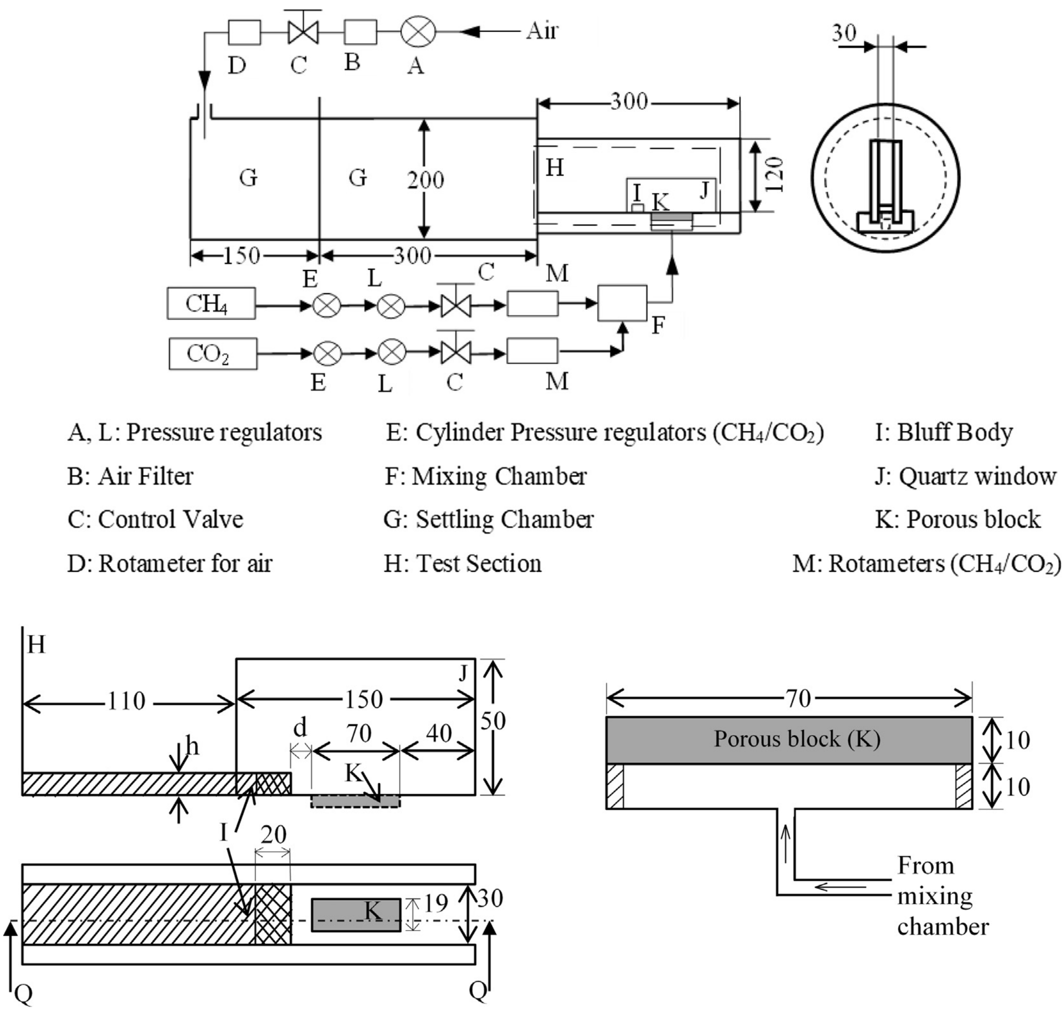

Fig. 1. Schematic of the experimental setup (top) and details of dimensions of obstacles and fuel injector (bottom). Cross hatch indicates rectangular cylinder bluff-body.

laminar boundary layer flow over a flat plate. Ramachandra and Raghunandan [5] experimentally studied the stability and extinction limits of laminar cross-flow diffusion flames. Effects of free stream temperature, oxygen and fuel concentrations, and injection velocity on stability limits have been studied. Hirano and Kanno [6] and Miller et al. [7] studied the effects of buoyancy, free stream velocity, presence of an obstacle such as backward-facing step, on flame stability through their experiments. These were investigated numerically by Wang et al. [8], and Gopalakrishnan and Raghavan [9].

The first known study to bring out the effects of the presence of a bluff-body in a laminar cross-flow diffusion flame was by Nicholson and Field [10]. Experimental techniques were developed to investigate the flame stabilization mechanism in the wake region of a bluff-body. This work was complemented by Williams and Shipman [11], where it was established that the flow pattern in the wake of an un-streamlined object plays an important role in stabilization of the flame. Theoretical understanding of flame stabilization using bluff-bodies was established by the works of Cheng and Kovitz [12], and Kovitz and Fu [13]. Experiments regarding the same were performed by Filipi and Mazza [14], and Maxworthy [15]. Mathematical modelling of flame stabilization using bluff-bodies was reported by Kundu et al. [16]. Analytical treatment of the phenomenon was reported using computational methods such as upwind based finite difference schemes, where approximate estimations of turbulence and combustion were reported.

Rohmat et al. [17] published a comprehensive experimental work paving insights into the behavior of laminar non-premixed cross-flow flames in the presence of backward facing steps and bluff-bodies. Stability maps in the coordinates of fuel and air velocities were reported and analyzed in detail. Shijin et al. [18] showed the importance of Damköhler number in analyzing the anchoring of the flame zone in the presence of a bluff-body. Detailed numerical study of non-premixed laminar cross-flow methane-air flames in the presence of a cylindrical bluff-body was carried out. The flame stabilization phenomenon was explained using the predictions of the flow, temperature, species and reaction fields. Shijin et al. [19] presented detailed insights into the effect of flame-vortex interaction on the unsteady dynamics of a separated flame. Further, Shijin et al. [20], extended the experimental work of Rohmat et al. [17] and experimentally investigated the characteristics of laminar cross-flow methane-air diffusion flame in the presence of bluff-bodies of different shapes, namely, rectangular, isosceles-triangular and semi-circular. The effect of addition of hydrogen to methane-air flame on flame stability was also studied. Wilson and Lyons [21] reported experimental results of turbulent, lifted, non-premixed flames in co-flow, and with dilution. Implications for several flame stabilization theories were reported along with biogas combustor design considerations. Keramiotis and Founti [22] presented a comprehensive experimental study on a porous burner fuelled with a simulated biogas mixture, and showed results in terms of thermal efficiency and pollutant emissions. Strong physical effects of the CO_2 addition was discussed in comparison to its chemical effects. Saediamiri et al. [23] experimentally studied the stability of turbulent non-premixed biogas flames by varying the fuel composition (carbon dioxide content in the mixture of CH_4 and CO_2) and altering the fuel nozzle geometry. Semi-empirical correlations capable of describing the flame stability limits