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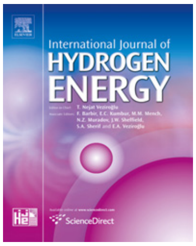

Combustion characteristics of natural gas–hydrogen hybrid fuel turbulent diffusion flame

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ABSTRACT

Combustion characteristics of natural gas – hydrogen hybrid fuel were investigated experimentally in a free jet turbulent diffusion flame flowing into a slow co-flowing air stream. Experiments were carried out at a constant jet exit Reynolds number of 4000 and with a wide range of NG–H_2 mixture concentrations, varied from 100%NG to 50%NG-50% H_2 by volume. The effect of hydrogen addition on flame stability, flame length, flame structure, exhaust species concentration and pollutant emissions was conducted. Results showed that, hydrogen addition sustains a progressive improvement in flame stability and reduction in flame length, especially for relatively high hydrogen concentrations. Hydrogen-enriched flames found to have a higher combustion temperatures and reactivity than natural gas flame. Also, it was found that hydrogen addition to natural gas is an ineffective strategy for NO and CO reduction in the studied range, while a significant reduction in the %CO_2 molar concentration by about 30% was achieved.

1. Introduction

In today's world, the problem of climatic change is one of the serious drawbacks driving mainly from the emission of large quantities of CO_2, the inevitable product of fossil fuel combustion [1]. This is not the only environmental hazard from fossil fuels, but its emission of noxious gases such as NO_x, CO and SO_2, results in critical environmental problems throughout the world [2]. In addition, the declining of fossil fuels supplies at an alarming rate exhibits the desire to use it economically [3]. In view of these problems, it will unquestionably require long-term changes in the fuels and technologies that we use to meet our energy needs. Hydrocarbon- hydrogen hybrid fuel has become as an attractive option for reducing the dependency on the fossil fuels, and provides a transition strategy to carbon free energy systems.

The choice of hydrogen as an essential participant in hybrid fuels is due to: firstly, its superior combustion characteristics such as wide flammability range, high laminar flame speed, and low ignition energy, in addition to its high molecular diffusivity [4,5]. Secondly, the environmental benefits of its combustion, as there is no CO_2, CO, SO_x and UHC emissions. Furthermore, hydrogen can be produced from a variety of feedstocks; from fossil resources and renewable resources [6]. In that manner, the utilization of hydrogen in blended form would reduce the problems of storage and flashback [4].

NG–H_2 hybrid fuel, in particular, became the subject of extensive research in recent years. A series of experimental and numerical investigations has been done to present a clearer understanding for its combustion characteristics.

Addition of hydrogen to natural gas combustion showed an increase in flame adiabatic temperature, a reduction in flame thickness and quenching distance and further enhances the auto-ignition characteristics and the global rate of heat release [7–10].

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Ilbas et al. [11] studied experimentally the influence of hydrogen enrichment on the natural gas laminar flame properties. They stated that increasing the hydrogen percentage in mixture caused an increase in the resultant burning velocity and also widening the flammability limits. So, adding hydrogen to natural gas can extend the combustion lean operation limit [12]. Such technique is currently recognized as an effective approach to fuel economy and NO_x emission reduction. Improvement of the natural gas flame stability behavior with hydrogen addition was a focal point of study for pre-mixed [13] and diffusion [5,14,15] flames.

Kumar and Mishra [16] performed an experimental investigation on laminar LPG-H_2 jet diffusion flame and observed an insignificant variation in the visible flame length upto 20% of hydrogen addition, but a subsequent reduction in the flame length was observed for the higher hydrogen concentrations. However, a continuous reduction in the NG-H_2 turbulent flame length with hydrogen addition was confirmed by Choudhuri and Gollahalli [17].

It is clear that the flame structure characteristic were deeply investigated. The height of the blue cone, a main parameter depicts the flame structure, was studied in different investigations [5,18]. It was observed that the height of the blue cone decreased significantly when the amount of hydrogen increased. Choudhuri and Gollahalli [4] explained in detail the flame structure in terms of in-flame profiles of temperature and composition at three axial locations of the flame.

As reported by Choudhuri and Gollahalli [17] a significant reduction in both CO emission and soot concentration with hydrogen addition was noticed in the turbulent jet diffusion flame. The tests of Burbano et al. [18] on two different atmospheric burners also affirmed the same issue. On other side, the results of Cozzi and Coghe [5] in a NG–H_2 diffusion swirled flame and Kumar and Mishra [16] in a LPG–H_2 laminar diffusion flame observed an increase in CO and soot concentrations with the increase of hydrogen content in the fuel stream.

Several attempts [4,5,19,20] have been made to predict the change of NO_x emission behavior in the NG-H_2 flame. All of these researches agreed upon that NO_x emission increases with hydrogen addition. However, they disputed about the formation mechanism responsible for the increase of NOx emission. Rortveit and Hustad [20] conducted a numerical and experimental study of counterflow NG/H_2 – air partially premixed flame. They evaluated the contributions of the thermal and the prompt NO_x mechanisms in the total NO_x formation and found that the prompt NO_x route was the main contributor. In contrast, the results of Naha and Aggarwal [19] confirmed that the thermal NO_x was more dominant than the prompt NO_x for the same flame configuration.

Although the above survey manifests many substantial efforts that have been devoted to investigate different characteristics of NG–H_2 hybrid fuel, a comprehensive understanding for its behaviors under the different operating conditions has not been yet consummated. Therefore, the author present a closer study to investigate experimentally fundamental combustion characteristics of NG–H2 hybrid fuel at a range of fuel jet Reynolds number varies from 3000 to 6500 is carried out, available in the thesis by El-Ghafour [21]. However, results in this paper selected only at a jet Reynolds number of about 4000. The experimental procedures were conducted in a simple free jet turbulent diffusion flame flowing into a slow co-flowing air stream.

2. Experimental setup and procedures

2.1. Experimental setup

Fig. 1(a) summarizes the experimental facility used in this study. The essential features of the setup are a combustion chamber, fuel and co-flow air supply systems, transverse mechanism, and measuring instruments.

The combustion chamber is similar to that described by Gollahalli and Wright [22], but with some modifications to match the objectives of the current experiments. The chamber is constructed of a 3.0 mm steel sheet and fabricated as a cuboid of a square cross section, 0.6 m × 0.6 m, and 1.24 m height. This chamber is erected vertically, to sustain an axial symmetry as far as possible, on a supporting frame and equipped with rectangular windows of dimensions 0.2 m × 1 m on all of its four side-walls. Three of these windows are fitted with high temperature air-cooled Pyrex glass plates of 3 mm thickness to allow visual observation of the test events and for direct photography. A steel sheet, provided with a longitudinal aperture, is fixed through the fourth window for introducing the intrusive instruments. At the top of the chamber, an exhaust duct of 0.85 m height is connected. The fuel jet is discharged vertically upward along the centerline of the combustor from a circular stainless steel burner of 3.5 mm inner diameter and 0.75 m long, which is long enough to achieve fully developed flow [4]. The burner is projected 100 mm above the combustor floor. At the combustor base, a vertical steel flow straightener tube, of 0.2 m inner diameter and 0.5 m long, is installed to ensure a uniform velocity of the co-flowing air stream.

The co-flowing air is supplied by a centrifugal blower of 0.37 kW. An arrangement of a 75 mm thick layer of small glass balls (9 mm diameter), a coarse wire mesh, and a fine wire mesh is placed in the straightener tube in series. The details of the co-flowing air section are shown in Fig. 1(c). The uniformity of the air flow, at the chamber circular opening exit, is verified by using a hot wire anemometer.

The fuel supply system is composed of separated natural gas and hydrogen feeding lines, mixing section, and manifold to the chamber burner. Commercial natural gas (mainly composed of 91.43% CH_4, 4.1% C_2H_6, 0.99% C_3H_8, 0.33%C_4H_{10}, 0.1%C_5H_{12}, 0.52% CO_2, 2.53%N_2), and hydrogen (99.94% purity) are used. A hydrogen flashback arrestor is positioned inline for safety reasons. The fuels flow rates are measured by two corrected rotameters. Hydrogen and natural gas are led to the mixing section where proper mixing is achieved, as shown schematically in Fig. 1(b). Inside this section, hydrogen is injected axially through a single hole nozzle, while natural gas is injected radially into the hydrogen stream, immediately downstream the hydrogen nozzle, through four holes equally distributed around a circumference perpendicular to the nozzle axis. Finally, a throttle part was employed to ensure