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Experimental studies of autoignition events in unsteady hydrogen–air flames

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An experimental study is presented of unsteady N_2-in-H_2 jet flames in a co-flow of hot combustion products from lean premixed hydrogen combustion for investigation of the statistical likelihood of autoignition events in the mixing region. The unsteady jet flame is characterized by rapid ignition followed by a gradual blowout of the flame. Audio recordings and Schlieren imaging high speed videos are used in investigating the unsteady flame. The frequency of the blowout re-ignition event is investigated as a function of nitrogen dilution mole fraction ($Y_{N_2} = 0.180$–0.566), co-flow equivalence ratio ($\Phi_{cf} = 0.20$–0.27) and jet velocity ($V_{jet} = 300$–500 m/s). The results from the audio recordings and Schlieren imaging indicate that autoignition dominates the re-ignition. The frequency of ignition increase with increasing nitrogen dilution until a maximum is reached after which it decreases with further nitrogen dilution. For increasing equivalence ratios a higher nitrogen dilution is needed in the jet for the flame to become unsteady. The effect of the nitrogen dilution is explained primarily through a reduction in reaction rates and increased jet momentum. Furthermore, the results suggest that the re-ignition rates are controlled by both chemistry and turbulent mixing. The results from the audio recordings and the Schlieren imaging videos correspond well which validates the use of audio recordings as a diagnostic for studying of unsteady hydrogen jet flames.

1. Introduction

Hydrogen and hydrogen-rich fuels are expected to contribute in producing clean energy in power generation systems due to the increase of the energy demand worldwide combined with the urgency in reducing anthropogenic emissions of green house gases [1]. These fuels are produced as a part of the pre-combustion Carbon Capture and Storage (CCS) value chain technology which is expected to play an important role in reducing the total global greenhouse-gas emissions. Fossil fuels such as coal can be converted to gas mixtures consisting mainly of H_2 and CO_2. The CO_2 can be separated from the mixture prior to combustion. In addition to a reduction of CO_2 emissions, hydrogen combustion will lower emissions of CO, unburned hydrocarbons, and particulates, (e.g. soot). [2]. Another advantage of using hydrogen as a fuel is an improved security of the energy supply since it can be produced from various sources such as natural gas, oil, coal and biomass [3].

A challenge associated with gas turbine combustion is achieving reliable ignition, high combustion efficiency and minimum pollutant emissions. State of the art technology for gas turbines apply combustors that are designed for natural gas and/or oil and will have to be redesigned to work optimally, safely and effectively with hydrogen as a fuel [4]. When hydrogen is used as a fuel together with air, the major pollutant is NO_x. Therefore the development of hydrogen fueled gas turbines is focused on safe operation and low NO_x emissions. NO_x production is highly dependent on temperature, residence time, mixedness, and pressure. The preferred method for reducing NO_x emissions from hydrogen combustion is fuel dilution [5]. Fuel dilution facilitates partially premixed combustion by increasing the momentum of the fuel jet and thereby allowing the flame to detach from the nozzle. Some air will entrain and mix with the fuel before it ignites leading to partially premixed combustion. Partially premixed combustion ensures lower peak temperatures and a smaller flame compared to non-premixed flames [6]. A smaller flame results in a lower residence time for the reactants in the high temperature zone and the lower peak temperature will lower the NO_x production. If the hydrogen being used comes from gasification of heavier hydrocarbons after decarbonization of the syngas, nitrogen will be present

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in large quantities [5]. By diluting the hydrogen with nitrogen and burning it in a partially premixed manner it is possible to reduce the NO_x emissions to an acceptable level.

Flame stabilization is of fundamental importance for turbulent combustion design. Flame stabilization is important due to issues of safety, efficiency and emission control. A stable flame is a flame that is anchored at a desired location and is resistant to flashback and blowout over the operating range of the device. Flame stabilization theories usually highlight local ignition, flame propagation, extinction and re-ignition as the important factors controlling stability. Ignition and extinction are two limiting combustion phenomena in which both fluid dynamics (transport) and chemical kinetics play an important role [7].

Working with hydrogen as a fuel is challenging compared with other more conventional fuels like natural gas. The major challenges with hydrogen combustion are the broad flammability limit, the high flame temperature and difficulties in stabilizing the flame. The hydrogen molecule has the lowest mass of any fuel and has high molecular and thermal diffusivity. These features lead to a high flame speed which combined with the high reactivity of premixed hydrogen–air mixtures leads to an increased risk of autoignition and flashback [4]. Detailed knowledge about the combustion characteristics of hydrogen is essential in overcoming these challenges.

The focus of this paper is on experimental investigation of hydrogen combustion using UC Berkeley's Vitiated Co-flow Burner (VCB). The vitiated co-flow burner was designed with the objective of decoupling the detailed fluid mechanics from the chemical kinetics in facilitating modeling while gaining insight into turbulence-chemistry interactions in a hot environment [8]. The VCB is a laboratory setup consisting of a central jet surrounded by a co-flow consisting of lean premixed combustion products of hydrogen and air. The fuel of the jet flame consists of a mixture of nitrogen-in-hydrogen. This configuration is used because it resembles the hot environment found in most practical combustion systems where the hot combustion products are recirculated enhancing flame stability. The reactants mix with a hot mixture of oxygen, nitrogen and reaction products. The products of lean premixed combustion are referred to as *vitiated* air.

The experimental setup of the jet flame surrounded by a hot co-flow has been frequently used in studying jet flames in a hot environment. Cabra [8] developed a design for a VCB and investigated hydrogen and methane flames on the VCB. The VCB design consisted of a jet surrounded by a perforated plate with 2000 small holes. This design was successful in providing a uniform and steady co-flow isolating the jet from the laboratory environment. Stabilization of hydrogen and methane was studied which resulted in the conclusion that lifted flames are stabilized by a combination of flame propagation, autoignition, and localized extinction processes [8–10].

Turbulent flames, including the flames considered in the present work, are complex due to their three dimensional nature that change in time because of the effects of extinction and re-ignition and due to the unstable nature of the flow. Jet flames have been a central topic of study in combustion research and the literature shows a great amount of studies of flame structure, chemistry, and dynamics. Lifted non-premixed flames have been the subject of extensive research for more than 40 years due to their important role in both practical applications and in understanding fundamental combustion phenomena. Lifted flames represent simple systems which exhibit important characteristics of turbulence-chemistry interaction, finite-rate chemistry, effects of heat release, local extinction and ignition, and several other effects [11].

A Direct Numerical Simulation (DNS) of a lifted turbulent hydrogen/air jet flame was performed by Chen et al. [12]. The study confirms the conclusion by Cabra et al. [9,10] that autoignition is an important mechanism for flame stabilization for jets issuing into a hot environment. Tacke et al. [13] performed a study on lifted turbulent non-premixed hydrogen and nitrogen diluted hydrogen flames. The results suggested a stabilization mechanism through large-scale structures and it was concluded that large-scale turbulence plays a dominant role in the stabilization mechanism of lifted turbulent non-premixed jet flames.

Autoignition behavior of hydrogen jet flames in a heated turbulent co-flow has been studied experimentally by Markides and Mastorakos [14]. They have also studied the behavior of other fuels such as acetylene [15]. The residence time up to autoignition was estimated and it showed that the autoignition delay times increased with the co-flow air velocity at constant co-flow temperatures. These results suggested that autoignition phenomena was not solely chemically controlled and that turbulent mixing delays autoignition.This work has been complemented with a DNS study of autoignition of a nitrogen diluted hydrogen plume in a turbulent co-flow by Kerkemeier et al. [16]. Under varying turbulent intensity, they could study in deeper detail the relationship between autoignition spots and the occurrence of favorable mixture fractions combined with low scalar dissipation rate as observed in the experiments. However, due to the intensity of the direct numerical simulations this study was restricted to one set of dilution conditions only. The effect of varying co-flow temperatures has been addressed in other studies. For example,lifted natural gas jet flames in hot co-flows and later ignition behavior in transient jets have been studied experimentally by Oldenhof el al. [17,18]. They conclude that the responsible mechanisms for flame stabilization is ignition kernel generation by autoignition, not flame propagation. An increase in Reynolds number leads to a reduction of the minimum distance from the jet nozzle at which the first ignition event occurred. Furthermore, they concluded that an increase in the co-flow temperature increased the ignition frequencies and that increasing the level of turbulence hinders autoignition processes more strongly in flames with long autoignition times. From the transient studies it was evident that ignition delays were not only a function of chemistry, or the response of the velocity field, but also the fluid dynamic response of the transient jets. Recent studies of similar but pulsed, turbulent jets, confirm these findings using simultaneously measured high-speed image sequences of mixture fraction and temperature fields [19].

The objective of this experiment is to investigate the statistical likelihood of autoignition of the hydrogen jet flame diluted with nitrogen (N_2-in-H_2 flame) under varying conditions and thereby determine to what extent hydrogen can be premixed with products of lean hydrogen combustion without the risk of flashback. Autoignition is local spontaneous ignition which can lead to ignition as a large scale phenomenon and a more or less stable flame. The understanding of how, and under what conditions a flammable mixture will autoignite is of tremendous importance for both preventing unwanted ignition and initiating ignition at the proper time. Since the purpose in practice is preventing ignition in the mixing section of a gas turbine, this research is focused on examining ignition (and extinction) during mixing.

The frequency of the blowout-autoignition events will give an indication of the statistical likelihood of autoignition under the various conditions. As the frequency of ignition is increased the statistical likelihood of autoignition is correspondingly increased. As the frequency of ignition is reduced, the statistical likelihood of autoignition is correspondingly reduced. The frequency of ignition has been discussed only in a small number of studies found in literature, for example in the context of investigating the effect of turbulence and mixing on autoignition chemistry by Markides and Mastorakos for nitrogen-diluted acetylene jets [15]. The present study will examine in detail the frequency of ignition *and* blowout of N_2-in-H_2 jet flames in air as a function of co-flow