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Ignition of ultra-lean premixed hydrogen/air by an impinging hot jet

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HIGHLIGHTS

- Ignition characteristics by impinging hot turbulent jet in a dual chamber system are proposed.
- The ratio of impinging distance to the nozzle diameter, H/D and the impinging angle, θ are examined.
- Using impinging jet ignition, a lower flammability limit of hydrogen/air is achieved.
- Numerical simulation of jet impingement process is performed.

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ABSTRACT

The ignition characteristics of a hot turbulent jet impinging on a flat plate surrounded by an ultra-lean premixed H_2/air was studied both experimentally and numerically. The hot turbulent jet was generated by burning a small quantity of stoichiometric H_2/air mixture in a separate small volume called the pre-chamber. The higher pressure resulting from pre-chamber combustion pushed the combustion products into the main chamber through a small nozzle (0.75–4.5 mm in diameter) in the form of a hot turbulent jet, which then impinged on a flat plate. Six different plates with varying impinging heights and angles were used. Two important parameters controlling the impinging characteristics of the jet, the ratio of the impinging distance to the nozzle diameter, H/D and the impinging angle, θ were examined. Simultaneous high-speed Schlieren and OH^* chemiluminescence imaging were applied to visualize the jet penetration/impinging and ignition process inside the main combustion chamber. Results illustrate the existence of two distinct types of ignition mechanisms. If the impinging distance is short and the hot turbulent jet hits the plate with high enough momentum, the temperature increases around the stagnation point and ignition starts from this impinging region. However, if the impinging distance is long, the hot turbulent jet mixes with the ambient unburned H_2/air in the main chamber and ignites the mixture at the upstream from the plate. For such type of ignition, the impinging plate has a minimum role on main chamber ignition. Employing the stagnation point ignition, a leaner limit of H_2/air in the main chamber was achieved. Numerical modeling of the turbulent hot jet impingement process was carried out to explain the impinging jet ignition mechanism. It was found that H/D ratio was the controlling parameter between the two ignition mechanisms. The limiting H/D ratio was found to be 21.6, below which ignition occurred via jet impingement. Unlike the H/D ratio, the impinging angle did not affect the ignition mechanism; however, it affected the main chamber burn time.

1. Introduction

Pre-chamber turbulent jet ignition (TJI) has been used as an advanced ignition technique for various combustion systems with applications ranging from pulse detonation engines [1], wave rotor combustor explosions [2], to supersonic combustors [3] and lean-burn natural gas engines [4]. The main reason that TJI has become attractive to gas engine manufacturers is that hot jet ignition can achieve faster burn rates due to the ignition system producing distributed ignition sites, which consume the main charge more rapidly and with minimal combustion variability. Compared to a conventional spark plug, the hot jet has a much larger surface area leading to multiple ignition sites on its surface which can enhance the probability of successful ignition and cause faster flame propagation and heat release. Over the last few decades, pre-chamber TJI had technologically advanced from conceptual design phase to actual gas engines. The early designs developed by Gussak [5], Oppenheim [6] and Wolfhard [7] showed the promise of lean ignition by a hot turbulent jet. Later, Ghoneim [8], Pitt [9], Yamaguchi [10], Sadanandan [11], Toulson [12], Gholamisheeri [13], Attard [14], Gentz [15], Perera [16], Carpio [17], Shah [18], Karimi

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[2], Vedula [19], and Biswas [20] further investigated in detail the parametric effects of turbulent jet ignition in laboratory-scale prototype combustors and at engine relevant conditions. These studies support that TJI possesses several advantages over traditional spark ignition such as higher ignition probability, multiple ignition kernels, and faster burn rates.

TJI, however, is a complicated phenomenon and our knowledge is far from complete. Several studies have examined the fundamental mechanisms behind TJI – the complex coupling between turbulent mixing and chemical reactions [13,20,21]. For example, the jet containing hot combustion products penetrates the lean fuel/air mixture that resides in the main chamber, providing a high-temperature environment for mixing and ignition. Depending on the operating condition, the jet may or may not contain active radicals such as H, O, and OH, which initiate chain-branching reactions [5,22]. We can expect that several factors, such as the radicals which are important for ignition chemistry, as well as the mixing process between the hot burned products and the cold fresh lean mixtures, all affect the ignition process.

TJI becomes even more complicated in an engine environment [23,24]. Along with turbulent mixing and complex chemical processes, the wall effect can be significant. Inside the small volume of the combustion chamber in the engine, the effect of confinement and chances of jet impingement becomes predominant. The hot jet issued from the pre-chamber may impinge onto the surface of the piston head or the wall of the main engine during the cycle. This is particularly true when multiple jets (typically 6–12) generated from pre-chamber combustion are utilized [25,26]. Motivated by this, the present study intended to understand the impact of impingement on TJI ignition process which has great significance for automotive and gas engine applications. In particular, the study focused on two variables: (1) the location of the impinging surface from the nozzle exit, which represents the motion of the piston head i.e. location of piston head at different crank angles, and (2) the angle of the impinging surface, which implies various design profiles of the piston head.

Although a large number of literature have discussed the physics of an impinging liquid or gas jet onto a plate from fundamental fluid dynamics and heat transfer standpoint, few studies have examined ignition of premixed fuel/air mixtures by an impinging hot jet. Most of the existing literature focused on heating of materials by steady flame impingement, a practice used in processing industries [27,28]. Among the very few studies that are relevant to reacting turbulent hot jet, Tajik and Hindasageri [29] numerically investigated the heat transfer and emissions characteristics of impinging radial jet reattachment combustion (RJRC) flame. RJRC flame jet is used in applications where the impingement surface is delicate and demands low impingement pressure. They found that the peak heat flux and the concentrations of NOx and CO emissions increased significantly with the increase in the Reynolds number. Additionally, as the nozzle-tip-to-plate spacing increased, the peak heat flux and the pressure coefficient decreased. Wang [30] studied the ignition process using a methane diffusion impinging flame and found the impinging distance played a key role in determining the ignition timing. Despite these studies, no work has been done on the ignition characteristics of a lean mixture by a highly-turbulent impinging hot jet. This motivated us to investigate the ignition of premixed H_2/air using a hot turbulent jet impinging on a flat plate. The knowledge developed from this work will be helpful for future pre-chamber designs and optimization for automotive and gas engine applications.

The goal of the present study was to examine the ignition behavior of ultra-lean H_2/air mixtures by a turbulent hot jet impinging onto a surface. Six different plates with varying heights and angles were used. In the experiment, the higher pressure resulting from pre-chamber combustion of stoichiometric H_2/air pushed the combustion products into the main chamber through a small nozzle (0.75–4.5 mm in diameter) in the form of a hot turbulent jet, which then impinged onto a flat plate which was placed inside the main combustion chamber filled with lean H_2/air mixture. Depending on the impinging distance and impinging angle, two ignition mechanisms exist: one is via impingement for which ignition takes place near the impinging point, and the other is via typical turbulent jet ignition where ignition takes place on the lateral sides of the hot jet before it hits the impinging plate. The effect of the different ignition mechanisms on the lean limit of the main chamber H_2/air mixture was investigated. Furthermore, detailed numerical simulations were carried out to understand the impinging jet dynamics which helped to explain the experimental observations.

2. Experimental methods

The schematic of the experimental setup and the dual combustion chamber are shown in Fig. 1(a) and (b) respectively. The experimental setup was thoroughly described in our earlier studies [31–36]. Thus, only a brief description is presented here. A small volume stainless steel pre-chamber was mounted on top of a carbon steel main chamber. The main chamber to pre-chamber volume ratio was 100:1. A stainless steel nozzle plate was placed between the two chambers to separate them. In our current experiment, a variety of nozzle diameters, D ranging from 0.75 to 4.5 mm (0.75, 1, 1.5, 2, 2.25, 3, 4.5 mm) were used. However, the ignition characteristics had been primarily investigated in detail for a nozzle diameter of 3 mm and 1.5 mm. Later, the effect of H/D ratio on ignition behavior was explored using other nozzle diameters. Thus, most of the experimental and numerical visualizations were for 3 mm diameter nozzle, unless otherwise stated. Initially, H_2/air mixtures in both chambers were kept at room temperature. The stoichiometric H_2/air mixture in the pre-chamber was ignited by an electric spark (using a Bosch Iridium spark plug) generated near the top of the pre-chamber. Once the spark ignited the pre-chamber fuel/air mixture, the combustion products entered the main chamber in the form of a hot jet, which, then impinged on the flat plate placed inside the main chamber and ignited the ultra-lean H_2/air in the main chamber. The lean limit for each nozzle/plate combination was found by gradually reducing the H_2/air equivalence ratio inside the main chamber until ignition could not occur anymore. Note the H_2/air equivalence ratio of the pre-chamber mixture was fixed at $\phi = 1$ for all cases, whereas the H_2/air equivalence ratio of the main chamber mixture was varied from $\phi = 0.5$ to the lean limit for the corresponding test condition. The equivalence ratio in both the pre-chamber and main chamber was determined using the partial pressure method. A high-accuracy, low-cost pressure transducer (Kulite XTEL 190, Omega PX51) was used to control the fuel/air ratio. The stoichiometric pre-chamber mixture was prepared in a separate mixing chamber.

Six different stainless-steel impinging plates were used in the present study. The schematic of the impinging plates and plate numberings are shown in Fig. 1(c). In the plate nomenclature, there are two quantities. The first quantity after 'H' denotes impinging height/distance in inch, which is the vertical distance between the nozzle exit and the impinging plate along the nozzle centerline. The second quantity, '∡' denotes the impinging angle, which is the angle of the impinging plane with the horizontal direction as illustrated in Fig. 1(b). Using this plate nomenclature scheme, H2.2 ∡0° denotes an impinging plate 2.2 in. away from the jet exit, and the impinging plane makes an angle zero degree with the horizontal direction.

The dimensions of the six impinging plates are reported in Table 1. For all the plates, the base length, width, and thickness were identical, which were 3, 2, and 0.2 in., respectively. The impinging surface was smooth and free from any irregularities. After every 5 tests, the surface was thoroughly cleaned to avoid water deposition which is the only product of lean hydrogen combustion. The two most important geometric parameters of the impinging jet experiment were H/D ratio and impinging angle, θ. The ignition results with and without an impinging plate were compared. The cases without an impinging plate were denoted as 'NP.'

The main chamber was installed with four rectangular