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Proceedings of the Combustion Institute 30 (2005) 423–430
Proceedings of the Combustion Institute
www.elsevier.com/locate/proci

Ignition of hydrogen in unsteady nonpremixed flows

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Abstract

The effects of unsteady strain on hydrogen (H_2) ignition in nonpremixed flows are investigated with both experimental measurements and numerical computations. A mixing layer is established in a counterflow configuration with a fuel stream containing N_2–diluted H_2 ($X_{H_2} = 0.08$) flowing against heated air. A reproducible ignition process is initiated by introducing atomic oxygen into the mixing layer with a pulsed ArF excimer laser, which photodissociates heated O_2 from the oxidizer stream. The temporal evolution of OH during ignition is measured by planar laser-induced fluorescence. Following the induction phase, the measured OH mole fraction increases rapidly to a super-equilibrium value that is 60% greater than the OH mole fraction in a steady diffusion flame. The peak OH mole fraction occurs at approximately 6 ms after the excimer laser pulse. To study the OH time history under transient strain, the fuel stream is pulsed at a fixed time after the initiation of ignition. The response of the ignition kernel is extremely sensitive to the time delay of the flow transient. The unsteady strain can delay the ignition time or extinguish the kernel. Comparisons between computations and experiments are made for the evolution of OH during autoignition both for steady and unsteady strain. For both steady and unsteady strain, the transient one-dimensional counterflow computations show excellent agreement with the experiment in terms of predicting ignition delays and the rate of OH accumulation during the induction period. The computations also capture the super-equilibrium OH during the transition to the formation of a steady flame, although not to the degree observed experimentally. The computations are further used to understand the influence of unsteady strain on the kernel evolution. It is found that the degree of super-equilibrium OH is sensitive to strain transients applied close to the time of thermal runaway.

Keywords: Transient; Unsteady; Strain; Ignition; Hydrogen

1. Introduction

Providing knowledge for accurate modeling of practical combustion processes is the goal of many studies. In practical systems, combustion takes place in nonuniform flows under transient conditions. In nonpremixed combustion, the nonuniform flow-field is characterized by the scalar dissipation rate [1–3]. The role of scalar

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doi:10.1016/j.proci.2004.08.254

dissipation rate and finite-rate chemistry on transient processes including autoignition and extinction has been the subject of a number of numerical and analytical studies [4–9]. The numerical studies employed detailed chemistry to study autoignition phenomena [8,9] and one-step chemistry to study extinction [7]. The analytical studies employed one-step chemistry [4–6]. Previous experimental studies on autoignition under nonpremixed conditions have been carried out on steady nonuniform flows [10–13]. Experimental studies of the response of the reactive layer in a nonpremixed flame to fluctuations in the strain rate are available [4]. Previous experimental studies on transient autoignition were focused on measuring ignition delay times in shock tubes [14,15] and rapid compression machines [16–19]. Experimental studies of ignition in jet stirred flow reactors are available [20]. The experimental studies in shock tubes, rapid compression machines, and flow reactors were conducted on homogeneous premixed systems. These studies have illustrated the key role of intermediate species and the OH radical in autoignition. Modeling combustion processes in practical systems requires understanding of mechanisms of autoignition in nonuniform flows with fluctuations in the scalar dissipation rate. Accurate modeling of the transient nature of the reactive flow-field from the time autoignition is initiated to completion is of interest. Some aspects have already been addressed in numerical studies [8,9]. In the present investigation, a well-controlled repeatable experiment is performed to study the time evolution of the ignition kernel in a nonpremixed strained flow. Furthermore, it is investigated how the ignition kernel is affected when a transient strain is introduced during the ignition event.

2. Experimental methods

Figure 1 shows a schematic illustration of the counterflow configuration employed in the present study of ignition of hydrogen in nonpremixed flows. Axisymmetric laminar flow of two counterflowing streams toward a stagnation plane is considered. The jets that flow into the mixing layer between the two ducts are characterized by values

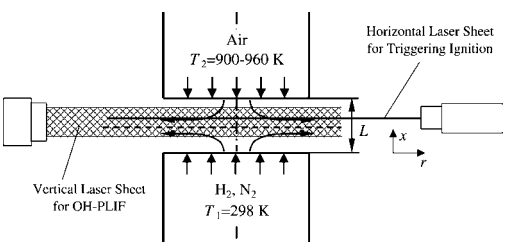

Fig. 1. Schematic illustration of the counterflow configuration.

of V_i and ρ_i, $i = 1,2$. Here, ρ denotes the density, and V denotes the component of the flow velocity normal to the stagnation plane at the exit of the duct. Subscripts 1 and 2 refer to the fuel boundary and oxidizer boundary, respectively. The tangential components of the flow velocities at the boundaries are presumed to be equal to zero (plug-flow boundary conditions). The value of the strain rate, defined as the normal gradient of the normal component of the flow velocity, changes from one duct exit to the other [21]. The characteristic strain rate on the side above the stagnation plane a_2 is presumed to be given by [21]

$$a_2 = \frac{2|V_2|}{L}\left(1 + \frac{|V_1|\sqrt{\rho_1}}{|V_2|\sqrt{\rho_2}}\right). \quad (1)$$

Eq. (1) is obtained from an asymptotic theory where the Reynolds numbers of the laminar flow at the boundaries are presumed to be large [21]. A detailed description of the burner is given elsewhere [10,22]. The flow rates of gases are measured by computer-regulated mass flow controllers. The calibrated accuracy of these mass flow controllers is ±1%. The velocities of the reactants at the boundaries are presumed to be equal to the ratio of their volumetric flow rates to the cross-section area of the ducts. Each main reactant stream is surrounded by a nitrogen curtain flow with comparable velocity. The oxidizer duct is equipped with a heating device that allows the stream to be preheated up to 1350 K. The temperature of the gas at the exit of the duct is measured using a Pt–Pt 13% Rh thermocouple with wire diameter of 0.07 mm and a junction diameter of 0.21 mm. The measured temperatures are corrected for radiative heat losses assuming a spherical junction, a constant Nusselt number of 2.0, and a constant emissivity of 0.2 [23]. The accuracy of the corrected temperature is expected to be better than ±15 K. At an oxidizer temperature of 940 K, the radial temperature variation is less than 5 K over a radius of 4 mm around the centerline. Therefore, gradients of scalar quantities in radial direction can be neglected. Experiments are conducted with the mole fraction of fuel, $X_{H_2,1}$, maintained at 0.08. The temperature of the fuel stream, T_1, is 298 K. The oxidizer stream is air with a mole fraction of oxygen $X_{O_2,2} = 0.21$. The distance between fuel and oxidizer duct is $L = 12$ mm. The experiments are performed at a constant pressure of 1 atm. The temporal evolution of the ignition kernel was recorded by measuring OH planar laser-induced fluorescence (LIF) at each phase of the ignition process. To excite OH LIF, the frequency-doubled output from a Nd:YAG-pumped dye laser was tuned near 283 nm to pump the $Q_1(5)$ transition of the A–X(1,0) band. The laser beam was formed into a vertical sheet that intersected the burner axis, as shown in Fig. 1. The OH fluorescence from the