Combustion and Flame 185 (2017) 265–277

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Ignition of fuel–air mixtures from a hot circular cylinder

Lorenz R. Boeck[a,*], Maxime Meijers[b], Andreas Kink[c], Remy Mével[a,d,e], Joseph E. Shepherd[a]

[a] Graduate Aerospace Laboratories, California Institute of Technology, Pasadena, CA 91125, USA
[b] École Polytechnique, 91128 Palaiseau Cedex, France
[c] Technische Universität München, 85747 Garching, Germany
[d] Center for Combustion Energy, Tsinghua University, Beijing 100084, China
[e] Department of Automotive Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 15 March 2017
Revised 10 July 2017
Accepted 10 July 2017
Available online 9 August 2017

Keywords:
Hot surface ignition
Cylinder
Interferometry
Heat transfer

ABSTRACT

Ignition of hydrogen–air, ethylene–air and n-hexane–air mixtures from a horizontally and vertically oriented heated circular cylinder was studied experimentally in a wide range of equivalence ratio. Initial pressure and temperature were 101.3 kPa and 296 K, respectively. The cylinder with outer diameter 10 mm and heated length 10 mm was designed for high temperature uniformity. Two-color pyrometry measured the surface temperature; Time-resolved Mach–Zehnder interferometry acquired ignition dynamics, gas temperature fields and heat transfer characteristics. Ignition from the horizontal cylinder occurred at temperatures between 960 K and 1100 K for hydrogen, between 1060 K and 1110 K for ethylene, and between 1150 K and 1190 K for n-hexane. Vertical cylinder orientation increased ignition thresholds by 50–110 K for ethylene and n-hexane, whereas only little variation was observed for hydrogen. Infinite-fringe interferograms visualized the ignition dynamics and identified the most favorable ignition locations, which coincided with locations of lowest wall heat flux (largest thermal boundary layer thickness) and long residence time. Gas temperature fields were obtained by post-processing the interferograms, resolving the temporal and spatial development of thermal boundary layers and enabling local heat transfer analysis. The convective pattern around a horizontal cylinder features distinctly shallow temperature gradients, i.e., low heat flux, at the cylinder top due to thermal plume formation, which promotes ignition compared to the vertical cylinder. An analytical scaling model for ignition from hot surfaces was evaluated to determine the sensitivity of ignition threshold to heat transfer variations, and to reveal the influence of chemical mixture properties. This analysis predicts a particularly low sensitivity for hydrogen–air mixtures at temperatures near the extended second explosion limit, and a larger sensitivity of ethylene–air and n-hexane–air mixtures, which is in accordance with the experiments.

1. Introduction

Ignition of reactive gas mixtures from hot surfaces constitutes a hazard in many industries. Parameters such as surface size, shape, material and heating rate affect the minimum surface temperature required for ignition, referred to as the ignition threshold. For a given hot object and heating rate, the ignition threshold is a function of gas mixture composition, initial thermodynamic state of the gas and the flow regime, i.e., whether the gas is initially quiescent or an external flow is present. The present paper focuses on localized hot surfaces located in a large volume of reactive mixture, in contrast to ignition from extended surfaces such as heated vessels. Ignition from localized hot surfaces which are not catalytic is dominated by the formation of a thermal boundary layer around the hot object and the competition between energy release and creation of reactive species from chemical reactions within the boundary layer and transport processes to the surface.

Literature on hot surface ignition spans several decades and there is a substantial body of empirical data that primarily focuses on critical temperatures for ignition and simplified analytical models. Rapidly heated wires with sub-millimeter diameters represent a classical experiment [1–16]. Rapid energy deposition into the wire leads to the separation of time scales for wire heating, thermal conduction into the gas and chemical reaction, and the temperature field can be treated as quasi one-dimensional in the limit of fast heating. Experiments on rods with millimeter-diameters [6,17–19] and heated foils [20–22] extended the range of surface sizes. Ignition from hot particles was investigated by [23–33]. Two trends emerge from the experimental studies: larger hot surfaces enable lower ignition thresholds, and quiescent initial

* Corresponding author. Current address: FM Global, Research Division, 1151 Boston-Providence Turnpike, Norwood, MA 02062, USA.
E-mail address: lorenz.boeck@fmglobal.com (L.R. Boeck).

http://dx.doi.org/10.1016/j.combustflame.2017.07.007
0010-2180/

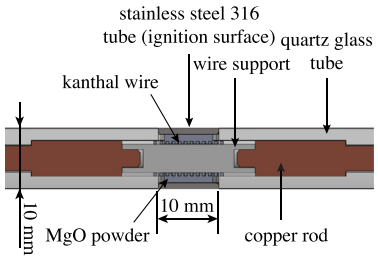

Fig. 1. Cross-sectional view of the heated cylinder.

conditions enable lower ignition thresholds compared to situations where external flow is present. The analytical studies have emphasized explaining these trends by balancing energy generation with heat losses to surfaces to predict ignition temperatures.

The accuracy of ignition experiments depends on the hot surface used and on the type of diagnostics [20,21]. The uniformity of surface temperature needs to be optimized and quantified to reduce uncertainties. The present study extends previous work that used a commercial glow plug as a hot surface [34–39]. To improve the surface temperature uniformity, a new cylindrical surface was developed with a unity aspect ratio of the hot surface section. Horizontal and vertical cylinder orientations were tested to examine the role of heat transfer variations on ignition thresholds. Heating times from ambient temperature to ignition temperature longer than 40 s allowed natural convection to fully develop, i.e., the flow field adapted quasi-instantaneously to changes in surface temperature, which distinguishes the present study from rapid heating experiments. Results in terms of ignition thresholds, ignition dynamics and heat transfer were obtained for hydrogen–air, ethylene–air and n-hexane–air mixtures in a wide range of equivalence ratio at an initial pressure of 101.3 ± 0.1 kPa and initial temperature of 296 ± 3 K. An analytical scaling model is applied to further study the effect of local heat transfer, surface orientation and chemical mixture properties on ignition thresholds.

2. Experimental setup

2.1. Combustion vessel

Ignition experiments were performed in a 2.2L closed prismatic vessel with internal dimensions $0.114\,\text{m} \times 0.114\,\text{m} \times 0.165\,\text{m}$. The vessel was evacuated to below 10 Pa and filled with fuel, oxygen and nitrogen using the method of partial pressures with a 10 Pa accuracy. The gases were mixed by a circulation pump and left to settle for 3 min to ensure quiescent initial conditions. Initial pressure and temperature before the start of the surface heating were 101.3 ± 0.1 kPa and 296 ± 3 K, respectively. Gaseous fuels, i.e., hydrogen and ethylene, were supplied from gas cylinders and liquid fuel, i.e., n-hexane, was injected as a liquid and evaporated. The vessel was equipped with lateral viewing windows providing optical access for pyrometric and interferometric measurements.

2.2. Heated cylinder

A well-defined experiment on hot surface ignition demands a hot surface with small spatial variations in temperature. Especially for small surfaces, this poses a design challenge. Non-uniformity in temperature may affect the development of natural convection and chemical activity. Likewise, a local measurement of surface temperature may not represent the actual surface temperature at the location of ignition.

A stainless steel (316) cylinder heated internally by a Kanthal A-1 FeCrAl alloy resistance heating wire subjected to electric current was selected as a hot surface in the present study. The dimensions of the hot surface were $D = 10$ mm outer diameter, $L = 10$ mm length (aspect ratio $L/D = 1$), and $d = 1$ mm wall thickness. Figure 1 presents a cross-sectional view of the device. The material, stainless steel (316), corresponds to previous work using a commercial glow plug as a hot surface [34–37,39]. The stainless steel tube was centered between two 30 mm long thermally and electrically insulating quartz glass tubes to create a continuous geometric contour and to limit axial heat loss. Compacted magnesium oxide powder filled the internal gap between the heating wire and the stainless steel tube, providing electrical insulation and high thermal conductivity [40]. Copper rods and attached cabling connected the heating wire to a constant electrical current source. The cylinder was mounted in the center of the combustion vessel. Both vertical and horizontal cylinder orientations were examined, see Fig. 2.

3. Diagnostics

3.1. Two-color pyrometry

The hot surface temperature was measured by two-color pyrometry. Near-infrared radiation emitted from the stainless steel surface was collected through a 75 mm focusing lens positioned at a distance of 140 mm and directed towards two InGaAs detectors (Thorlabs PDA10DT) by a dichroic beam splitter with a cut-off wavelength of 1800 nm. The focusing lens was made of uncoated N-BK7 with a high transmission between 350 nm and 2.0 µm and a design wavelength of 587.6 nm. Focal shift due to chromatic aberration was compensated by adjusting the detector positions. The two detectors were equipped with a different bandpass filter each with central wavelengths 1705 nm and 1940 nm and FWHM 97 nm and 105 nm, respectively. The ratio of bandpass-filtered radiation intensities, I_1/I_2, correlates with the surface temperature T_S. For

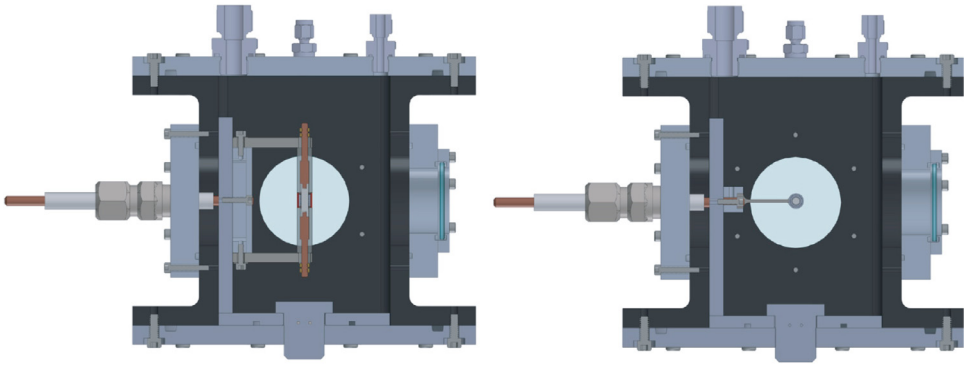

Fig. 2. Combustion vessel with heated cylinder mounted vertically (left) and horizontally (right).