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Experimental Investigation of Hot Surface Ignition of Hydrocarbon-Air Mixtures

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We have performed experiments on the continuous ignition of gaseous hydrocarbon-air mixtures within a closed vessel. During our experimental investigation, distinct regimes of ignition and flame propagation behavior were observed for different initial pressures and equivalence ratios. Single ignition, multiple ignition events, and puffing flame behavior were witnessed. The focus of the present report is the observed “puffing” instability of flame propagation in fuel-rich mixtures. Schlieren observations are compared to two-dimensional unsteady numerical simulations based on a flame sheet model. A new and unique mode of stabilized premixed combustion is observed in very rich mixtures.

1 Introduction

Isolated hot surfaces surrounded by a flammable mixture such as a pipe carrying hot gas in a flammable leakage zone in an aircraft or the overheating of a failing electrical or mechanical device, are potential ignition sources. Some basic research has been performed to investigate this type of ignition hazard, for instance, [1] lists required temperatures of heated wires, rods, and tubes to ignite a variety of mixtures. Standardized tests exist to evaluate various properties of fuels, including the ASTM E659 [2] for autoignition temperature of fuels, and the ASTM D56 [3] for the flash point. However, no standard test exists for hot surface ignition [4] and there have been few efforts to develop realistic models to quantify ignition thresholds. In this study we investigate flame propagation behavior and compare these to computational results. Our ultimate goal is to develop sufficiently realistic and detailed models that these ignition thresholds and ignition transients can be accurately predicted.

2 Experimental Setup

The experimental setup consists of a glow plug, metal foil, or wire supported in a closed combustion vessel of either 2 or 22 liters. For each experiment the vessel is evacuated then filled with a mixture of hexane, oxygen, and nitrogen. The gas mixture is circulated for 2 minutes using either a mixer or circulation pump. Power is applied to the heating element using a DC power supply (up to 50 A at 20 V), increasing its temperature until ignition is observed. The time to reach ignition temperature varies with the size and resistivity of the element from 5 to 10 seconds. A thin wire K-type thermocouple is used to measure the temperature for all hot surfaces except the wire. The nominal response time of the thermocouple is 0.5 sec. The combustion is visualized using a conventional schlieren system and recorded with a high-speed video camera.

3 Results

During the investigation of the dependence of hot surface ignition temperature on various parameters, such as pressure, equivalence ratio, and surface size, it was observed that a periodic flames (puffing) develop at higher equivalence ratios. The puffing is characterized by a cyclic instability that occurs after the initial transient associated with ignition (first 4 frames of Figure 2). After the initial ignition of the mixture the hot surface serves only as a flame holder. Approximately 1 cycle of the periodic puffing behavior can be seen in the last 4 images of Figure 2. The cycle repeats until either the power is turned off and the hot surface temperature drops or until all the reactants in the vessel are consumed [5]. At atmospheric pressure, puffing was observed in mixtures of hexane and air from $\phi = 2.5$ to 3.0; the upper flammability limit is $\phi = 3.6$ [6]. In previous experiments, a small increase in puffing frequency was observed as the equivalence ratio is increased [5].

In order to examine the origin of the instability, we investigated the effect of the hot surface size and volume of the combustion vessel. The measurements in Table 1 show that there is a very limited dependence of the puffing frequency on volume, igniter size, or power input. These observations suggest that the frequency is a function of the flame dynamics and the flow induced by the flame and is independent of the igniter and vessel size.

Table 1: Puffing behavior for fuel rich hexane air mixture ($\phi = 3.0$).

Hot Surface	Power [W]	Area [m ²]	V _{vessel} [m ³]	T _{ign} [K]	Freq. [Hz]
Bosch Glow Plug ¹	≈100	8 × 10 ⁻⁵	2 × 10 ⁻³	920-975	12-13 (+1/-1)
Autolite 1110 Glow Plug	96	1.5 × 10 ⁻⁴	2 × 10 ⁻³	775-825	12-13 (+1/-2)
			22 × 10 ⁻³	1120	14-15 (+1/-1)
Nickel Foil 0.05 mm	≈400	2.4 × 10 ⁻⁵	2 × 10 ⁻³	980	20 (+8/-2)
Chromel Wire \varnothing 0.13 mm	≈10	2.4 × 10 ⁻⁶	2 × 10 ⁻³	n/a	14 (+3/-2)

¹ non-commercial Bosch (961) 64 978801-0485 Duraterm, n/a - not available

3.1 Experimental Schlieren Results

The usual combustion mode for ignition in a closed vessel is a single quasi-spherical flame that spreads in all directions, and is distorted by buoyancy at low propagation velocities, i.e. very lean or rich mixtures. In the present case, the hot surface establishes a thermal plume as it is heated from room temperature to the ignition temperature of the mixture. This thermal plume is shown in the first schlieren image in Figure 2. The mixture then ignites near the tip of the glow plug and propagates quickly upward along the thermal plume. At this high equivalence ratio, the laminar burning velocity is very low and due to the temperature differential and vertical velocity in the plume, the horizontal flame propagation velocity is significantly slower than the upward flame propagation velocity. In the schlieren images it can also be observed that the flame does not propagate downward after ignition due to the upward flow velocity at the glow plug base. The upward velocity is induced initially by the thermal plume of the glow plug and subsequently by buoyancy of the combustion products.

Once ignition has occurred, the temperature in the region above the hot surface is determined by combustion products. The upward motion of the buoyant hot products entrains cold premixed, but unreacted, gas. The entrainment velocity also limits the horizontal spreading of the flame. The puffing behavior appears to be a result of the instability of the flow and the flame sheet due to the interaction between the entrainment, buoyancy-induced flow, and flame dynamics. Following the initial ignition transient, the temperature distribution and flow field is determined by the continuous but periodically varying cylindrical flame extending upward from the thermal ignition source. Radial entrainment provides a continuous source of fresh reactants. The resulting configuration appears to be an axi-symmetric “V-flame” with a flow driven by buoyancy and anchored by the ignition source.

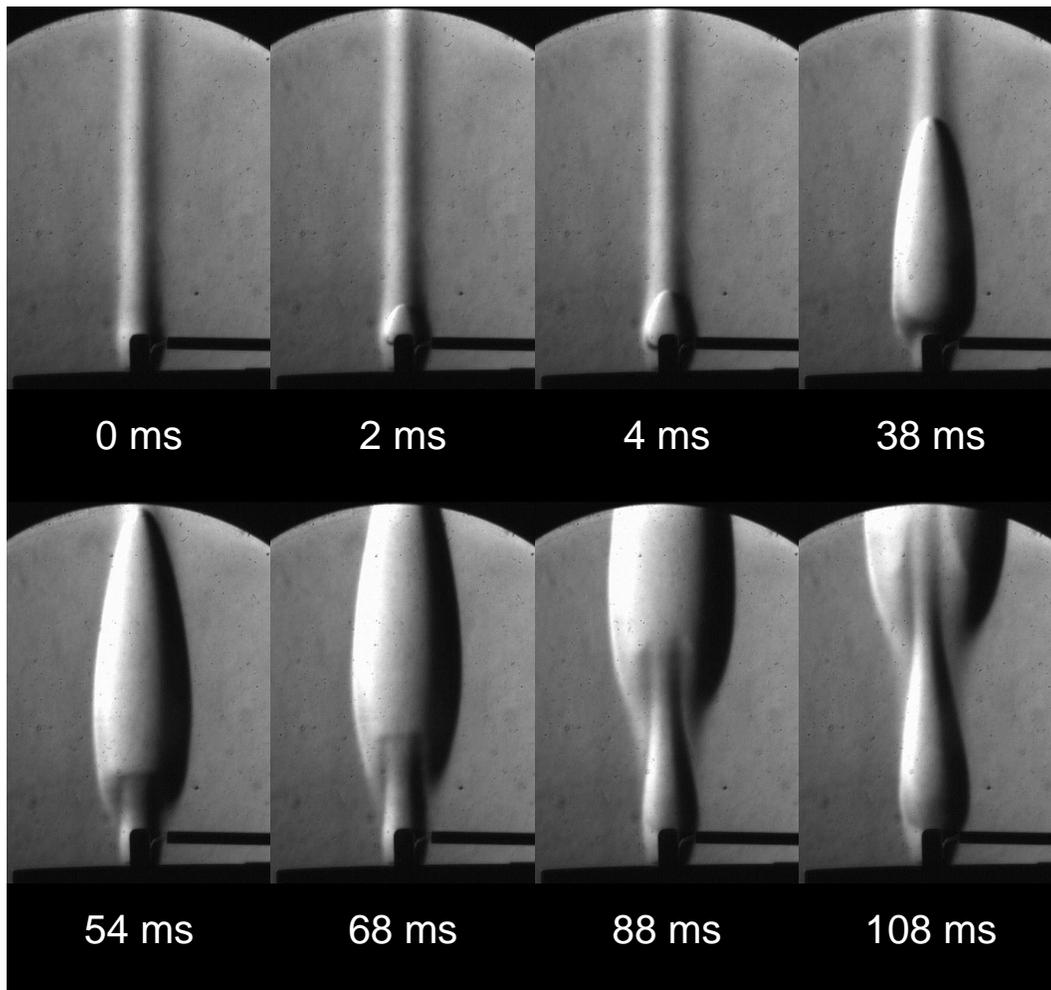


Figure 1: Schlieren images of ignition and subsequent flame propagation in a mixture of hexane in air at atmospheric pressure ($\phi = 3.0$). The hot surface is a Autolite 1110 glow plug in a 60 mm diameter aluminum cylinder in a closed 22 liter combustion vessel. The hot surface temperature is measured by a fine wire K-type thermocouple, where the glow plug is hottest.

3.2 Computational Results

We performed a two-dimensional unsteady simulation based on a flame sheet model [5]. Ignition was simulated by creating a small spherical flame sheet at the top of the glow plug inside the established thermal plume. Simulations for a fuel rich ($\phi = 2.5$) heptane-air mixture using the geometry and temperature of the Autolite 1110 glow plug give good qualitative agreement with the observed experiments. The simulations show the slow burning velocity competing with flow entrained by the thermal plume and subsequently the instability of the flame sheet surrounding the buoyant hot combustion plume. The strong dependence of the burning velocity on temperature is visible in the significantly faster propagation speed at the top than at the sides during the ignition transient. Although the computational domain is at least 10 times smaller in volume than the experimental situation, the ignition transient and subsequent flame instability are qualitatively quite similar.

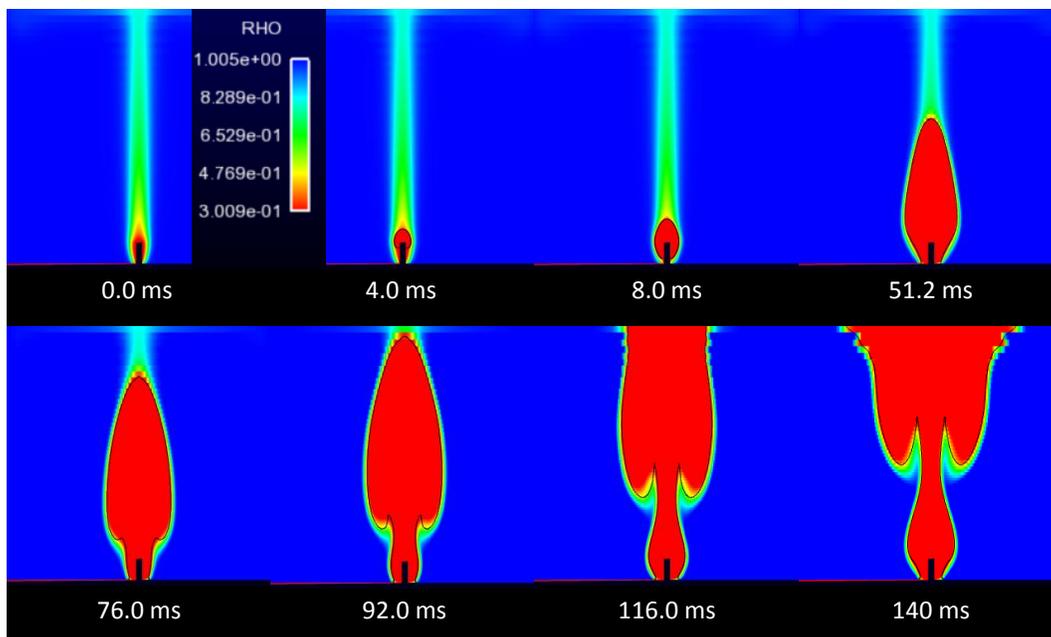


Figure 2: Simulations of heptane in air ($\phi = 2.5$) using experimentally measured temperature distribution at the glow plug surface. Shown here are contour plots of the density distribution.

4 Concluding Remarks

We have discovered an unusual flame propagation mode in fuel-rich mixtures ignited in the plume above a hot surface. This mode consists of a cylindrical flame sheet anchored to the ignition source. The flow “puffs” with a well-defined traveling spatial disturbance or instability visible on the flame sheet. By varying the size of the hot surface, power input, and combustion vessel volume, we determined that the instability is a function of the interaction of the flame with the fluid flow induced by the combustion products rather than the initial plume established by the hot surface. The details of the instability mechanism and the structure of the disturbance flow field are under investigation.

Acknowledgments

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