Effect of Equivalence Ratio on Ignition and Flame Propagation of *n*-Hexane-Air Mixtures using Moving Hot Particles

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1 Introduction

Assessing the risk of accidental ignition of flammable mixtures is an issue of importance in industry and aviation. Of particular interest are the risks introduced by the use of carbon fiber reinforced polymers (CFRP) as an alternative to aluminum alloys in aircraft manufacturing. In aircraft, potential ignition sources include lightning strikes, sparks from electrical equipment, electrostatic discharge in fuel tanks, and overheated pumps. In the case of a lightning strike on the aircraft structure, hot particles are often ejected from the surface that is struck due to resistive heating. Such hot particles represent a potential ignition hazard if they are ejected into flammable vapor. With this motivation, the present study is a contribution to understanding the phenomena of ignition by a single hot (inert) particle under well characterized conditions.

Previous experiments involving hot particle ignition include a particle heated in a furnace and then injected into an explosive atmosphere, as well as a stationary particle placed in an explosive atmosphere and heated via infrared laser light. The former experiment was performed by Silver [1] using two different particle materials, quartz and platinum. Varying the particle material had minimal effect on the minimum ignition temperature of three different flammable mixtures: a 10% coal-gas/air mixture, 3% pentane/air mixture, and a 20% hydrogen/air mixture. For a fixed gas mixture, the results suggest that the size and temperature of a particle are important factors in determining whether ignition occurs. The data indicate that as particle size is increased, the minimum temperature required for ignition is decreased. The experiments performed by Silver were done with particle speeds varying from $2 - 5$ m/s; however, the effect of particle speed was not investigated systematically. Beyer and Markus [2] performed studies using inert particles suspended in an explosive atmosphere and heated via infrared laser light. The combustible mixtures used by Beyer and Markus were pentane/air, propane/air, ethylene/air and hydrogen/air. The studies showed that the particle ignition temperature was weakly dependent on the mixture composition but was highly dependent on which combustible gas was used. The particle ignition temperature was also highly dependent on the particle diameter. More recently, Roth et. al [9] studied the ignition of hydrogen/air mixtures by submillimeter-sized particles and determined that the particle material (silicon nitride, tungsten carbide, steel, casting steel, and aluminum) had an effect on the ignition temperature for a fixed mixture composition. The study by Roth et . al suggests that chemically inert particles show the lowest surface temperature required for ignition when compared to the metal particles. Additional work on stationary hot particle ignition via laser light has been performed by Dubaniewicz et. al [3], Dubaniewicz [4, 5], Bothe et al. [6], Beyrau et al. [7], and Homan [8]. A comparison of the experimental data of Beyer and Markus, and Silver, for a pentane/air mixture suggests that, controlling for the diameter of the particle, a moving particle will have a higher ignition temperature than a stationary particle. Having reviewed these previous experiments, it is our view that existing work on moving hot particles in a flammable mixture is limited and deserves further study. Our study focuses on inert particles to minimize the complexity of the problem.

The aim of this work is to investigate the ignition of *n*-hexane-air mixtures (kerosene surrogate) using moving hot spheres. Tests are performed using alumina spheres with a diameter of 6.0 mm and varying particle surface temperatures and mixture compositions.

2 Experimental Setup

The ignition experiments were performed in a closed, cylindrical, stainless steel combustion vessel with a volume of approximately 22 L, shown in Fig. 1. Two parallel flanges are used to mount windows for visualization. Above the 22 L vessel sits a cylindrical, aluminum chamber with a volume of approximately 0.1 L, also shown in Fig. 1. The aluminum chamber is used to heat small spheres. The chamber has two parallel flanges that are used to mount titanium supports, one of which can be actuated linearly through a double acting pneumatic actuator. To heat a sphere, the titanium supports make contact with the sphere on opposite sides thereby maintaining it in place. The spheres are irradiated on opposite sides with a continuous CO_2 laser (Synrad) with an emission wavelength of 10.6 μm and a maximum power output of 80 W. The laser beam is split into two equal parts in order to irradiate the sphere on both sides.

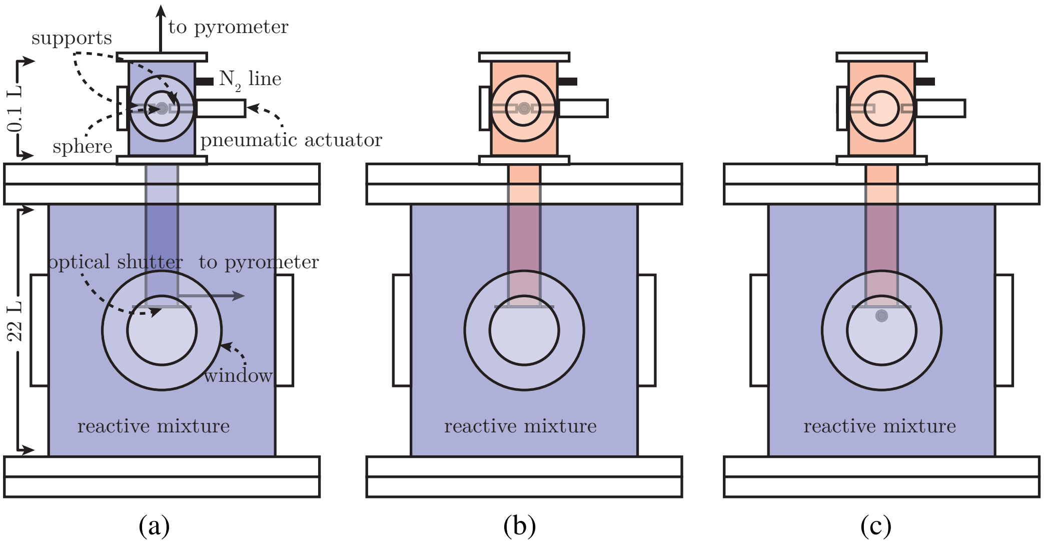


Figure 1: Experimental procedure for igniting a reactive mixture using a moving hot sphere, reactive mixture is shown in blue and N_2 is shown in red

Once a sphere is in place, a remotely controlled plumbing system is used to evacuate the combustion vessel and accurately fill it with the reactive mixture using the method of partial pressures, shown in Fig 1(a). A Heise manometer with a precise digital readout measures the static pressure so the gases can be filled to within 0.01 kPa of the desired gas pressure, providing precise control over the mixture composition. The aluminum chamber and a cylinder, shown in Fig. 1(b), are filled with nitrogen through a port on the chamber. The free end of the cylinder has an electric optical shutter that is closed once there is only nitrogen in the chamber and cylinder. This ensures that during heating, the sphere is in an inert environment and there is minimal diffusion of the nitrogen from the chamber into the reactive mixture. The bottom of the cylinder is vertically aligned with the top of the combustion vessel windows. A PID controller interfaces with the laser controller thereby allowing precise control of the sphere surface temperature. Once the desired sphere surface temperature is reached, one of the titanium supports retracts allowing the sphere to fall, shown in Fig. 1(c). The sphere travels through the cylinder, containing nitrogen, then exits through the open optical shutter into the combustion vessel, containing the reactive mixture, coming into the field of view of the windows. A two-color pyrometer is used to measure the sphere surface temperature during heating and prior to entering the reactive mixture as indicated in Fig. 1(a). The pyrometer has a response time of 10 μs which is fast enough to capture the temperature of the falling sphere. Due to the large size of the sphere, the temperature drop from heating to the second temperature measurement is less than 2%; this suggests that there is a negligible temperature drop as the sphere passes through the optical shutter. Three different methods were used for ignition detection. First, the pressure rise from the combustion was measured using a pressure transducer. This measurement also allowed us to determine the peak pressure rise in the vessel.

Second, the temperature rise was detected using a K-type thermocouple located inside the vessel. The third method used to detect ignition was a shearing interferometer shown in Fig. 2. The shearing interferometer was built using Wollaston prisms and a Coherent Sapphire 532 nm single mode laser. The interferometer was used to visualize the ignition and flame propagation using a high-speed camera at 10,000 frames per second and a field of view of approximately 30 mm.

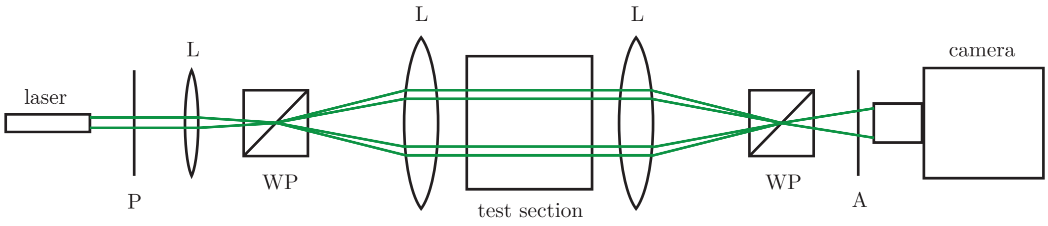


Figure 2: Shearing interferometer schematic (P: polarizer, L: lens, WP: Wollaston prism, A: analyzer)

3 Results

3.1 Overview

Ignition tests were performed for *n*-hexane-air mixtures at an initial temperature and initial pressure of 298 K and 100 kPa, respectively. The mixture equivalence ratio, Φ, was varied from 0.9 to 2.2 and alumina spheres 6.0 mm in diameter were used as the ignition source. Figure 3 shows interferometer frames of a no ignition event and an ignition event taken at similar times, from 0.0 ms to 12.5 ms. Each interferometer image shows contours of constant index of refraction integrated through the field of view. The flow field is axisymmetric about the path of the particle motion so that the Abel inversion can be used to determine the radial distribution of the index of refraction from the images. These images can be further post-processed to quantitatively extract the index of refraction which can then be used to calculate the gas density and temperature. The outer contour surrounding each sphere is analogous to the edge of the thermal boundary layer. The thin fringes represent regions in which a large temperature gradient is present, and the thicker fringes represent smaller temperature gradients. The no ignition images show that the temperature gradient is largest at the front stagnation point (as indicated by the thin fringes), and decreases (as indicated by the increase in thickness of the fringes) with increasing thermal boundary layer thickness along the streamwise direction until the flow separates. The flow appears steady and axisymmetric; the wake is composed of a steady toroidal vortex for Reynolds numbers between 20 and 210 in uniform temperature flows, as discussed by Johnson and Patel [10]. In the current study the Reynolds number is not uniquely defined due to the strong variation of the fluid properties through the boundary layer and wake region. In the ignition case of Fig. 3, the flow around the sphere remains similar to the no ignition case between 2.5 and 5.0 ms, after that time, the fringes begin to expand outwards away from the wake of the sphere indicating that ignition has taken place. At later times in the ignition case, the fringe contours in the recirculation region of the sphere appear to be discontinuous. The discontinuity suggests that there is no flame propagation directly behind the sphere. This indicates that at the time of ignition, the recirculation region of the sphere is entirely composed of N_2; therefore, a flame cannot propagate in the wake of the sphere. The flame geometry was also seen in preliminary numerical studies done by Coronel et. al [11]. In the last ignition frame, at 12.5 ms, the axisymmetry of the wake is evident by the two lobes behind the sphere indicating that the flame geometry is toroidal.

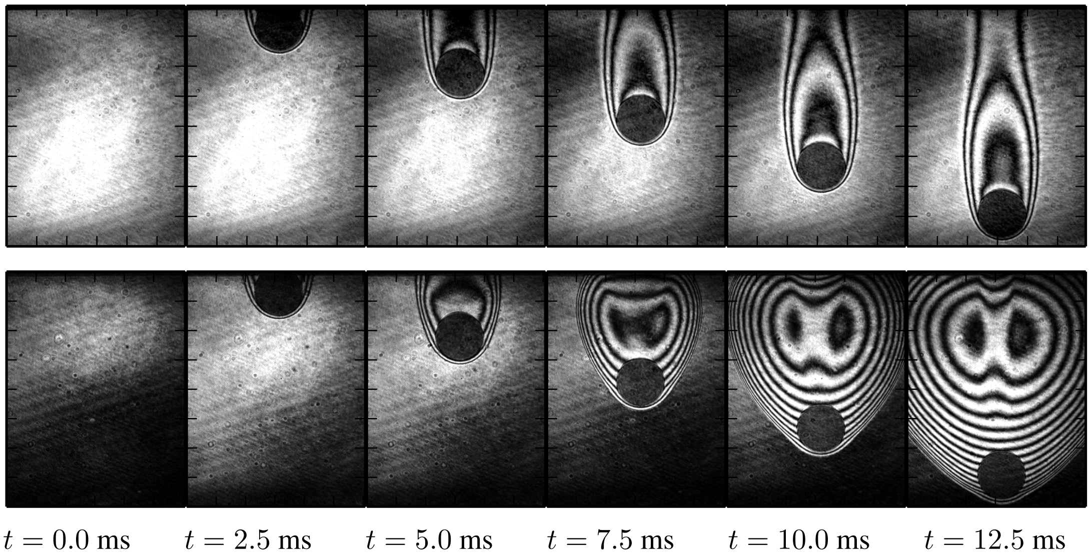


Figure 3: Infinite fringe interferometer images of a no ignition (top) and ignition (bottom) events with sphere temperatures of 979 K ± 27 K and 981 K ± 1 K , respectively, in *n*-hexane-air with an equivalence ratio of 0.9

3.2 Ignition Threshold

The sphere surface temperature was varied from approximately 750 K to 1200 K; ignition and no ignition events are shown in Fig. 4. The ignition threshold appears insensitive to the mixture composition over the equivalence ratios tested. Bayesian statistics of the ignition data yields a 50% probability of ignition at 980 K. Previous work done by Boettcher [12] using a glow plug to ignite *n*-hexane-air mixtures indicates that the ignition threshold is independent of the composition away from the flammability limits. Boettcher found an ignition threshold of 920 K ± 20 K using a glowplug that was 9.3 mm in height and 5.1 mm in diameter, this is approximately 6% lower than the average threshold found in the current study.

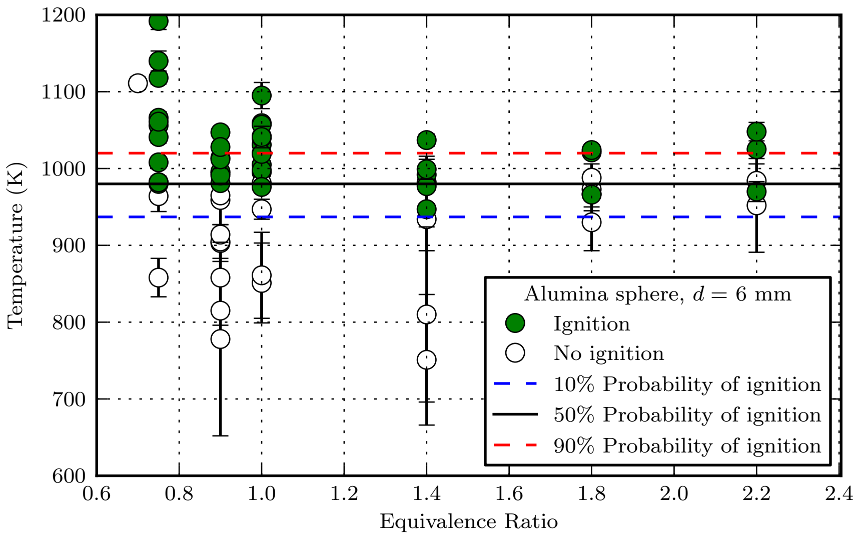
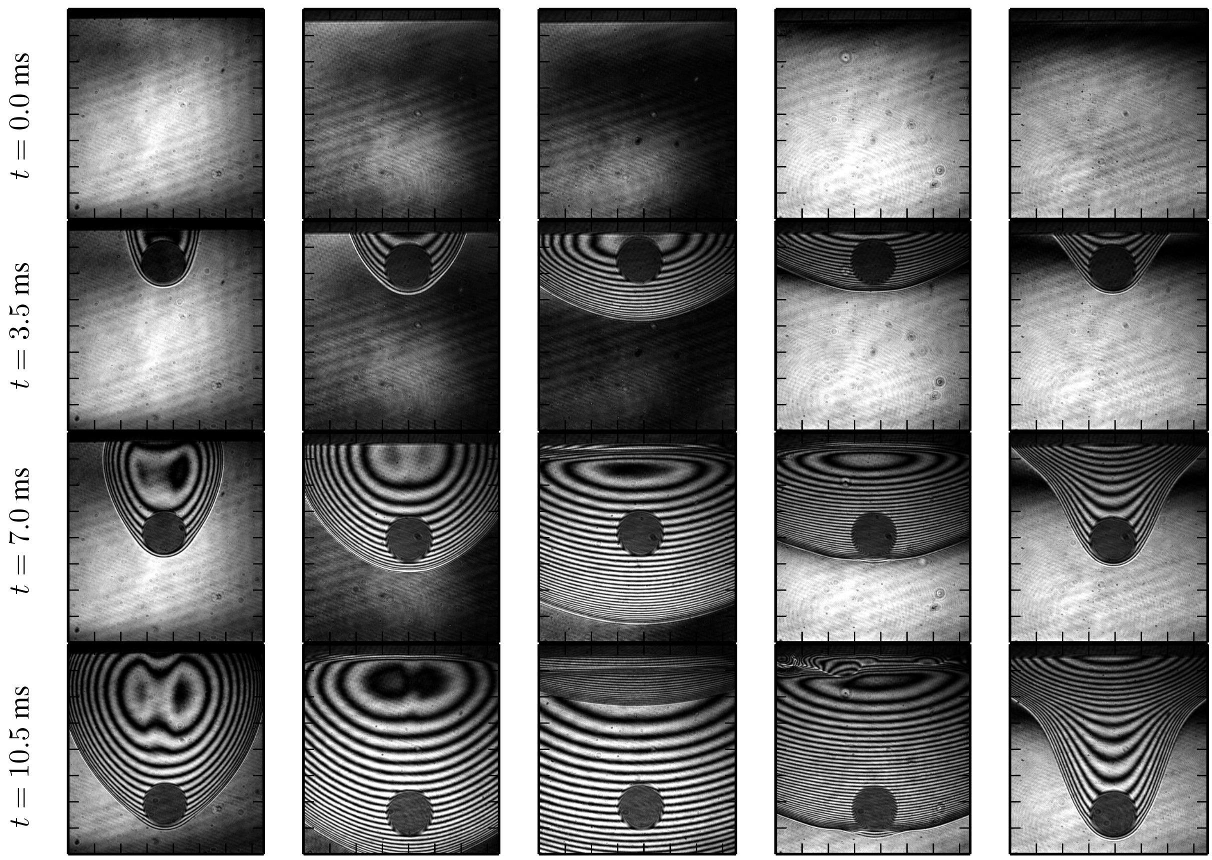


Figure 4: Hot particle ignition temperature as a function of equivalence ratio at atmospheric temperature and pressure

3.3 Flame Propagation

According to studies by Davis and Law [13] and Coronel et. al [14], the laminar burning speed of n-hexane-air mixtures at an initial temperature and pressure of 298 K and 100 kPa, respectively, reaches a maximum at $\Phi = 1.1$. The effect of mixture composition on the flame speed is shown in Fig. 5 at $\Phi = 0.9 - 2.0$. The surface temperature in each case is higher than the ignition threshold, therefore ignition occurs as soon as the sphere comes in contact with the reactive mixture. At $\Phi = 0.9$, the flame has a propagation speed of approximately 2.6 m/s [14] which is comparable to the sphere speed of 2.4 m/s. Figure 5(a) shows a flame that propagates outwards except near the front stagnation point where it remains anchored to the sphere. The flame geometry and flame/sphere interaction at $\Phi = 0.9$ suggests that the sphere speed is larger than the flame propagation speed. Figure 5(b) shows a flame that moves ahead of the sphere near the front stagnation point suggesting that the flame propagation speed is larger than the sphere speed. The change in curvature of the flame ahead of the stagnation point of the sphere at 7.0 ms and 10.5 ms suggests that the flame geometry is affected by the presence of the sphere. Previous work measured a flame propagation speed of 2.9 m/s at $\Phi = 1.0$ [14]. Figure 5(c) shows a flame that propagates away from the sphere in all directions and is not significantly affected by the presence of the sphere.



(a) $\Phi = 0.9$ (b) $\Phi = 1.0$ (c) $\Phi = 1.2$ (d) $\Phi = 1.7$ (e) $\Phi = 2.0$

Figure 5: Flame propagation in n-hexane-air at various equivalence ratios and an initial temperature and pressure of 298 K and 100 kPa, respectively

The flame shape closely resembles that produced by a stationary ignition source. Figure 5(d) shows a flame with a propagation speed that is smaller than the sphere speed. The sphere eventually begins to break through the flame front at 7.0 ms. Figure 5(e) shows a flame at $\Phi = 2.0$ with the smallest propagation speed observed in this study. The sphere appears to have already broken through the flame front at 3.5 ms. At later times, the burned products are entrained in the wake of the sphere yielding the flame/burned products geometry observed in Fig. 5(e).

3 Conclusions

In the present study, the ignition of *n*-hexane-air mixtures by moving hot spheres has been investigated experimentally for a range of equivalence ratios. The ignition threshold for the equivalence ratios tested was on average 980 K for a 6.0 mm sphere traveling at 2.4 m/s. A wider range of equivalence ratios needs to be tested to determine if the ignition threshold is independent of the mixture composition away from the flammability limits of *n*-hexane-air mixtures as concluded by Boettcher [12]. Interferometry images showed that for certain mixture compositions there is an interaction between the sphere and the flame that leads to: anchoring of the flame to the front stagnation point and puncturing of the flame front by the sphere. Further postprocessing of the interferometer images will provide insight into the ignition location as well as the flame propagation behavior for very rich mixtures.

Acknowledgements

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