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Experimental and numerical study on moving hot particle ignition

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ABSTRACT

Ignition thresholds for *n*-hexane-air were experimentally and numerically determined using a moving hot sphere of 6 mm in diameter. The novel experimental setup built for this purpose was described in detail. Two-color pyrometry was used for surface temperature measurements, and shearing interferometry flow field visualization was used to observe the onset of an ignition kernel, and subsequent flame formation and propagation. The probability of ignition was found to be 90% at a sphere surface temperature of 1224 K. Analysis of the interferograms at the ignition threshold indicated that ignition occurs near the region of flow separation. Numerical simulations of the transient development of the 2-D axisymmetric motion and ignition were performed. Four reduced chemical mechanisms, including high and low temperature chemistry, and two diffusion models were used to determine their impact on the numerical prediction of ignition thresholds. The simulation results were unaffected by the choice of diffusion model but were found to be sensitive to the chemical kinetic mechanism used. The predicted ignition threshold temperatures were within 6–12% of the experimentally determined values. The numerical fields of the energy source term and a wall heat flux analysis confirmed the experimental observation that ignition occurs near the region of flow separation at the ignition threshold. Detailed analysis of the species temporal evolution at the ignition location revealed that *n*-hexane is present in small amounts, demonstrating the importance of accounting for fuel decomposition within the thermal boundary layer when developing simple chemical reaction models.

1. Introduction

The motivations of the present study are the analysis and mitigation of potential fire and explosion hazards in industrial and transportation systems. This is a critical design issue for commercial aircraft under a range of normal operating conditions as well as anticipating equipment failures. One of the potential hazards that must be considered as part of certification is the ignition of flammable fluids (aviation kerosene, engine oil, hydraulic fluids) by hot surfaces which may be present by design (engines, hot air ducts) and can also occur due to events like lightning strike, rotor burst or electrical system failures. At present, the analysis of hot surface ignition relies extensively on legacy guidelines that are based on empirical test methods that often have little relation to the actual hazards. The goal for the future is the development of more applicable tests and analysis methods based on the numerical simulation of thermal ignition.

The present study focuses on the canonical situation of a hot spherical particle (inert) entering a well characterized flammable atmosphere of a single component hydrocarbon fuel well mixed with air. Previous experiments on hot particle ignition include particles heated in a furnace and then injected into an explosive atmosphere, as well as stationary particles placed in an explosive atmosphere and heated via laser light. Silver [1] performed moving hot particle experiments 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 (coal-gas is composed of CO_2, CO, CH_4, and H_2), a 3% *n*-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 were the most important factors in determining whether ignition occurs. The experiments performed by Silver [1] were done with particle speeds of 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 laser light. The combustible mixtures used in the experiments were *n*-pentane-air, propane-air, ethylene-air,

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and hydrogen-air. The studies showed that the minimum ignition temperature was weakly dependent on the equivalence ratio but was highly dependent on the fuel used. The minimum ignition temperature was also highly dependent on the particle diameter. More recently, Roth et al. [3] studied the ignition of hydrogen-air mixtures by sub-millimeter-sized particles and determined that the particle material (silicon nitride, tungsten carbide, steel, casting steel, and aluminum) had an effect on the minimum ignition temperature for a fixed mixture composition. For example, the aluminum particles had the lowest ignition thresholds (920–1060 K) over a wide range of diameters and the steel type 1.4034 and 1.3541 had the highest ignition thresholds (1150–1310 K). Additional work on stationary hot particle ignition via laser light was performed by Beyrau et al. [4,5], Bothe et al. [6], Dubaniewicz et al. [7,8], Dubaniewicz [9], and Homan [10].

A comparison of the experimental data of Beyer and Markus [2] and Silver [1] for a *n*-pentane-air mixture suggests that controlling for the diameter of the particle, a moving particle will have a higher minimum ignition temperature than a stationary particle. Paterson [11] saw a 300 K increase in the ignition threshold for a 2 mm diameter particle injected into a 9% coal-gas-air mixture at 10 m/s vs. 65 m/s. In addition, Paterson [12] performed experiments, similar to Silver [1], in coal-gas-air, *n*-pentane-air, and hydrogen-air, at particle speeds of 1.2 m/s compared to Silver's speeds of $2-5$ m/s. At 1.2 m/s, the minimum ignition temperature of a 3% pentane-air mixture in Paterson's study was 100 K lower than the temperature obtained in Silver's study with higher particle velocities.

A review of previous work on experimental hot particle ignition indicates that the processes in the gas adjacent to the particle prior to and after ignition have not been examined carefully; previous experimental studies have been limited to ignition threshold measurements. Numerically, the dynamics of ignition of stoichiometric hydrogen-air mixtures by hot particles and the importance of differential diffusion effects on the prediction of ignition thresholds were topics of recent studies [13,14]. Additionally, a simplified model was used by Mével et al. [15] to analyze the chemical kinetics of *n*-hexane-air along streamlines in the thermal boundary layer of a moving hot particle. Häber et al. [16] performed simulations of hot stationary particles suspended in a reactive mixture (similar to the setup found in Roth et al. [3]) using a one-dimensional (radial) diffusion-chemical reaction model and a 2-D OpenFOAM model. Finally, Zirwes et al. [17] studied the effect of hot particle velocity on the ignition of hydrogen-air mixtures using 2-D axisymmetric and 3-D numerical simulations.

The specific objectives of the present investigation are: (1) develop an experimental technique for creating a moving hot particle with a well characterized and controlled temperature, (2) measure ignition temperature thresholds for a particle diameter of 6 mm, (3) make detailed optical observations of events in the gas near the particle surface at the ignition threshold, and (4) investigate numerically the key physical and chemical processes taking place at and near the ignition location.

2. Technical approach

2.1. Experimental methodology

The ignition experiments were performed in a closed, cylindrical, stainless steel combustion vessel with a volume of approximately 22 L, shown in Fig. 1. The combustion vessel had a height of 37.5 cm and an inner diameter of 30.2 cm. Two parallel flanges were used to mount 12 cm diameter windows for visualization. Above the vessel sat a cylindrical aluminum chamber with a volume of approximately 0.1 L, also shown in Fig. 1. The small chamber had an inner diameter of 4 cm and a height of 8.9 cm. At the bottom of the small chamber was an opening with a hollow cylinder attached to it; the cylinder extended into the inside of the combustion vessel and could be closed off with a remotely controlled electrical shutter.

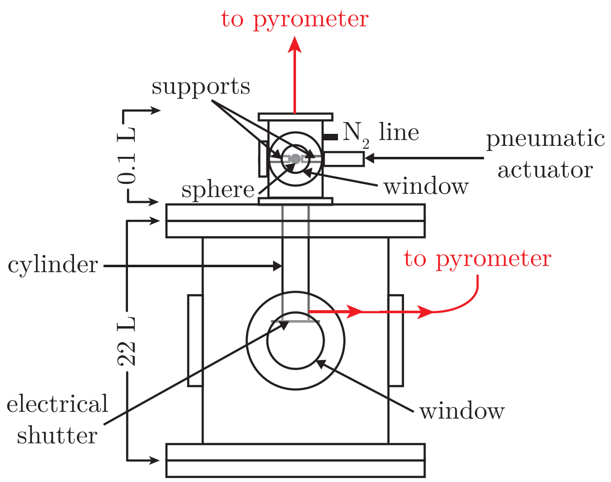

Fig. 1. Combustion vessel and small chamber with components labeled; the red lines correspond to locations where temperature measurements are made using a two-color pyrometer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The aluminum chamber was used to contain the heated spheres; it had two parallel flanges that were used to mount titanium rod supports. One support was actuated linearly through a double acting pneumatic actuator, the other support was fixed. The titanium supports made contact with the sphere on opposite sides, holding it in place. The other two sides of the chamber held ZnSe (Zinc-Selenide) windows with a field of view of approximately 1.9 cm. A high power CO_2 laser (Synrad ti80, 80 W) was used to heat each sphere with illumination from both sides.

Once a sphere was in place, a remotely controlled plumbing system was used to evacuate the combustion vessel to less than 7 Pa and accurately fill it with the reactive mixture using the method of partial pressures. A Heise manometer with a precise digital readout measured the static pressure so the gases could be filled to within 10 Pa of the desired gas pressure, providing control over the mixture composition. The aluminum chamber and attached cylinder were filled with nitrogen through a port on the chamber labeled "N_2 line" (see Fig. 1). The bottom end of the cylinder had an electrical shutter designed for optical systems that was closed once the chamber and cylinder were completely filled with nitrogen. This ensured that during heating, the sphere was in an inert environment and there was minimal diffusion of the nitrogen from the chamber into the reactive mixture. The bottom end of the cylinder was vertically aligned with the top of the combustion vessel windows to allow for flow visualization.

A PID (Proportional, Integral, Derivative) feedback controller used a two-color pyrometer output to adjust the CO_2 laser power, thereby allowing precise control of the sphere surface temperature during heating. An example of the power modulation during heating of a 6 mm diameter sphere is shown in Fig. 2. Once the desired sphere surface temperature was reached, one of the titanium supports retracted, allowing the sphere to fall. The sphere traveled through the cylinder (containing nitrogen) and then exited through the now open optical shutter into the combustion vessel (containing the reactive mixture) and came into the field of view of the windows. A two-color pyrometer measured the sphere surface temperature during heating (Fiber A in Fig. 3) and prior to entering the reactive mixture (Fiber B in Fig. 3) as indicated in Fig. 1. The two-color pyrometer used in this study, shown in Fig. 3, consisted