Spark Ignition of Kerosene-Air Mixtures

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1 Introduction

Determining the risk of accidental ignition of flammable mixtures is a topic of tremendous importance in industry and aviation. The concept of minimum ignition energy (MIE) has traditionally been the basis for studying ignition hazards of fuels, and standard test methods exist for determining the MIE of a given mixture using a capacitive spark discharge as the ignition source. Researchers at the Bureau of Mines in the 1940s used this test method to perform pioneering work on determining MIE values for many different fuels [1], and their data is still extensively cited in the literature. Since the work at the Bureau of Mines, other researchers have used similar test methods to determine MIE values for pure C_1 to C_{10} hydrocarbon fuels [2–5].

However, in aviation the actual threat is ignition of aviation kerosene (Jet A), a fuel that is a blend of 100-200 different hydrocarbons with a wide range of carbon atoms per molecule. While MIE values have been determined for many pure hydrocarbon fuels, very little experimental work has been done on investigating the ignition energies of kerosene-air mixtures. Nestor [6] and Ott [7] performed studies to determine the flammability limits of jet fuels, given in terms of the temperature range within which there is sufficient fuel vapor pressure to make the fuel-air mixture flammable. Following the crash of Trans World Airlines Flight 800 in 1996, a series of studies were performed at the California Institute of Technology by Shepherd et al. [8] and Lee and Shepherd [9] on the flammability and MIE of Jet A. They found that the MIE of Jet A-air mixtures varied from 100 J for a fuel temperature of 25°C to 40 mJ for a fuel temperature of 55°C. Despite these previous efforts, we are still lacking a comprehensive database of ignition energy data for use in safety assessment.

In the current work, ignition of kerosene is examined experimentally using very short duration (< 50 ns), low energy (< 10 mJ) capacitive sparks as the ignition source. Ignition tests are performed with varying spark energies and a range of fuel temperatures. In previous work on spark ignition [10, 11] a single threshold minimum ignition energy was not observed, but rather the ignition was found to be probabilistic in nature at low spark energies. Therefore, as in the previous work, the results of the kerosene tests are analyzed using statistical tools to obtain probability distributions for ignition versus spark energy or spark energy density. The results are then compared with results from our previous work on ignition of lean hydrogen-based mixtures used in aviation testing [10, 11] and two hexane-air mixtures [11].

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2 Experimental Setup and Methods

Ignition experiments were performed in a closed, cylindrical, stainless steel combustion vessel approximately 22 L in volume. Two parallel flanges were used to mount the spark gap electrodes, and the other two flanges held windows for visualization. The low-energy capacitive spark ignition system used is described in detail in Bane et al. [10] and Bane [11]. The gas pressure was measured using a piezoresistive pressure transducer with the output displayed using National Instruments LabVIEW software, and an exhaust line was installed to circulate fresh air through the vessel. A variable-speed fan mixer, mounted near the top of the vessel, was used to mix the air and kerosene vapor to ensure homogeneous composition. Kerosene has a very low vapor pressure at room temperature, so to increase the fuel vapor concentration the fuel must be heated. Therefore, a heating system was designed to heat the vessel up to approximately 200°C. Flexible silicone heaters were mounted on the surfaces of the vessel and flanges and divided into four zones, each with a separate temperature controller.

Three different methods were used to reliably detect whether or not ignition occurred. First, the pressure rise from the combustion was measured using the pressure transducer. This measurement also allowed us to determine the peak pressure rise in the vessel. Secondly, the temperature rise was detected using a K-type thermocouple inside the vessel. The third method used to detect ignition was schlieren visualization of the flame propagation recorded using a high-speed camera.

In previous testing with gaseous fuels at room temperature, the vessel was first evacuated and then filled using the method of partial pressures. However, with kerosene or other fuels with low vapor pressure, the experimental method is considerably more complicated. First, the fuel mass loading (mass of liquid fuel divided by the vessel volume) must be chosen to determine the volume of fuel. With the vessel at room temperature, the kerosene is then poured into the bottom of the vessel before sealing and heating the vessel. The heating zone at the bottom of the vessel, closest to the liquid pool of fuel, was set to the desired fuel temperature. The other zones were heated to a higher temperature to prevent condensation of the fuel. Once the desired temperature was attained and the fuel vapor and air were sufficiently mixed, a spark with pre-determined stored energy was initiated inside the vessel. If ignition occurred, air was circulated through the vessel and then the lid was removed so that the inside walls and electrodes could be cleaned. After three successful ignitions, the kerosene was removed and fresh kerosene was introduced to keep the fuel vapor concentration as consistent as possible.

3 Preliminary Results

In the present work, ignition of kerosene-air mixtures at atmospheric pressure and various fuel temperatures is examined. The first set of 12 tests was performed using 1-K kerosene and a fuel temperature of 60°C and a fuel mass loading of approximately 50 kg/m^3. A fixed spark gap of 3.3 mm was used in the first tests, and the spark energy was varied by changing the discharge circuit capacitance. The spark energies ranged from 0.45 mJ to 2.2 mJ, and the results of the 12 tests are shown in Figure 1. The range of the spark energy where the tests with ignition overlap with the tests with no ignition is highlighted in gray. The lowest spark energy that ignited the mixture was 0.65 mJ, while the highest spark energy that did not ignite the mixture was 1.75 mJ. The contradictory data points demonstrate the probabilistic nature of ignition near the minimum ignition energy, and there is a non-zero probability of ignition in the data overlap region rather than a single well-defined MIE threshold. In the previous work performed at Caltech [9], the highest fuel temperature tested at atmospheric pressure was 52°C. The lowest spark energy to cause ignition at this temperature was found to be approximately 40 mJ, nearly two orders of magnitude larger than the lowest energy to cause ignition in the preliminary tests for this work (0.65 mJ). This large discrepancy may be explained by the large difference in the fuel temperature; the va-

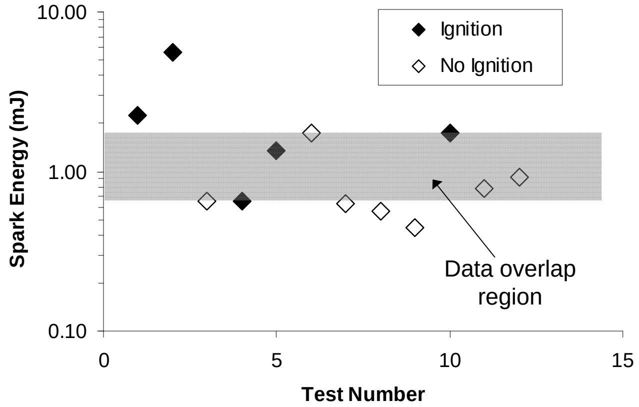

Figure 1: Data points from the 12 spark ignition tests performed in kerosene-air at 60°C. The data overlap region is shown in gray.

por pressure scales exponentially with the temperature, so the increase in temperature can significantly affect the fuel vapor/air ratio.

We also compare the results of the current work with the results of previous ignition tests in hydrogen and hexane [10, 11]. We have performed spark ignition tests in the lean hydrogen test mixture recommended by the SAE for use in aviation safety testing [12] (5% H_2, 12% O_2, 83% Ar), as well as in mixtures with 6 and 7% H_2 to examine the effect of fuel concentration. The test results were analyzed using statistical methods [10] to derive probability distributions for ignition versus spark energy. These probability distributions for the hydrogen test mixtures are shown in Figure 2 with the results from the preliminary tests in kerosene-air. The figure shows that in two of the kerosene tests where ignition occurred, the spark energies were comparable to the required ignition energies for the 5% H_2 mixture. The preliminary results indicate that under certain conditions, the kerosene may be more sensitive, and hence easier to ignite, than the standard hydrogen test mixture.

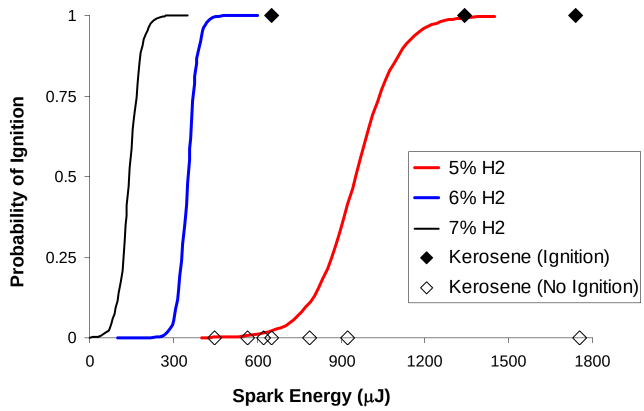

Figure 2: Ignition probability distributions derived from test data for the 5% H_2 mixture recommended by the SAE for aviation testing [12] and mixtures with 6 and 7% H_2 [10]. The data from the present kerosene ignition tests are shown for comparison.

The preliminary results of the current work indicate that kerosene can be ignited with lower spark energies than previously thought possible. Continuing with this investigation, the fuel temperature is varied to identify the temperature (and associated fuel-air ratio) that has the lowest overall ignition energy. Additionally, the test results for each temperature are analyzed using statistical tools to obtain probability distributions for ignition versus the spark energy. Finally, the results for ignition in the kerosene-air mixtures are compared with the results of previous work using hydrogen and hexane test mixtures. This study provides new, important data on the sensitivity of kerosene and the threat it poses relative to hydrogen and hexane.

References

[1] Lewis B and von Elbe G. (1961). Combustion, flames and explosions of gases. 2nd ed. New York: Academic Press

[2] Calcote H, Gregory C, Barnett C, and Gilmer R. (1952). Spark ignition effect of molecular structure. Ind. Eng. Chem. 44: 2656.2662

[3] Metzler A. (1952). Minimum ignition energies of six pure hydrocarbon fuels of the C2 and C6 series. NACA Research Memorandum E52F27

[4] Metzler A. (1953). Minimum ignition energies of 12 pure fuels at atmospheric and reduced pressure. NACA Research Memorandum E53H31

[5] Moorhouse J, Williams A, and Maddison E. (1952). An investigation of the minimum ignition energies of some C1 to C7 hydrocarbons. Combust. Flame 23: 203.213

[6] Nestor L. (1967). Investigation of turbine fuel flammability within aircraft fuel tanks. Final report DS-67-7, Naval Air Propulsion Test Center, Naval Base, Philadelphia, PA

[7] Ott E. (1970). Effects of fuel slosh and vibration on the flammability hazards of hydrocarbon turbine fuels within aircraft fuel tanks. Technical report AFAPL-TR-70-65, Fire Protection Branch of the Fuels and Lubrication Division, Wright-Patterson Air Force Base, Ohio

[8] Shepherd J, Krok J, and Lee J. (1999). Spark ignition energy measurements in Jet A. Graduate Aerospace Laboratories Report FM 97-9, California Institute of Technology

[9] Lee J and Shepherd J. (2000). Spark ignition energy measurements in Jet A: part II. Graduate Aerospace Laboratories Report FM 99-7, California Institute of Technology

[10] Bane S, Shepherd J, Kwon E, and Day A. (2010). Statistical analysis of electrostatic spark ignition of lean H2/O2/Ar mixtures. Int. J. Hydrogen Energy, article in press, doi:10.1016/j.ijhydene.2010.05.082

[11] Bane S. (2010). Spark ignition: experimental and numerical investigation with application to aviation safety. Ph.D. dissertation, California Institute of Technology

[12] SAE International. (2005). Aerospace recommended practice lightning test methods, ARP5416