n-Heptane Ignition: High-Speed Imaging in a High-Pressure Shock Tube

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1 Introduction

Conventional distillate fuels are complex hydrocarbon mixtures. Understanding the low-temperature, high-pressure chemistry of these fuels and their surrogate components is critical to understanding auto-ignition and knocking behavior in real engines [1,2]. Simple modeling of ignition behind reflected shock waves assumes that these processes are zero-dimensional. However, there is growing evidence of inhomogeneous ignition processes occurring under certain conditions in these facilities. Conventional methods of studying these processes in shock tubes, i.e. using pressure transducers, emission, and line-of-sight laser absorption, may not be sufficient to distinguish between inhomogeneous and homogenous ignition modes, necessitating more sophisticated methods to identify homogeneous ignition. One such method is high-speed end-wall imaging [3,4].

Recently, high-speed imaging was used in low-pressure shock tubes [3,4,5-7] and rapid compression machines (RCM) [8-11] to study the localized point ignitions. Troutman et al. [3] pioneered this endwall high-speed imaging method to investigate ignition phenomena in shock tubes. Tulgestke et al. [4] studied homogeneous and inhomogeneous ignition of real and surrogate fuels at low pressures. Figueroa-Labastida et al. [5] studied ethanol preignition using high-speed imaging in a high pressure shock tube. Vasu et al. [6-8] studied the auto-ignition of highly CO2 diluted mixtures using high-speed imaging at low pressures in a shock tube. Mansfield et al. [9] observed auto-ignition properties of iso-octane mixtures in rapid compression machines using high-speed imaging through a transparent end-wall. Leschevich et al. [10] captured ultrafine particle ignition during stoichiometric methane oxidation in an RCM using two-frame imaging. Wang et al. [11] studied hot-spot induced deflagration to detonation using high-speed imaging on an RCM. Buttgen et al. [12] studied ethanol ignition under engine relevant conditions in a RCM using high-speed imaging. However, high-speed imaging has not yet been applied to the study of auto-ignition in a shock tube at elevated pressures.

In this study, we implemented high-speed imaging of reactive n-heptane mixtures behind reflected shock waves in a high-pressure shock tube, using a modified shock tube endwall to investigate homogeneous and inhomogeneous ignition behavior. n-Heptane was selected for study because of its strong NTC behavior. Of interest in the present study is that the presence of strong NTC behavior may make the fuel more susceptible to thermal boundary layer ignition [13].

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2 Experimental Setup

All experiments were performed using the Stanford high-purity, 5 cm inner diameter, high-pressure helium-driven shock tube. Test times, typically 2 ms, were extended to 6 ms, when needed, by tailoring the driver gas with nitrogen and using a driver insert to maintain constant non-reactive pressure profiles. The shock tube imaging setup was the same as that first reported by Troutman et al. [3]. A Vision Research Phantom v710 high-speed CMOS camera coupled to a UV intensifier was used to collect OH* chemiluminescence isolated using an Asahi Spectra high-transmission band-pass filter centered at 313 nm with 10 nm FWHM through a sapphire endwall of the shock tube. Additional diagnostics included: fuel concentration measurement by IR laser absorption at 3.41 μm, and sidewall PZT pressure measurement. More details about sidewall fuel concentration and pressure measurements were discussed in earlier high-pressure large hydrocarbon ignition studies [14].

3 Results and Discussion

Two low-temperature ignition experiments are discussed: near-homogeneous ignition at 876 K and near-homogeneous ignition at 799 K with evidence of hot spot ignition.

Figure 1 shows a case with n-heptane/air mixture at T_5 = 876 K, P_5 =16.0 atm and ϕ=0.5. The non-reactive pressure trace shows the pressure trace is almost flat before ignition with a maximum deviation of about 10%. The reactive pressure trace indicates ignition occurs at 4.5 ms. This is consistent with the rapid drop in 341 μm absorbance that occurs at the same time. In the images of Fig. 1, emission first occurs at the bottom of the tube at 3.92 ms, but it does not cause a strong combustion wave that could affect the core region of the tube. Instead, it expands uniformly over the tube before main ignition happens. This is a typical example of near-homogeneous auto-ignition at low temperatures.

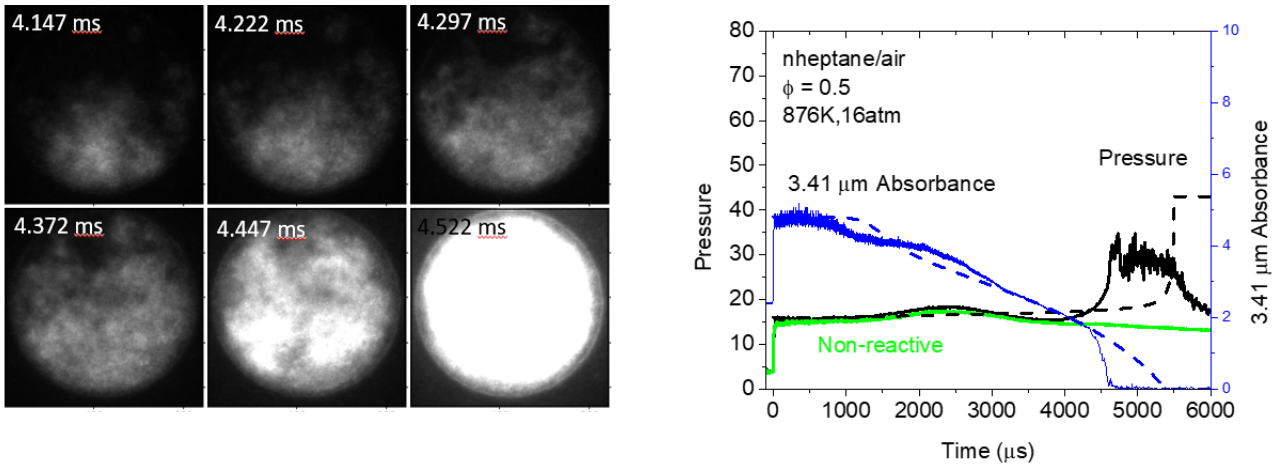

Fig. 1. Near-homogeneous ignition in the HPST; n-heptane/air, ϕ=0.5, T=876 K, P=16.0 atm. Dashed lines are simulated fuel and pressure time histories using the Lawrence Livermore National Laboratory (LLNL) gasoline surrogate detailed mechanism and a constant volume Chemkin model [1].

Hot-spot induced local ignition can be a major cause of non-ideal ignition events [4], however, they have not been observed at high pressures. With low fuel loading, it is less likely for hot-spots to form an ignition kernel and induce a deflagration. Hot-spot ignition is more likely with higher fuel loading, where more energetic ignition can cause oscillations in the measured sidewall laser absorption and pressure signals, and can be easily identified. Frequent cleaning of the shock tube can aid in getting rid of the hot-spots. [4]

Figure 2 shows a representative experiment with an n-heptane/air mixture at T_5 = 799 K, P_5 = 16.0 atm and ϕ=1. The measured 3.41 μm absorbance and the pressure signal are smooth and well behaved. Based on prior low-pressure shock tube experience relating to how hot-spot ignition could be identified, the laser absorption and pressure signal of this experiment would not be readily associated with hot-spot ignition. However, we do see OH* emission near hot-spots in the imaging plots of Fig. 2. Despite these local ignition points, a deflagration or detonation is not formed, and the core region experiences a nearly homogeneous ignition event.

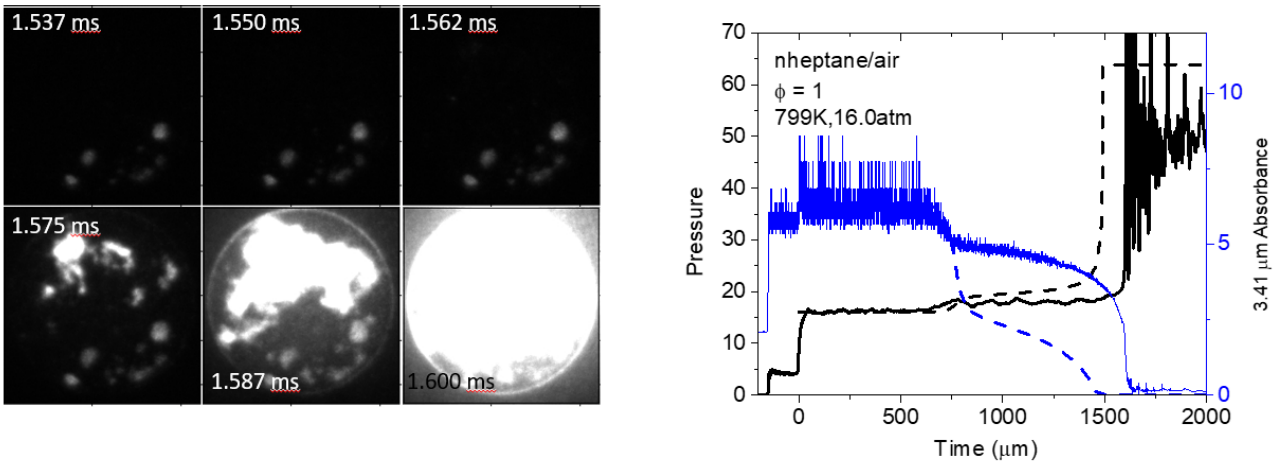

Fig. 2. Near-homogeneous ignition in the HPST; n-heptane/air, ϕ=1, T=799 K, P=16.0 atm. Dashed lines are simulated fuel and pressure time histories using the Lawrence Livermore National Laboratory (LLNL) gasoline surrogate detailed mechanism and a constant volume Chemkin model [1].

Conclusion

Homogeneous and inhomogeneous ignition modes of one major distillate fuel surrogate component, n-heptane, were studied in a high-pressure shock tube using high-speed endwall imaging. High-speed imaging provided unequivocal evidence of homogeneous or inhomogeneous ignition behavior beyond that inferred from conventional sidewall pressure and laser absorption fuel signals. Endwall imaging studies can thus be used to significantly improved confidence in low-temperature, high-pressure ignition delay time studies where extended ignition delay times can be susceptible to non-ideal processes.

Acknowledgements

This work was supported by the U. S. Army Research Laboratory and the U. S. Army Research Office under grant number W911NF-17-1-0420 and the Air Force Office of Scientific Research through AFOSR Grant No. FA9550-16-1-0195, with Dr. Chiping Li as contract monitor,

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