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Shock tube studies of ethanol preignition

Miguel Figueroa-Labastida[a], Jihad Badra[b], Ayman M. Elbaz[a,c], Aamir Farooq[a,*]

[a] Clean Combustion Research Center, Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
[b] R&DC, Fuel Technology Division, Saudi Aramco, Dhahran 31311, Saudi Arabia
[c] Faculty of Engineering – Mattaria, Helwan University, Cairo Egypt

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ABSTRACT

Understanding premature ignition or preignition is of great importance as this phenomenon influences the design and operation of internal combustion engines. Preignition leading to super-knock restricts the efficiency of downsized boosted engines. To gain a fundamental understanding of preignition and how it affects an otherwise homogeneous ignition process, a shock tube may be used to decipher the influence of fuel chemical structure, temperature, pressure, equivalence ratio and bath gas on preignition. In a previous work by Javed et al. (2017), ignition delay time measurements of n-heptane showed significantly expedited reactivity compared to well-validated chemical kinetic models in the intermediate-temperature regime. In the current work, ethanol is chosen as a representative fuel that, unlike n-heptane, does not exhibit negative temperature coefficient (NTC) behaviour. Reactive mixtures containing 2.9% and 5% of ethanol at equivalence ratios of 0.5 and 1 were used for the measurement of ignition delay times behind reflected shock waves at 2 and 4 bar. Effect of bath gas was studied with mixtures containing either Ar or N_2. In addition to conventional side-wall pressure and OH^* measurements, a high-speed imaging setup was utilized to visualize the shock tube cross-section through a transparent quartz end-wall. The results suggest that preignition events are more likely to happen in mixtures containing higher ethanol concentration and that preignition energy release is more pronounced at lower temperatures. High-speed imaging shows that low-temperature ignition process is usually initiated from an individual hot spot that grows gradually, while high-temperatures ignition starts from many spots simultaneously which consume the reactive mixture almost homogeneously.

1. Introduction

Preignition, which is an ignition event before it is expected and generally where it is not expected, is a type of abnormal combustion that has been observed since the 1920s [2] in systems such as aircraft [3] and automotive internal combustion (IC) engines [4]. As these engineering systems have evolved with time, the factors that lead to preignition back then could be different to those observed nowadays [5]. Generally, preignition hypotheses revolve around the existence of hot surfaces [6] or hot particles [7–9] that can be the source of end-gas ignition during an engine cycle. The importance of understanding preignition lays on the negative effects that it can cause on engines, such as high-pressure events identified as knock [10] or the more dramatic superknock [11], and the limitations it puts on designing modern downsized engines.

Shock tubes provide a nearly ideal chemical reactor [12] to study ignition phenomena as a function of temperature, pressure and fuel/oxidizer mixture composition. Conscious of the different nature of physics happening in a shock tube and in an engine, one has to be careful in directly extending the conclusions drawn from shock tube experiments to engines and other devices. Nevertheless, a shock tube provides a well-controlled and simple environment to study preignition than trying to decouple it from many other phenomena in an engine. Previously, Uygun et al. [13] observed appreciable preignition pressure rise during the ignition of 2-methylfuran in a shock tube. They used schlieren imaging to show that the main ignition event was preceded by deflagrative flame kernels. Javed et al. [1] reported expedited shock tube ignition delay measurements of n-heptane in the intermediate temperature (or NTC) region. Computational fluid dynamic (CFD) simulations of a randomly located hot spot in the test section showed that energy release from the hot spot can expedite ignition delay times, in agreement with their experimental observations. Troutman et al. [14] analyzed the inhomogeneous combustion of n-heptane mixtures and related their findings to optical window

* Corresponding author.
E-mail address: aamir.farooq@kaust.edu.sa (A. Farooq).

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recessions and cleanliness in the shock tube facility. Recently, Ninnemann et al. [15] observed preignition for high-concentration hydrogen/oxygen mixtures, identifying mild combustion events starting with weak flame kernels.

Preignition phenomenon has also been studied in rapid compression machines (RCMs). Walton et al. [16] used high-speed imaging in their rapid compression facility and observed localized reaction front propagation for fuel concentrations above a critical value in syngas and iso-octane mixtures. Wang et al. [17] also utilized high-speed imaging in an RCM to describe the superknock process for iso-octane, where they identified deflagration, detonation and posterior pressure oscillations.

High-speed imaging is a non-intrusive technique that can give a good physical insight of the processes leading to preignition events and the way this phenomenon evolves in the system. High-speed analyses have been performed in engine cycles [18], rapid compression machines [16,17,19], flames [20] and spray characterization [21]. High-speed OH* chemiluminescence may be related to the rate of heat release of the observed phenomenon [22]. Some imaging experiments have recently been performed in shock tubes for the investigation of combustion homogeneity with various fuels, such as n-heptane, hydrogen and syngas [14–15,23–27].

In the current work, ethanol is chosen as a representative non-NTC fuel which is thought to be quite prone to preignition [28,29] due to its relatively small laminar flame thickness. The combustion chemistry of ethanol has been extensively studied previously with experiments and modelling [30], and the literature kinetic models are, generally, quite reliable. Here, measured ignition delay times of ethanol are compared with chemical kinetic simulations to illustrate the effects of preignition on the autoignition characteristics of ethanol. Additionally, high-speed OH* chemiluminescence setup is used to record two-dimensional images of the reaction sequence through the shock tube end-wall. The imaging results are used to understand the processes and thermodynamic conditions that dictate ethanol preignition.

2. Experimental details

2.1. Ignition delay time setup

Ignition delay times of various mixtures of ethanol/oxygen/argon and ethanol/oxygen/nitrogen were measured behind reflected shock waves using the low-pressure shock tube (LPST) facility at King Abdullah University of Science and Technology (KAUST). The driver and driven section of this facility are each 9.1 m long, separated by a polycarbonate diaphragm, with an inner diameter of 14.2 cm. The driver section is modular with four sub-sections, and the number of sections used depends on the desired test time of the experiment. To study ethanol ignition at low temperatures, long test times were achieved by using the full length of the driver section and employing driver gas tailoring [31]. Incident shock speed was measured using a series of five piezoelectric PCB pressure transducers over the last 1.5 m of the shock tube. Reflected shock temperatures and pressures were determined from the measured incident shock speed and normal shock relations [32]. A Kistler 603B piezoelectric pressure transducer, located at 2 cm from the driven section endwall, was used to measure pressure time-histories. A line-of-sight OH* emission diagnostic was implemented using Thorlabs PDA36A detector at the sidewall of the shock tube. Ignition delay times reported here were deduced from pressure traces by extrapolating a line tangent to the point of maximum rate-of-change of pressure. Gaseous mixtures were prepared using a magnetically-stirred mixing vessel and a well-furnished mixing manifold. The shock tube and mixing tank can be heated to temperatures up to 100 °C with a heating jacket [1]. Ethanol (> 99.8%) from Sigma-Aldrich, oxygen, nitrogen and argon gas (99.999%) from Air Liquide were used.

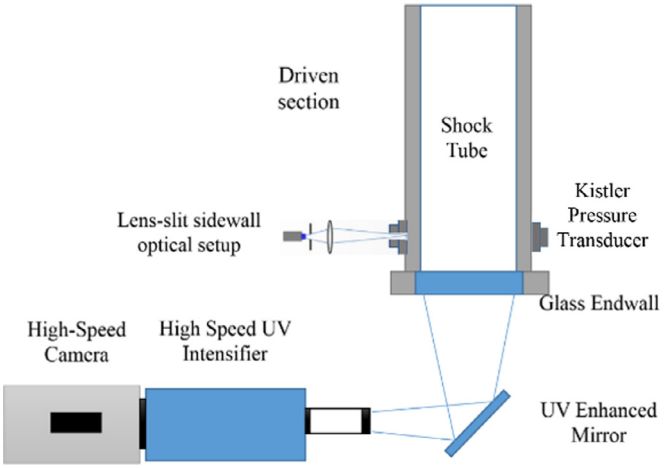

Fig. 1. High-speed OH* imaging setup through the quartz (glass) endwall. Sidewall OH* emission and pressure diagnostics at 2 cm from endwall are also shown.

2.2. High-speed imaging setup

High-speed OH* chemiluminescence imaging experiments were performed using the setup shown in Fig. 1. The objective of the imaging experiments was to visually explore the conditions that showed some sign of preignition occurrence during the ignition delay measurements. A high-speed camera (LaVision High Speed Star 6), coupled to a high-speed UV Intensifier (LaVision IRO) and a VZ-UV focusing objective, was operated at 10 kHz to capture shock tube cross-sectional images. A 100 mm x 100 mm UV-enhanced mirror was used to deflect the emission at right angle. A 310 nm bandpass filter with a FWHM of 10 nm was placed on the camera lens. An IRO controller was used to synchronize the imaging system with the reflected shock wave. For the IRO system, a gate opening time of 3000 ns was used, and the gain was varied from 57 to 65 depending on the intensity or counts registered in the experiments to avoid signal saturation and to achieve adequate signal level.

The transparent endwall consisted of a fused silica disk with 16.4 cm diameter and 45 mm thickness. Special rubber gaskets were needed to minimize the strain due to the contact of the glass and steel and to ensure good vacuum conditions inside the shock tube. The location and orientation of the UV-enhanced mirror was optimized to get complete image of the region of interest. Optimal location and focus point of the imaging optics were found using standard grids and optical references. The trigger signal used to start the recordings was a TTL signal obtained from a Stanford Research Systems DG535 delay generator connected to the pressure transducer closest to the shock tube endwall.

3. Results and discussion

3.1. Ignition delay time measurements

Ignition delay times (IDTs) were initially measured for stoichiometric ethanol/oxygen/argon mixtures containing 2.9% of ethanol at a pressure of 2 bar. This specific mixture and conditions were chosen to be compared with high-temperature ($T > 1100$ K) ignition delay measurements by Noorani et al. [33]. The two data sets agreed very well, as depicted in Fig. 2. Our measurements were extended to lower temperatures ($\sim$ 900 K) and modeled using the chemical kinetic model of Metcalfe et al. [34]. Simulations were