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Ignition delay times of Jet A-1 fuel: Measurements in a high-pressure shock tube and a rapid compression machine

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Abstract

Ignition delay time (IDT) measurements for Jet A-1 fuel samples have been performed with a rapid compression machine (RCM) and a high-pressure shock tube (ST). The IDT measurements span a pressure range from 7 to 30 bar, a temperature range from 670 K to 1200 K, and fuel/air equivalence ratios ϕ from 0.3 to 1.3. Expressions fitting the experimental data sets were obtained, with fitting parameters being provided. The combined RCM/ST data aimed at providing information on the two-stage ignition behavior and on the transition from NTC chemistry to high-temperature radical chain-branching, which are important and hard to meet targets in the development of chemical surrogates.

Keywords: Jet fuel; Rapid compression machine; Shock tube; Ignition delay time; Fuel surrogate

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1. Introduction

Autoignition properties of liquid fuels are accounted for in terms of octane (ON) and cetane (CN) ratings, with the former being an assessment of the resistance of gasoline to autoignition, while the latter gauges ignition propensity of Diesel fuel. However, none of these ratings is included in jet fuel (kerosene) specifications, even though there is evidence for a correlation between fuel's derived cetane number (DCN) and the occurrence of lean blow-off [1–3].

Measurements of autoignition in shock tubes (ST) and rapid compression machines (RCM)

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provide insights into the effects of fuel composition, equivalence ratio, pressure, and temperature on autoignition-related phenomena. The assessment of these effects is particularly important when new jet fuel mixtures are proposed, especially, those containing biofuel components. Dooley et al. [4,5] and Hui et al. [6] reported measurements of ignition delay time for alternative jet fuels made from hydro-processed esters and fatty acids (HEFA) based on vegetable oils and animal fats, Fischer–Tropsch fuels made from coal and natural gas (GtL), and surrogate mixtures for these alternative fuels. Their results indicated that all alternative fuels presented higher reactivity than Jet A, with GtL and camelina HEFA being consistently the more reactive, reinforcing the need for the assessment of combustion properties of new fuels, in relation to established fuels, before the new mixtures are widely used.

The comparison of the behavior of the ignition delay time of a complex fuel with that of pure species provides general guidelines for the development of chemical surrogates amenable to theoretical studies using detailed chemical kinetics mechanisms. The comparisons are needed in a large range of temperatures and pressures [2,6], usually achieved by a combination of measurements in shock tubes (ST) and rapid compression machines (RCM). However, several autoignition studies for jet fuels [6–13] showed that even when using the same fuel sample the agreement between different sets of data is limited. While measurements of Vasu et al. [7,8] using ST and Dooley et al. [9] using ST and RCM for Jet A (POSF 4658) at 650–1250 K and 20 bar presented good agreement, the RCM results of Kumar and Sung [3,10] at 650–770 K and 15 bar using the same facility of Dooley et al. [9], compare well with previous ST measurements at 15 bar but do not present the behavior expected from the previous RCM measurements obtained at 7 bar. The experiments at lower temperature require care in properly vaporizing the fuel since kerosene contains species with relatively low vapor pressure. Also, cracking of the fuel molecules may occur at higher preheating temperatures, an effect whose extent is hard to evaluate. While it is possible to work with the liquid fuel injected into the test chamber of the ST and the RCM [11,14,15], in most facilities the fuel and oxidant are premixed in the gas phase before feeding the reactor.

Here, we present measurements of ignition delay time of a Jet A-1 fuel produced in Brazil in the 660–1250 K temperature range at pressures of 7, 15, and 30 bar and at equivalence ratios from 0.3 to 1.3, using the high-pressure shock tube at IVG and the rapid compression machine at KIT. The measurements aimed at detecting the extent of the NTC behavior and the occurrence of two-stage ignition to aid in the selection of an appropriate surrogate mixture to emulate ignition delay time. These measurements will be used as one of the validation targets for the development of chemical surrogates for the Jet A-1 fuel.

2. Jet fuel and surrogates

The kerosene obtained from fractional distillation of crude oil has a typical carbon number distribution between 8 and 16 mostly formed by paraffinic, naphthenic (cycloalkane), and aromatic hydrocarbons with boiling point in the 200–300 °C range. Wood et al. [15] developed one of the earlier surrogate mixtures, a 14-components blend, in an attempt to match JP-4 and JP-5 boiling range, atomization quality and combustion behavior. Since then, surrogate fuels evolved to include from simpler mixtures of hydrocarbons, adequate to computational fluid dynamic (CFD) studies, to more elaborate blends designed to emulate chemical, physical, or combustion properties in detailed chemical kinetics and experimental investigations.

A surrogate fuel is usually defined in terms of the number of species in its composition and its behavior relative to ‘targets’. Farrell et al. [16] defines three main types of targets, in order of increasing complexity: property targets, development targets, and application targets. A property target refers to chemical and physical fuel properties, like the hydrogen-to-carbon ratio and the distillation curve. Development targets are the chemical kinetics and thermophysical behavior typically evaluated in experiments under well-controlled conditions, such as ignition delay time (IDT) measurements in shock tubes and rapid compression machines, species evolution profiles in flow reactors, or multicomponent spray vaporization. Application targets are based on measurements obtained from engine tests in transient and steady-state operation, such as combustion efficiency, and gaseous and particulate emissions.

Regarding the availability of validated oxidation mechanisms for relevant hydrocarbons, Colket et al. [17], Farrell et al. [16], and Pitz et al. [18] pointed out that, as late as 2006, only linear alkanes (n-heptane, n-decane, n-dodecane, n-hexadecane) and one branched alkane (iso-octane) received sufficient attention to enable reliable modeling of their oxidation, while mechanisms for naphthenic and aromatic compounds lacked validation. Further studies [5,19] have indicated that jet fuel is better approximated by alkanes with one or two branches, instead of highly-branched molecules like iso-cetane (2,2,4,4,6,8,8-heptamethylnonane). However, highly-branched alkanes and linear ones are much more affordable to formulate fuel mixtures for large-scale experiments. Therefore, since the earlier studies with surrogate fuels, it has become common practice to select one or more ‘reference fuels’ from

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