Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

The effects of hydrogen addition on the auto-ignition delay of homogeneous primary reference fuel/air mixtures in a rapid compression machine

Hyunsoo An [a], *Jinhwa Chung* [b], *Seunghyeon Lee* [a], *Soonho Song* [c,*]

[a] *The Graduate School, Department of Mechanical Engineering, Yonsei University, 134 Sinchon-dong, Seodaemun-gu, Seoul, 120-749, Republic of Korea*

[b] *Doosan Infracore CO., 489, Injung-ro, Dong-gu, Incheon, Republic of Korea*

[c] *Department of Mechanical Engineering, Yonsei University, 134 Sinchon-dong, Seodaemun-gu, Seoul, 120-749, Republic of Korea*

ARTICLE INFO

Article history:
Received 7 June 2015
Received in revised form
6 August 2015
Accepted 7 August 2015
Available online 10 September 2015

Keywords:
N-heptane
Iso-octane
Hydrogen
Ignition delay
Rapid compression machine
Chemical kinetics

ABSTRACT

The ignition delay time with mixtures of primary reference fuels (PRFs) and hydrogen were measured using a rapid compression machine (RCM), where the concentration of hydrogen was systematically varied. The experiments were performed for compressed temperatures in the range 735–847 K. The fuel/air equivalence ratio was varied to investigate its effects on the ignition delay of *n*-heptane and iso-octane. Hydrogen was added with hydrogen-energy-share ratios in the range of 0–10%, meaning that the energy of the hydrogen replaced 0–10% of that of either *n*-heptane or iso-octane. When hydrogen was added to *n*-heptane, there was a significant increase in the ignition delay, especially during the first-stage reaction region. This was explained using the chemical kinetic analysis software package CHEMKIN PRO; hydrogen consumed radical species related to the ignition of hydrocarbon fuels. With iso-octane, there was a significant increase in the ignition delay not only in the fist-stage reaction region, but also in second-stage reaction region. The effects of the hydrogen concentration were found to depend on the equivalence ratio and temperature for both fuels.

Abbreviations: HCCI, Homogeneous Charge Compression Ignition; RCM, Rapid Compression Machine; LTC, Low Temperature Combustion; SA, Sensitivity Analysis; NO_x, Nitrogen Oxide; HC, Hydrocarbon; PM, Particulate Matter; LHV, Lower Heat Value; TWC, Three Way Catalytic; CFR, Cooperative Fuel Research; DME, Dimethylether; NG, Natural Gas; LTR, Low Temperature Region; HTR, High Temperature Region; TDC, Top Dead Center; RON, Research Octane Number.

* *Corresponding author*. Tel.: +82 2 2123 2819.
E-mail address: soonhosong@yonsei.ac.kr (S. Song).

http://dx.doi.org/10.1016/j.ijhydene.2015.08.022

Nomenclature

τ	Induction time, ms
Ø	Equivalence ratio
P_0	Initial pressure, MPa
P_c	Compressed pressure, MPa
T_0	Initial Temperature, K
T_c	Compressed Temperature, K
ρ	Density, kg/m^3
C_v	Heat capacity
C_p	Heat capacity
κ	Thermal conductivity, W/mK
γ	Heat capacity ratio
E	Energy, MJ/kg

Introduction

Recently, there has been growing interest in reducing dependence on fossil fuels in response to concerns over environmental issues such as global warming. This has led to the growth of interest in more efficient and environmentally benign technologies, and research into renewable energy sources has intensified. Many governments have supported this trend by establishing systems of subsidies [1–3].

To reduce emission levels and improve combustion efficiency, an understanding of the chemical reaction dynamics of combustion in internal combustion engines is necessary. Internal combustion engines can be classified as either spark ignition (SI) or compression ignition (CI) engines. SI engines have the advantage of producing almost no soot, operating close to the stoichiometric fuel–air ratio (i.e., with $\lambda = 1$), and do not produce significant emissions of nitrogen oxides (NO_x), hydrocarbons (HCs), or carbon monoxide (CO) because of the application of three-way catalytic converters (TWCs). However, with SI engines, the compression ratio is limited by knocking, which leads to poor efficiency, which is exacerbated by pumping losses from throttling under partial load. Diesel engines have the advantage of a higher combustion efficiency; however, issues with particulate matter (PM) and NO_x emission remain, because of the stratified charge [4,5].

It follows that methods to combine the advantages of both SI and CI engines are desirable, leading to both high efficiency and low emissions. Homogeneous charge compression ignition (HCCI) has become the focus of much research because of the high efficiency and low emissions. HCCI engines offer potential to increase the fuel efficiency, which provides lower emission levels of NO_x and soot than conventional engines [6–8]. Although HCCI combustion has been considered an alternative to conventional engines, a number of developments are required prior to the commercialization of HCCI engines. Problems associated with HCCI combustion include control of ignition and combustion, expansion of the operating range, improvement of the cold-start stability, and high HC and CO emissions. Ignition and combustion control is one of the greatest challenges for HCCI engines. Direct control over HCCI combustion is not available, and much work is required to identify effective indirect control strategies; this is considered the key to realizing successful operation of HCCI engines [9,10]. Because HCCI combustion is controlled by the chemical kinetics of the fuel, an understanding of combustion characteristics of the fuel is essential, as this determines the ignition delay. Therefore, an improved fundamental understanding of the auto-ignition chemistry that governs HCCI combustion is a prerequisite for development of this technology [9,11].

The processes of fuel vaporization and mixing, heat transfer, diffusion, and combustion in the internal combustion engine are complex. In addition, because of differences between cycles, it is difficult to investigate the chemical characteristics of the fuel itself. To address these problems, various experimental devices including shock-tubes [12,13], rapid compression machines (RCMs) [14,15], and jet-stirred flow reactors [16] have been investigated to simulate the combustion phenomena in the cylinder of internal combustion engines. Among these devices, the RCM is particularly suitable for measurements of the global parameters, including the ignition delay at low to intermediate temperatures. Control over the boundary conditions and the initial conditions, as well as installing visualization windows, is straightforward with an RCM [17]. Furthermore, there is little variation between cycles, and the test period can be extended, which makes it appropriate for investigating combustion in internal combustion engines [18].

The use of various fuels to control HCCI combustion has been investigated [19–21], including dual fuels [15,20–22], as well as various devices to expand the operating range of HCCI combustion [23,24]. There have been several studies into the effects of dual fuels or fuel additives, because of the low costs of modifying the experimental apparatus that is required. Tanaka et al [20] used 2-ethyl-hexyl-nitrate and di-tertiary-butyl-peroxide as the additives, and found that the use of additives reduced the ignition delay but did not affect the burn rate. These results indicate that the ignition delay and the burn rate can be controlled independently by varying the molar ratio of fuel to oxygen, using additives, by controlling the initial temperature, and by varying the octane number. Salvador et al [21] performed a numerical evaluation of various fuels and additives with HCCI combustion. A list of candidate HCCI fuels was identified, and the required operating conditions were determined (i.e., compression ratio, equivalence ratio, and intake temperature). Several additives have been identified which can advance combustion by a crank angle of almost 11° when added to the intake mixture at a concentration of 10 ppm, including alktlhydroperoxide peroxy radicals and ozone, which are advantageous in terms of stability and transportability.

Hydrogen is a promising future fuel, which can meet energy requirements in an environmentally sustainable manner, with potential applications as an alternative for fossil fuel systems for internal combustion engines [25,26]. Compared to conventional fuels, hydrogen has lower ignition energy, a higher diffusivity, and more rapid flame propagation. For these reasons, many fundamental and applied studies have been carried out into hydrogen-enriched combustion. The addition of hydrogen to an SI engine extends the lean-operational limits, and allows an SI engine to operate at leaner conditions with reduced NOx emissions [27–31].

The effects of the addition of hydrogen on HCCI combustion have been studied by many researchers. Hongsheng et al