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Laminar burning velocity and Markstein length of ammonia/hydrogen/air premixed flames at elevated pressures

Akinori Ichikawa*, Akihiro Hayakawa, Yuichi Kitagawa, K.D. Kunkuma Amila Somarathne, Taku Kudo, Hideaki Kobayashi

Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan

ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form
27 March 2015
Accepted 5 April 2015
Available online 13 June 2015

Keywords:
Ammonia
Hydrogen
Effects of pressure
Laminar burning velocity
Markstein length

ABSTRACT

Ammonia shows promise not only as a hydrogen-energy carrier but also as a carbon-free fuel. However, combustion intensity of ammonia must be improved to enable its application to practical combustors. In order to achieve this, hydrogen-added ammonia/air flames were experimentally and numerically investigated at elevated pressures up to 0.5 MPa. The hydrogen ratio, which is defined as the hydrogen concentration in the fuel mixture, was varied from 0 to 1.0. The unstretched laminar burning velocity and Markstein length of spherically propagating laminar flames were experimentally evaluated. The results showed that, unstretched laminar burning velocity increases non-linearly with an increase in the hydrogen ratio. The Markstein length varies non-monotonically with an increase in the hydrogen ratio. The unstretched laminar burning velocity, and the Markstein length decrease with an increase in the initial mixture pressure. Although the decrease in the Markstein length is larger when the initial mixture pressure increases from 0.1 to 0.3 MPa, the values of Markstein lengths at 0.5 MPa are almost the same as those at 0.3 MPa.

Introduction

Ammonia is interested much as hydrogen energy carrier [1] because it has some advantages. For example, 17 wt% of hydrogen can be stored in ammonia molecules [2]. Also manufacturing process of ammonia, i.e. the Harber–Boch process, is well established, as is the infrastructure for its distribution and ammonia can be easily stored because it liquefies at the same level as propane. At present, ammonia is widely used as a chemical fertilizer. Fossil fuels is required for the ammonia manufacture by the Harber–Boch process at this moment, a study of a new ammonia manufacturing procedure by renewable energy, such as solar energy, has been conducted [3].

Ammonia is not only a hydrogen energy carrier but also as a carbon-free fuel. However, ammonia has not been considered as a fuel owing to its lower combustion intensities, i.e., narrower flammable range [4], lower laminar burning velocity [5], lower flame temperature [6] and so on. Thus, few studies of

* *Corresponding author*. Tel.: +81 22 217 5273; fax: +81 22 217 5323.
E-mail address: a.ichikawa@flame.ifs.tohoku.ac.jp (A. Ichikawa).
http://dx.doi.org/10.1016/j.ijhydene.2015.04.024

ammonia combustion have been conducted. Hayakawa et al. [7] experimentally investigated the effects of pressure on NO formation/reduction mechanisms for stoichiometric ammonia/air premixed flames. It was clarified that, the NO mole fraction decreases with an increase in pressure and the reaction $OH + H + M = H_2O + M$ is an important one for NO reduction at high pressures. Hayakawa et al. [8] also experimentally evaluated the unstretched laminar burning velocity and Markstein length not only at atmospheric pressure but also at high pressures. From the stand point of chemical reaction, the detailed reaction kinetics developed by Tian et al. [9], Konnov [10], Miller et al. [11] and Lindstedt et al. [12] are available for ammonia combustion at the present. However, validation of these mechanisms is insufficient due to few experimental results.

In order to improve the lower combustion intensity of ammonia, the addition of hydrogen has been considered [13–16]. Kumar et al. [13] evaluated the laminar burning velocity as related to heat loss from ammonia/hydrogen/air flames and pointed out the importance of OH, H and O radicals for the laminar burning velocity. Lee et al. [14, 15] experimentally clarified the laminar burning velocity and Markstein number of ammonia/hydrogen/air flames under atmospheric pressure. Li et al. [16] investigated the characteristics of NOx formation from ammonia/hydrogen/air flames and clarified that the NOx concentration decreases with an increase in the concentration of ammonia in the fuel at stoichiometric conditions. There are many fundamental study of multi-component fuel. Experiments of hydrogen/methane/air from spherically propagating premixed flames in a constant volume combustion chamber not only at atmospheric pressure [17,18]. Chen [19] performed the numerical simulation of hydrogen/methane/air flames during flame propagation.

Ammonia flame has some advantages. For example, the generation of thermal NO_X is expected to be low owing to its lower flame temperature, CO_2 and soot are not generated from ammonia flame, and ammonia has an antiknock characteristic because of its high octane number. Thus, some applicative studies of ammonia flame for practical combustors, especially for spark ignition (SI) engines, have been conducted. Liu et al. [20] performed a numerical simulation on ammonia flame assuming the compression ratio of 15 conditions and investigated the laminar burning velocity and NO mole fraction in burned gas of ammonia flame. Recently, Frigo et al. [21] investigated the applications of ammonia/hydrogen in an SI engine and showed that the possibility of improvement of engine brake thermal efficiency by the increase in compression ratio although the efficiency decreases with the increase in ammonia concentration in the fuel. Westlye et al. [22] investigated the emission characteristics of an ammonia/hydrogen engine in detail using an FT-IR analyzer and showed the difference of emission gas characteristics between an ammonia/hydrogen engine and a gasoline engine.

Since a practical combustor is operated at high pressure conditions, understanding of the flame characteristics at high pressure is important for the improvement of the efficiency of combustor. Therefore, many experimental studies at high pressures have been performed. Qin et al. [23] investigated the laminar burning velocity of hydrogen/air flames at various equivalence ratios and pressure conditions using a PTV technique and proposed a new rate-coefficient. Kitagawa et al. [24] clarified the laminar and turbulent flame characteristics of hydrogen/air premixed flames using a constant volume combustion chamber and showed the importance of the turbulence Reynolds number as well as the Lewis number. However, no experimental studies at high pressure for ammonia/hydrogen flames have been performed. The experiment of multicomponent fuel at high pressure have also performed. Hu et al. [25] revealed that the flame characteristics of methane/hydrogen/air flames at elevated pressure.

The purpose of the present study is to clarify the flame characteristics of hydrogen-added ammonia/air flames using a constant volume combustion chamber up to an initial mixture pressure of 0.5 MPa for the first time. The laminar burning velocities and Markstein lengths were also experimentally clarified. In addition, numerical simulations with detailed chemical kinetics, which are applicable to ammonia flame, were conducted. Then, the laminar burning velocities obtained from numerical simulations were compared with those obtained from the experiments.

Experimental setup and numerical method

Laminar flame which spherically propagated in a high pressure constant volume chamber were observed. A schematic of the experimental setup is shown in Fig. 1. The configuration of the constant volume chamber used in this experiment was cylindrical. The inner diameter and length of the chamber were 270 mm and 410 mm, respectively, and volume of the chamber was about 23 L, which is equivalent to that of a sphere with a diameter of 355 mm. Two stainless steel sticks 1.5 mm in diameter, were inserted into the chamber as ignition electrodes. The spark gap was located at the centerline of the chamber and was set to 2 mm. The unburned mixture was ignited by an ignition spark. Capacitor discharge ignition (CDI) equipment was used in order to ignite the premixed gas. Electrostatic energy, which was charged in the capacitor, was varied from 0.28 to 2.8 J depending on the hydrogen ratio. This energy was the minimum electrostatic energy which was able to ignite the mixture at a given hydrogen ratio at the atmospheric pressure.

Two optical windows made of quartz glass were installed in the chamber. Spherically propagating premixed flames were observed by the schlieren technique with a high-speed camera (Photron FASTCAM SA5), a macro-lens (Nikon, Ai AF Micro-Nikkor 200 mm f/4D IF-ED) and a continuum light source (Photron, HVC-SL) via the optical windows. Schlieren images of up to 60 mm in diameter could be observed using this experimental setup. The flame rate for the schlieren observation was varied from 1000 to 10,000 fps depending on the experimental conditions and the resolution was set to 768×768 pixels. Thus, the spatial resolution of the schlieren images was approximately 0.1 mm. The pressure inside the chamber during flame propagation was measured for stoichiometric ammonia/air premixed flame using a pressure sensor (P1 in Fig. 1, Kyowa, PVL-10KD) and HiCORDER (HIOKI, MEMORY HiCORDER LR8431). The pressure within the observation range of the schlieren image was found to be less than 2% from initial mixture pressure. Thus, it could be assumed