INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 13121–13133

Available online at www.sciencedirect.com

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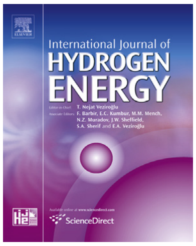

Scale effects on premixed flame propagation of hydrogen/methane deflagration

Minggao Yu [a,*], Kai Zheng [a], Ligang Zheng [b], Tingxiang Chu [a], Pinkun Guo [a]

[a] State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, PR China
[b] School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, PR China

ARTICLE INFO

Article history:
Received 22 April 2015
Received in revised form
21 July 2015
Accepted 26 July 2015
Available online 20 August 2015

Keywords:
Hydrogen/methane
Premixed flame
Deflagration
Scale

ABSTRACT

An experimental study of scale effects on hydrogen/methane deflagration of premixed flame in venting ducts is presented. The experiments focused on the effect of scale on flame structure, premixed flame propagation speed and overpressure during hydrogen/methane deflagration. Six ducts with different cross-sections and lengths were used in the experiments. Tests were performed for stoichiometric hydrogen/methane mixtures with five hydrogen fractions (hydrogen fraction from 0 to 100%) under ambient conditions. In the experiment, the "tulip" flame disappeared with increasing cross sectional area and hydrogen fraction. Meanwhile, the tulip flame gradually appears and a more pronounced "tulip" flame is observed with increasing duct length. The effect of cross sectional area coupled with duct length on flame propagation can be attributed to the influence of aspect ratio, while the "tulip" flame formation is only found when the aspect ratio > 6.7. In the experiments, the maximum flame speed has the similar trend with laminar flame speed regardless of whether there was "tulip" flame formation and the maximum flame propagation speed occurs with an aspect ratio of 10. The maximum overpressure decreases with cross sectional area and increases with the length of the duct. The time corresponding to maximum overpressure, t_{max} decreases with hydrogen addition. Meanwhile, t_{max} increases with cross sectional area and length of duct.

Introduction

The reduction of greenhouse gas emissions and utilization of clean energy have been the focus of much research in recent years. One effective measure to solve the problem is to mix natural gas with hydrogen, which is an excellent additive to improve the combustion of methane. However, full exploitation of these fuels as effective alternatives could be limited by some of their properties, such as low ignition energy, high laminar flame speed, wide flammability limits, high reactivity and burn temperature [1–5]. Obviously, these properties increase the danger of explosion and limit the safe application of hydrogen/methane mixtures. Therefore, it is essential to investigate the behavior of such gaseous

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* Corresponding author. 174 Shazhengjie, Shapingba, Chongqing, 400030, China. Tel.: +86 3913989616.
E-mail address: 13333910808@126.com (M. Yu).

http://dx.doi.org/10.1016/j.ijhydene.2015.07.143

mixture releases upon ignition in both confined and unconfined areas. The results can be used to improve safety and reduce the risk of a deflagration to detonation transition [6].

The understanding of premixed flame propagation in deflagration has attracted increased interest for safety applications. Under certain conditions, a slow deflagration flame can accelerate and transition to a detonation referred to as DDT [7]. Earlier studies on premixed flame propagation in a duct focused mainly on two different mechanisms of flame acceleration in a duct that is smooth or filled with obstacles. In the presence of obstacles, the flame–obstacle interaction generates turbulence, distorts the flame front, causing a laminar flame to become turbulent, resulting in flame acceleration [8–11]. On the other hand, premixed flame propagating in smooth ducts is intrinsically unstable, is able to self-accelerate and can exhibit different behaviors [12]. Four stages of flame dynamics and shape changes of premixed flame in a venting duct have been proposed by Clanet and Searby [13]. In the early stage, acceleration happens when the flame front develops from a spherical kernel to become finger shaped, with surface area growing exponentially. The thermal expansion of the reactants plays a key role in the early flame acceleration [14]. A simple geometrical model for this process has also been provided and validated [13,15]. The flame acceleration is terminated when the flame front touches the sidewall of the duct, with the subsequent formation of the so-called “tulip” flame.

There is substantial literature associated with the study of “tulip” flame formation both in venting and closed ducts [12–19,24–33] and a variety of mechanisms have been proposed to explain the phenomenon, e.g., Darrieus–Landau (DL) instability [16], flame–shock interaction [17], the “squish” flow [18] and reduction of the flame area [19]. However, the propagation of premixed flame in a duct is a complex phenomenon, and can be affected by various factors, e.g., shock formation ahead the flame [20,21], boundary layer [22,23], acoustic waves [27] and scale effects [28,31]. Therefore, it appears that currently there is no decisive and single principle can explain the “tulip” flame formation mechanism [24,25]. Rather than put forward another alternative explanation, many recent research efforts into the study of “tulip” flame have been numerical and experimental analysis that focus on the conditions that lead to these flames and their behavior. Hariharan and Wichman [30] performed an experimental and numerical investigation of premixed flame propagation in a rectangular duct with an aspect ratio of six to understand the influence of pressure waves, instabilities, and flow field effects causing changes to the flame structure and morphology. Using the PIV images and the direct visualization, Ponizy and Claverie [31] confirmed that the intrinsic instabilities of the flame front are not involved in this process and the inversion of the flame front observed in the “tulip” flame phenomenon results from a simple hydrodynamic process. Furthermore, results of experimental and numerical simulation performed by Xiao et al. [24,25,32,33] demonstrated a distorted “tulip” flame, resulting from the Taylor instability driven by the abrupt deceleration of the flame front, can be produced after the full formation of classic “tulip” flame in hydrogen/air mixtures in a closed duct.

Nevertheless, all the studies mentioned above only focused on the premixed flame propagation of a single fuel, e.g., methane, hydrogen or propane, and the premixed flame of hydrogen/methane mixtures is seldom considered. In order to utilize hydrogen/methane mixtures safety, the explosion behavior of hydrogen/methane mixtures must be adequately quantified [34–37]. All of the results showed that the hydrogen addition can enhance the explosion reactivity and increase the maximum overpressure and flame propagation speed significantly, but few studies are targeted at the premixed flame propagation of a hydrogen/methane mixture. However, it is worth noting that the effect of hydrogen addition on propagation characteristics has been experimentally studied recently [38], and it was found that the tendency of flame instability and the premixed hydrogen/methane flame undergoes complex shape changed with hydrogen addition. Only the effect of equivalence ratios on premixed flame propagation of hydrogen/methane mixtures has been investigated here. As mentioned above, the premixed flame propagation can be affected by various factors; thus, it is necessary to investigate the influence of other conditions on hydrogen/methane mixtures premixed flame propagation, e.g., scale effects, which has a major impact on the basic “tulip” flame formation [28,31].

In this paper, experimental studies of premixed flame propagation in smooth venting ducts were conducted and six ducts are tested collectively to provide a comprehensive investigation of scale effects on deflagration of hydrogen/methane mixtures. The deflagration characteristics of hydrogen/methane mixtures including flame structure, flame propagation speed and overpressure were studied.

Experimental setup and mixture composition

The experimental set-up used is similar to that used in our previous study [38], as shown in Fig. 1. The experiments were conducted in square cross-section ducts and six ducts were used, divided into two types; all of the same length but different cross sections (Configuration A, B and C) and all of the same cross section but different lengths (Configuration D, E and F), producing an aspect ratio range from 5 to 20. Full details of the ducts employed are given in Table 1. The ducts were placed horizontally, and were made from 20 mm thick Plexiglas, which allows optical access permitting high-speed flame visualization. The right side, which is the ignition end of the duct, is closed by a steel plate and the left side, which is referred to as the “venting” end, is completely open and covered with a thin PVC membrane. The PVC membrane is used to retain the hydrogen/methane mixtures in the duct.

A piezoresistive pressure transducer was located at 20 mm from the center of steel plate mounted on the ignition end. A photodiode transducer positioned outside the duct points to the ignition spark, as shown in Fig. 1. The pressure transducer with a measurement range of −1.0–1.0 bar was used to monitor the overpressure during flame propagation. It was made by Mingkong Sensor Technology Co. Ltd. in China and has a total error <0.25%. The photodiode transducer was used to detect the onset of ignition and trigger the data acquisition card and the high-speed video camera with a photoelectric