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Combined effect of ignition position and equivalence ratio on the characteristics of premixed hydrogen/air deflagrations

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ABSTRACT

Premixed hydrogen/air deflagrations were performed in a 100 mm × 100 mm × 1000 mm square duct closed at one end and opened at the opposite end under ambient conditions, concerning with the combined effect of ignition position IP and equivalence ratio ∅. A wide range of ∅ ranging from 0.4 to 5.0, as well as multiple IPs varying from 0 mm to 900 mm off the closed end of the duct were employed. It is indicated that IP and ∅ exerted a great impact on the flame structure, and the corresponding pressure built-up. Except for IP_0, the flame can propagate in two directions, i.e., leftward and rightward. A regime diagram for tulip flames formation on the left flame front (LFF) was given in a plane of ∅ vs. IP. In certain cases (e.g. the combinations of ∅ = 0.6 and IP_{500} or IP_{700}), distorted tulip flames were also observed on the right flame front (RFF). Furthermore, the combinations of IP and ∅ gave rise to various patterns of pressure profiles. The pressure profiles for ignition initiated at the right half part of the duct showed a weak dependence on equivalence ratio, and showed no dependence on ignition position. However, the pressure profiles for ignition initiated at the left half part of the duct were heavily dependent on the combination of IP and ∅. More specifically, in the leanest (∅ = 0.4) and the richest (∅ = 4.0–5.0) cases, intensive periodical oscillations were the prime feature of the pressure profiles. With the moderate equivalence ratios (∅ = 0.8–3.0), periodical pressure oscillations were only observed for IP_{900}. The maximum pressure peaks P_{max} were reached at ∅ = 1.25 rather than at the highest reactivity ∅ = 1.75 irrespective of ignition position. The ignition positions that produced the worst conditions were different, implying a complex influence of the combination of IP and ∅.

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Introduction

Hydrogen, as one of the new energy sources, has broad application prospects in the future. Due to its lower ignition energy, wider explosion limits, and larger laminar burning velocity and diffusivity, it is more explosive and hazardous than hydrocarbon and other gaseous fuels [1–3]. Hydrogen, in the production and transportation process, is confronted with a great risk. Therefore, it is of great significance to conduct an experimental study on the deflagration characteristics of premixed hydrogen/air gas. Deflagration is a combustion wave propagating in a premixed gas medium at subsonic velocity. Usually it is associated with a high overpressure, and even develops into detonation, forming a huge destructive force. As a complex problem involving chemical reaction and fluid mechanics, it is affected by many factors such as reactivity (fuel type, equivalence ratio, initial pressure, initial temperature, etc.) and external conditions (vessel or pipe scale, obstacles and ignition positions, etc.) [4]. At present, most of the means employed for fuel transportation and storage are pipes and high-pressure storage tanks. In view of the unique nature of hydrogen, it is liable to leak, and the location of the ignition source is often uncertain. Thus it is of practical significance to study the influence of ignition source position on the parameters of hydrogen deflagration.

The existing studies indicated that the location of ignition source exerted an important influence on the deflagration, as complied in Table 1. It is generally acknowledged that for duct-vented explosions, central ignition would produce higher overpressure within small vessels, and instead, rear ignition would produce higher overpressure within larger vessels [5]. However, for simply vented explosions, this finding did not hold. As argued by Bauwens et al. [6], no single ignition location was found to be the most severe for all cases and the most severe ignition location depended on the overall configuration of the test such as vent size and obstacle. Even in closed vessels, a unified conclusion cannot also be drawn from the investigation so far.

Through a brief review, it is demonstrated that the effect of ignition position on explosion will be different from case to case, and there is no consensus to be achieved from the existing references. Moreover, most of studies only focused on two or three ignition locations (i.e., front, central and rear) in compact vessels (i.e., small length to diameter ratio L/D) [18,27–29], and primarily concerned with the maximum pressure peak P_{max} (i.e., the worst case). As is well known, the flame dynamics in an elongated duct may differ in a compact vessel [30]. In real workplaces, hydrogen can be leaked into an elongated space of large length to diameter ratio such as tunnels, conduits, passageways, corridors and galleries, forming an explosion of any concentration of hydrogen-air mixtures within the explosion limits. In consequence, further studies in an elongated duct should be deserved. However, rare data is available for the combined effect of ignition position and equivalence ratio on the characteristics of hydrogen/air explosions in a large aspect ratio duct closed at one end and open at the opposite end. Therefore, in this work, experiments were carried out in a lab-scale horizontal square tube to study the characteristics of hydrogen/air explosions with a variety of equivalence ratios and different ignition positions. Especially, the study has put the emphasis on the pressure profiles as well as P_{max}. Additionally, flame transient structures were incorporated to analyze the generation mechanism of the pressure profiles. It is expected that the results will provide a basis for the safe use of hydrogen-air premixed gases, the investigation into the cause of hydrogen explosion accidents, and the CFD simulations of hydrogen explosions.

Experimental details

The experimental apparatus is similar to that used in the previous study [31], as shown in Fig. 1. It was comprised of an explosion duct, flame image acquisition system, pressure and optical signal acquisition system, gas distribution system and an ignition system. The explosion duct, made of plexiglas with

Table 1 – A summary of previous research looking at the effect of ignition position on premixed explosions in vessels.

Authors	Vessel shape	V/m^3	Fuel	Worst case	Vented	Ref.
Razus et al.	Spherical/cylindrical	0.0017–0.00118	C_3H_6	Central	No	[7]
Vishwakarma et al.	Cylindrical	–	CH_4	Central	No	[8]
Xiao et al.	Square	$0.082^2 \times 0.53$	H_2	5 cm off	No	[9]
Kindracki et al.	Cylindrical	0.0687	CH_4	Central	No	[10]
Xiao et al.	Curved	–	C_3H_8	No explicit comparison	No	[11–13]
Rocourt et al.	Cubic	0.15^3	H_2	Central	Simply	[14]
Park et al.	Rectangular	$1.0 \times 0.95 \times 0.235$	CH_4	Rear	Simply	[15]
Bauwens et al.	Square/cylindrical	$4.6^2 \times 3.0/2.42$	C_3H_8	Configuration dependence	Simply	[6]
Wang et al.	Square	$4.6^2 \times 3.0$	C_3H_8	Rear	Simply	[16]
Lowesmith et al.	Square	$8.25 \times 3.0 \times 2.8$	CH_4/H_2 blend	Rear	Simply	[17]
Raheem et al.	Square	$0.05^2 \times 0.25$	H_2	Rear	Simply	[19]
Guo et al.	Cylindrical	0.00196	H_2	Central	Simply	[19–21]
Ponizy et al.	Cylindrical	0.0036	C_3H_8	Central	Ducted	[22]
Kasmani et al.	Cylindrical	0.2	C_3H_8/CH_4	Rear	Ducted	[23]
Willacy et al.	Cylindrical	0.2	C_3H_8	Rear	Ducted	[24]
Ferrara et al.	Cylindrical	0.2	C_3H_8	Rear	Ducted	[5]
Zheng et al.	Square	$0.1^2 \times 1.0$	CH_4	Front	End	[25]
Zheng et al.	Square	$0.1^2 \times 1.0$	H_2/CH_4 blend	H_2 fraction dependence	End	[26]