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The characteristics of flame propagation in ammonia/oxygen mixtures

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ABSTRACT

As a carbon free fuel and a hydrogen-energy carrier, ammonia is expected to be one of the promising energy carriers and to be widely used in industries. In this study, the parameters of ammonia/oxygen flame, such as laminar flame speed, the Markstein length, laminar flame thickness, and critical radius of flame instability onset have been investigated experimentally and numerically. A spherical ammonia /oxygen flame propagated in a constant volume chamber and a high speed digital Schilieren photograph system were used in the study. The influences of initial pressure and equivalence ratio on flame propagation have been investigated. It was found that the maximum laminar flame speed in ammonia/oxygen mixture is 1.09 m/s. The flame thickness decreases with the initial pressure increase. Generally, Markstein length increases with the increasing of equivalence ratio while it decreases with the increasing of initial pressure. The minimum critical radius in ammonia/oxygen is 1.8 cm. And the critical radius decreases with the increase of initial pressure. The mechanisms of flame instability in ammonia/oxygen mixture were analyzed, and the stabilize effect of flame stretch in ammonia/oxygen have been observed.

1. Introduction

Ammonia is a colorless gas with a characteristic pungent odor. It is widely used in agriculture, industrial process and power engineering. Ammonia is directly or indirectly the precursor to most nitrogen-containing compounds. Because of its vaporization properties, anhydrous ammonia is widely used as a high energy efficiency and low cost refrigerant in industrial applications. As a carbon-free fuel and a hydrogen-energy carrier, ammonia is considered to be one of the promising energy carriers in the future.

Ammonia is sometimes proposed as a practical alternative to fossil fuel for internal combustion engines [1]. Its high octane rating of 120 [2] and low flame temperature allows the use of high compression ratios without a penalty of high NOx production. Since ammonia contains no carbon, its combustion cannot produce carbon monoxide, hydrocarbons or soot. Compared to hydrogen as a fuel, ammonia is much more energy efficient, and it would be a much lower cost to produce, store, and deliver hydrogen as ammonia than as compressed and/or cryogenic hydrogen. The rocket engine that powered the X-15 hypersonic research aircraft used liquid ammonia as one component fuel. In addition to direct utilization of ammonia as a fuel in combustion engines there is also the opportunity to convert ammonia back to hydrogen where it can be used to power hydrogen fuel cells or it can be directly used within high temperature fuel cells [3]. Combustion and explosion hazards caused by ammonia leakage may result in serious loss to human life and property. The accident in a poultry processing plant caused 121 people died and 76 people injured on June 3rd, 2013 in Northeast China's Jilin province, and the direct reason is the combustion and explosion of ammonia which leaked from the refrigeration facility. The ammonia deflagration accident on august 31, 2005 in Henan Province caused 3 people dead and 9 people poisoned, and the direct reason of the accident is the burst of charging tube of an ammonia tank truck.

The ignition and combustion characteristics such as the laminar flame speed, the Markstein length and the ignition delay time of ammonia flame were of great important to ammonia combustor design and safety evaluation of ammonia related industrial application. The auto-ignition behavior of $NH_3/CH_4/H_2$/air mixtures is investigated experimentally for pressures up to 7500 kPa [4]. The experimental results were used to assess realistic AIT values in the pool reactor and the ammonia scrubber, operating at a pressure of 15 000 kPa.

The ignition characteristics of ammonia/air mixtures at low temperature have been studied by busing a micro flow reactor with a controlled temperature profile [5]. The laminar flame speed and ignition delay time of the NH_3 flame at various H_2 blending levels, are numerically investigated [6]. The unstretched laminar flame speed and

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Nomenclature

A	Area of a flame surface
C_p	Specific heat at constant pressure
D_k	Equivalence diffusion coefficient of species k into the rest of the mixture
k	Stretch rate
L_d	Unburned gas Markstein length
Le	Lewis number of deficient species
Le_k	Lewis number of species k
$Lecr$	*Critical* Lewis number
P	Initial pressure
$Pecr$	Peclet number
Rcr	Critical radius
r_b	Radius of spherical burned gas
$R_{ignition}$	The minimum radius of spherical flame unaffected by ignition process
$R_{confine}$	The maximum radius of spherical flame unaffected by the confinement of the vessel
s_a	Absolute velocity
s_c	Consumption flame speed
s_d	Displacement velocity
s_L	Laminar flame speed
t	time
u	Gas velocity
V	Volume
Y_P	Mass fraction of product
Y_P^2	Mass fraction of product of burned side
α	Thermal diffusivity
δ	Flame thickness
λ	Thermal conductivity
ν	Kinematic viscosity
$\varnothing$	Equivalence ratio
ρ	Density of gas mixture
ρ_b	Gas density of burned side
ρ_u	Gas density of unburned side
ω_P	Production rate of product

the Markstein length of ammonia/air premixed flames at various pressures up to 0.5 MPa were experimentally studied [7]. Results indicate that the maximum value of unstretched laminar flame speed is less than 7 cm/s within the examined conditions and is lower than those of hydrocarbon flames. The unstretched laminar flame speed, and flame response to stretch (represented by the Markstein number) for laminar premixed hydrogen-added ammonia/air flames were studied both experimentally and computationally [8]. Results show the substantial increase of laminar flame speeds with hydrogen substitution, particularly under fuel-rich conditions. The combustion characteristics of premixed ammonia-air mixtures, with equivalence ratios around unity, at elevated pressure and temperature conditions were numerically studied and the laminar flame speed, final flame temperature and species concentration were determined [9].

In order to design an ammonia fueled combustor and to evaluate the safety of ammonia related industrial process, fundamental flame characteristics of ammonia must be understood. However, knowledge of the characteristics of ammonia/air or oxygen flames, has been insufficient. In this study, the unstretched laminar flame speed and the flame response to stretch (represented by the Markstein length), and the critical radius of spherical ammonia/oxygen flames at various pressures were experimentally and numerically studied. The premixed ammonia/oxygen spherically flames, which propagate in a constant volume combustion chamber, were observed using high-speed Schlieren photography.

2. Experimental set-up and procedure

The experimental set-up is schematically shown in Fig. 1. It consists of a combustion chamber, a gas distribution system, an ignition device, a high speed Schlieren photography system, and a control unit. The combustion and flame propagation were performed in a cylindrical combustion chamber of inner diameter 300mm, length 350mm and wall thickness 30mm, which could withstand an inter pressure of 300 bar. Two high-strength quartz windows of diameter 200mm were mounted on the opposite head walls of the combustion chamber for optical access. The chamber was equipped with several ports for gas feed and evacuation valves, and for mounting ignition electrodes, pressure meter, pressure sensors and thermal couples. The gas distribution system consists of an ammonia cylinder, anoxygen cylinder, flow meters, a gas distribution unit, and a vacuum pump. The hydrogen and oxygen were filled into the combustion chamber separately by using the gas distribution system. A high speed Schilieren photography system with a Z type arrangement was used to record the flame front movement during the flame propagation process. It consists of a lamp, condenser lenses, a slit, plane and parabolic mirrors, a knife edge, a high speed digital camera and a computer. The ammonia/oxygen mixtures were ignited by an electric spark ignition system, which

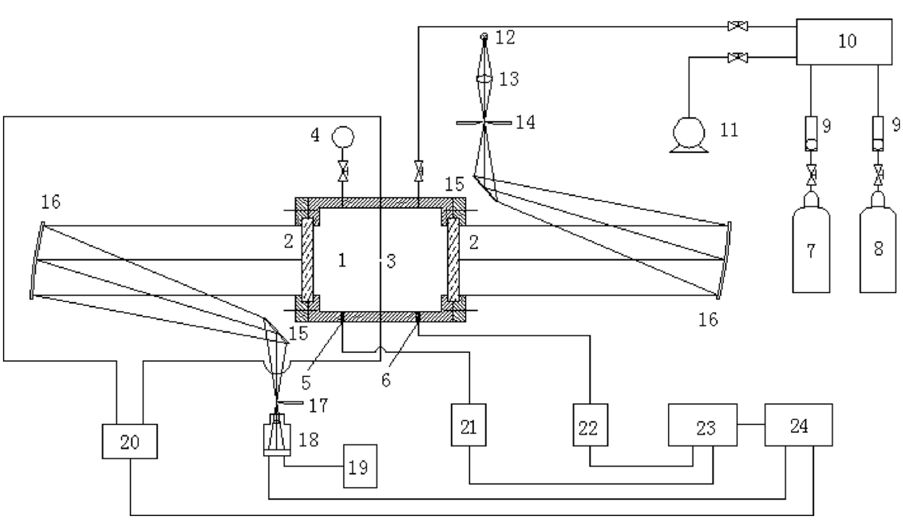

Fig. 1. Schematic diagram of the experimental set-up. 1- combustion chamber 2- quartz window 3- ignition electrodes 4- pressure meter 5- pressure sensors 6- thermal couples 7- ammonia cylinder 8- oxygen cylinder 9- flow meters 10- gas distribution unit 11- vacuum pump 12- lamp 13- condenser lens 14- slit 15- plane mirror 16- parabolic mirror 17- knife edge 18- a high speed digital camera 19- computer 20- ignition device 21- pressure adapter 22- temperature adapter 23- data acquisition system 24- control unit.