INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 43 (2018) 5199–5205

Available online at www.sciencedirect.com

ScienceDirect

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

Blow-off process of highly under-expanded hydrogen non-premixed jet flame

Shohei Yamamoto [a], *Ryo Sakatsume* [b], *Keiji Takeno* [b,*]

[a] *Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei-city, Tokyo 184-8588, Japan*

[b] *Department of Advanced Science and Technology, Toyota Technological Institute, 2-12-1 Hisakata, Tenpaku-ku, Nagoya 468-8511, Japan*

ARTICLE INFO

Article history:
Received 7 August 2017
Received in revised form
29 November 2017
Accepted 21 January 2018
Available online 15 February 2018

Keywords:
Under-expanded jet
Blow-off
Turbulence
Non-premixed flame
Notional nozzle

ABSTRACT

Relationships between flame lift-off heights and reservoir pressure were experimentally investigated in order to clarify blow-off process of hydrogen non-premixed jet flames with a highly under-expanded jet structure. In this study, straight nozzles with diameters of 0.34, 0.53, 0.75 and 1.12 mm were used with maximum reservoir pressure for spouting hydrogen of 13.2 MPa. Experimental results are shown that lift-off heights in stable under-expanded jet flames do not vary significantly and are independent of the reservoir pressure in the range of studied pressure. However, the lifted heights are affected by the nozzle diameters and become smaller as the nozzle diameters increase. From experimental results, the condition for the blow-off process of under-expanded subsonic jet flames was proposed. It was concluded that the under-expanded jet flame could be blown off when the maximum waistline position, where radial distance from the jet axis to an elliptic stoichiometric contour reaches its maximum comes closer to the nozzle exit than the edge of the jet flame base.

Introduction

Storing gaseous hydrogen in high pressure vessels under high pressure is the most common way to make it available as an energy carrier because of its low volumetric energy density. The hydrogen pressure for vehicular fuel cell applications can reach 70 MPa. At such a high pressure, if a hydrogen release from the vessel ignited, a non-premixed jet flame with the structure of a highly under-expanded jet would be formed.

The characteristics of an under-expanded hydrogen jet flame have been investigated by many researchers [1–9], and the results could be used for establishing safety evaluation criteria. Straight nozzles were used in experiments with diameters ranging from 0.32 to 10.0 mm. All experiments were performed by Takeno et al. under a maximum reservoir pressure of 40 MPa for spouting hydrogen [4–9]. The conditions at the nozzle (diameter and reservoir pressure) required for stable under-expanded hydrogen jet flames were explained in Refs. [4,6] and an empirical equation for the length of the under-expanded hydrogen jet flame was provided. The formula is expressed as a function of the nozzle diameter and the reservoir pressure [4,5]. As for researches for the length of hydrogen jet flames, Molkov et al. have reviewed in their literature [7]. It was also reported that an ignited flame propagates at over 600 m/s in the hydrogen jet immediately

* *Corresponding author.*
E-mail address: takeno@toyota-ti.ac.jp (K. Takeno).

https://doi.org/10.1016/j.ijhydene.2018.01.116
0360-3199/

after hydrogen release [8–10]. However, the stability and blow-off mechanism of the jet flame formed after ignition were not mentioned.

An increase of pressure in the reservoir results in blow-off for the stable subsonic non-premixed jet flames. Studies on blow-off velocities for various fuels have been performed [11–13], and the blow-off phenomena was also suggested [14,15]. Experimental investigation of blow-off stability for non-premixed jet flames in various fuels was done by Kalghatgi [11]. Correlations for the blow-off velocity were proposed based on the reported experimental results [11,12]. Wu et al. suggested the condition for the blow-off process in a turbulent non-premixed jet flames based on the theoretical and experimental investigation of fuel distribution concentration in jets [15].

Birch et al. showed conditions required for stable under-expanded natural gas jet flames [16]. The straight nozzles with diameters from 5.5 to 38.1 mm were used for their experiments, and the maximum reservoir pressure was 10 MPa. They suggested that the blow-off pressure can be predicted from extrapolating blow-off velocities measured in subsonic jets by applying a notional nozzle concept where it was assumed that jets appeared as if they originate from notional nozzles [17]. They also reported that the blow-off in under-expanded jet flames occurs when the storage pressure decreases [18]. However, the blow-off process of under-expanded jet flames is unclear.

In the present paper, the blow-off pressure is predicted and is compared with the experimentally obtained blow-off pressure based on the notional nozzle concept [19–22] and the subsonic jet flame blow-off condition proposed by Wu et al. [15]. The condition for the blow-off process of under-expanded jet flames is proposed.

Experimental setup and conditions

Fig. 1 shows the schematic diagram of the experimental setup and the optical system used in this study. The highly under-expanded jet was formed by blow-down of hydrogen from a high pressure cylinder through a straight nozzle with a round outlet. The jet was ignited by a non-premixed natural gas jet flame, which was located at the position of 70 mm downstream in the jet axis direction. The ignition source was removed after the ignition of hydrogen jet was confirmed. The release of hydrogen from the high pressure cylinder was manually controlled by a needle valve, and pressure in the passage was measured by a pressure transducer (TP-AR, TEAC) at 520 mm upstream of the nozzle exit. The measured maximum pressure was almost constant (deviations were within 0.20 MPa) when the needle valve was fully opened. Output signals from the pressure transducer was amplified by an amplifier (DAS-406B, Minebea) and recorded by a data acquisition unit (GL-7000, GRAPHTEC). Data sampling frequency was set at 10 kHz. The pressure data was acquired synchronously with schlieren imaging. Diameters d of straight nozzles used in this study and the values of the maximum reservoir pressure p_{max} measured in experiments are listed at Table 1.

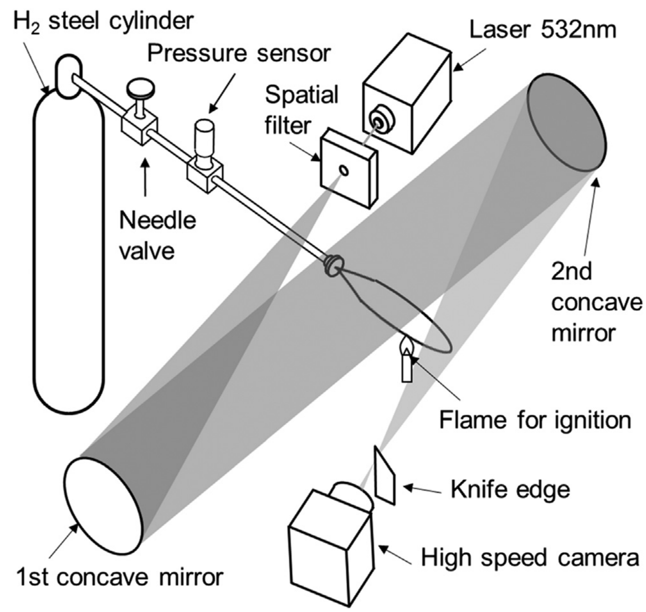

Fig. 1 – Schematic diagram of experimental set up.

Table 1 – Experimental conditions of nozzle diameters d and maximum reservoir pressure p_{max}.

d [mm]	Maximum reservoir pressure p_{max} [MPa]
0.34	12.6
	13.2
0.53	9.5
	13.1
0.75	3.6
	5.5
1.12	0.7
	2.2

In this study, lift-off heights in highly under-expanded hydrogen jet flames were measured from schlieren images. A schlieren optical system was consisted of a laser (wave length: 532 nm, maximum output: 50 mW, G50-B, KATO KOKEN), a spatial filter, two concave mirrors (diameter: 150 mm, focus length: 1500 mm) and a knife edge. Schlieren images were recorded by a high speed camera (UX100, Photron) at 1000 fps frame rate and 12.9 μs exposure time.

Experimental results and discussion

Variations in lift-off height and mach disk position

Fig. 2 shows schlieren images obtained in the single experiment under the condition of d = 0.53 mm and p_{max} = 13.1 MPa. The values of pressure in these images denote the measured reservoir pressure p_1 at photographing time, and the variation in p_1 was caused by continuously closing the needle valve. A Mach disk approaches gradually the nozzle exit as p_1 decreases. As shown in Fig. 3, the measured L_{MD} (distance along the nozzle axis direction from the nozzle exit to the Mach disk) coincides well with L_{MD} predicted by an empirical equation $L_{MD}/d = 0.62\ \eta_0^{\ 0.51}$