EXPERIMENTAL STUDY OF FLASHBACK CHARACTERISTICS IN A PARTIALLY PREMIXED HYDROGEN COMBUSTOR

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Abstract

This paper experimentally investigated the flame structure and flashback characteristics of a partially premixed hydrogen nozzle without a central bluff-body structure. The blow-off and flashback limits of the flame were observed according to the bulk air velocity and equivalence ratio. In this experiment, the flashback was based on the strongest part of the flame, that is, the core of the flame exists inside the nozzle. At low air flow rates, a flashback of the flame occurs regardless of the equivalent ratio. In this section, the flame is fixed inside the nozzle, and the V-shaped flame shape is not shown. As the flow rate increases, the flame moves out of the nozzle, and a V-shaped flame is formed in the low equivalent ratio section. The injected fuel forms a weak flame along the central low-speed section. After that, the flame is formed at the nozzle outlet where the flow rate decreases, and the flame is divided into two. This form is due to the swirl flow of the shear. When the equivalent ratio increases, the overall flame strength increases. The flame core moves to the shear as the equivalent ratio increases, and when the flame speed catches up with the nozzle outlet speed, the flame is shown inside the nozzle.

1 Introduction

The interest in global warming, including air pollution, has been increasing significantly in recent times. According to research results, various meteorological phenomena occurring worldwide are believed to be caused by global warming. As a result, carbon emissions are evaluated as a major factor in global warming, leading to stronger regulations. Consequently, there is also a growing interest in hydrogen fuel as an eco-friendly alternative. However, there are still many obstacles to using hydrogen as the main fuel source.

The major risk of using hydrogen as a fuel is the potential for flashback, a phenomenon in which a flame propagates through a nozzle due to the high reactivity and flame speed of hydrogen. The nozzles used with hydrogen fuel have weaker heat resistance than the combustion chambers, which can lead to system failure or destruction [1]. Flashback is highly dependent on flame speed, and the flame speed of hydrogen is over six times higher than methane in laminar flow conditions [2]. Furthermore, the flame speed increases even more in turbulent flow conditions with turbulent intensity [3]. Therefore, the risk of flashback is significantly greater with hydrogen fuel compared to methane.

The objective of this study was to analyze the overall combustion operation limit of a partially premixed hydrogen flame. To achieve this, a nozzle structure without a central bluff-body (unlike conventional swirl combustors) was designed for future application to multiple nozzle combustors. Additionally, a low swirl axial swirler (swirl number, $S < 0.6$) was installed to increase flame anchoring and mixing. A quartz tube was installed just before the combustion chamber to detect flashback phenomenon and visualize flame behavior. Furthermore, the study the flame structure through OH* chemiluminescence imaging.

2 Experiment result

The combustor, as shown in Fig. 1, was used to analyze the flame structure and operation limit of a partially premixed hydrogen flame. The combustion chamber has a square section of 40x40 mm², with its length adjustable from 350 to 750 mm by moving the plug nozzle at the rear end. The plug nozzle, with a blockage ratio of about 90%, forms an acoustically closed boundary. Combustion instability conditions were avoided by adjusting the length of the combustion chamber. A quartz window was installed 200 mm from the dump plane of the combustor to visualize the flame structure. The quartz tube, installed at the front of the dump plane to detect the flashback of the flame. There is a 7 mm gap between the quartz tube and the quartz window.

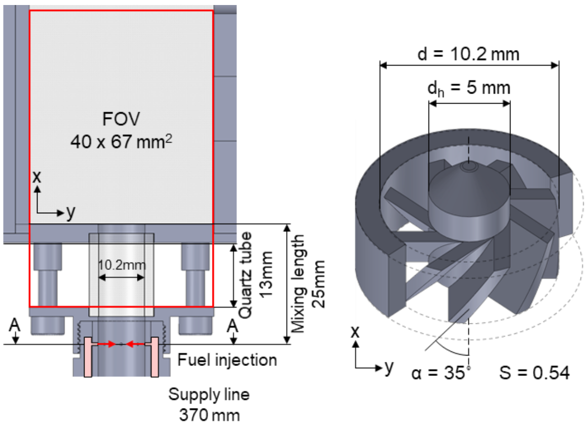

Figure 1. (a) Schematic of single hydrogen nozzle combustor.

Fuel and air were controlled individually through mass flow controller (MFC Korea, ±1% of full scale (200 lpm) accuracy for air, ±1% of full scale (80 lpm) accuracy for H2). The nozzle diameter is 10 mm. The air is supply to the center tube from the bottom. Fuel is injected in the flow vertical direction through 8 circular holes. The mixing length of the fuel and air is 25 mm. This form a jet-in-crossflow type of mixing. The injection hole diameter of fuel is 0.6 mm. The flat vane axial swirler is installed 120 mm forward the dump plane. The swirl number is approximately 0.54, which is low swirl region. The swirl number was calculated using Eq. 1, along with the geometric parameters of the nozzle.

$Sg = 2/3((1-(dh/d)3)/(1-(dh/d)2)\tan(\alpha)$ (1)

To visualize the flame structure, OH* chemiluminescence image, OH* image, was used. A high-speed camera with an intensifier (Lavision, high-speed star 8 with IRO intensifier) was used to visualize the OH* image. An UV lens (f = 100 mm, f/2.8) and a bandpass filter (320 ± 20 nm) were also used. The field of view (FOV) was selected to include a portion of the quartz window and the quartz tube, thus showing a complete image of the swirl hydrogen flame. Table 1 Experimental setup conditions.

Parameters[unit]	Values
Combustor area [mm^2]	40×40
Nozzle diameter, d [mm]	10
Swirler bluff body diameter, d_h [mm]	5
Swirler vane angle, α [deg]	35
Swirl number, S [-]	0.54
Supply line length, L_s [mm]	360
Mixing length [mm]	25
Fuel / Oxidizer	H_2/Air
Air flow speed, u_a [m/s]	5 – 25
Equivalence ratio [-]	0.5 – 1.3

The experiment was conducted to construct a broad-range flame stability map for the partially premixed hydrogen flame. The blow-off limit, BOL and flashback limit, FL of the flame were measured with respect to the bulk air velocity at the nozzle exit, u_a and the equivalence ratio, ϕ of the mixture. The experiment was conducted at bulk velocities ranging from 5 m/s to 25 m/s.

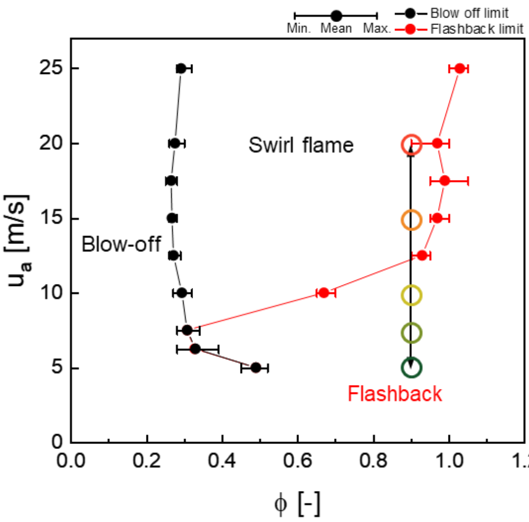

Figure 2. Flame stability map with bulk air velocity and equivalence ratio.

The BOL was defined as the equivalence ratio at which the flame extinguished before 1 minute from the change in equivalence ratio. On the other hand, the FL was defined as the minimum ϕ for each iteration where flashback appeared. The average value of the data obtained by repeating the experiment five times was used to account for variability. The results of the measured BOL and FL are shown in Fig. 2, with the maximum and minimum values displayed based on the average value of each point. The flame blow-off occurred at an equivalence ratio of around 0.25, except for the 5m/s case. Until the flow speed reached 15 m/s, BOL decreased. However, it increased after 15 m/s, although the difference was not significant. The BOL was higher in the 5-7.5 m/s section, contrary to the general expectation that BOL is low at low flow speeds. The experiment controlled the air flow speed by controlling the overall flow rate of air. Hence, even with the same equivalence ratio, the heat output increases at a high velocity cases. Therefore, the heat output to maintain the flame is insufficient compared to the total combustor system at a low flow rate (5-7 m/s). This can be seen from the fact that the heat output is similar in the 0.7-0.8 kW range at a low flow rate.

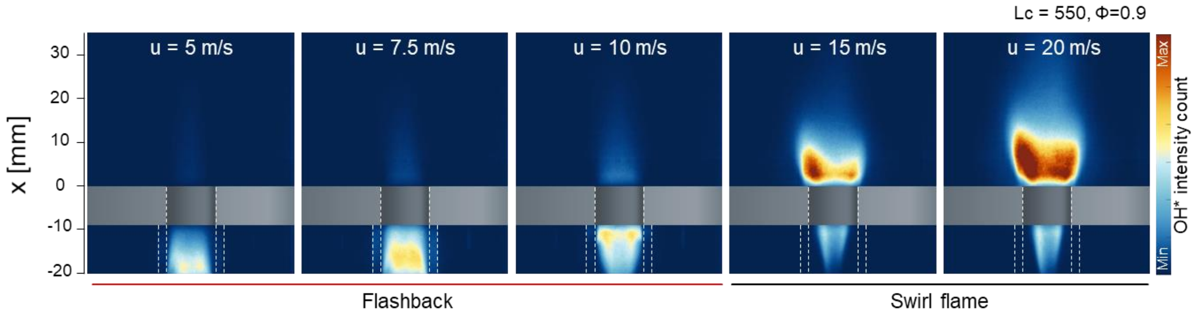

Figure 3. OH* chemiluminescence image with various air flow velocity at $\phi = 0.9$ and Lc = 550 mm.

This study defined a flashback flame as a flame with the flame core located inside the nozzle. For cases with $u_a \leq 6.3$ m/s, the flame was located inside the nozzle regardless of the equivalence ratio due to the low overall bulk air speed and reduced fuel injection speed. FL increased with u_a increase, but there was a significant increase in FL only up to 12.5 m/s. The heat output increases as the flow rate increases, leading to an increase in the total combustor temperature in the same equivalence ratio, and the intensity and size of the flame also increase. Fig. 3 shows the flame OH* image with various air flow velocity, with a flashback flame observed at air flow speeds below 15 m/s. At high flow rates (ua = 15, 20 m/s), the flame core appears outside the nozzle. The swirl flame, defined as a non-flashback flame, starts at the bottom of the quartz tube, but the flame inside the nozzle is faint, and the flame core appears fixed outside the nozzle. The center V-shaped structure inside the nozzle seems to be a structure formed by a slow center flow after the swirler.

3 Conclusion

The study aimed to investigate the combustion operation limit of partially premixed hydrogen flames in stable condition. The partially premixed flame under weak swirl conditions typically exhibited a V-shaped flame structure starting from inside the nozzle due to the low flow rate in the central region without a blue body. The stability map of the flame was established for a wide range of air flow rates and equivalence ratios, with a focus on the flashback area that was mainly observed due to the use of hydrogen as the main fuel. The results showed that flashback did not occur in the fuel lean region at an air flow rate of 12.5 m/s or higher. Flashback flames mostly occurred inside the nozzle, with only a small portion appearing outside the nozzle.

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