Development of a water-cooled multi-hole calibration burner for optical measurements of flames with high pressures and temperatures

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Abstract

High temperature flames, which can be produced via oxygen-enriched combustion, potentially have improved the combustion characteristics over air-only combustion flames due to their substantially higher flame temperatures. These conditions necessitate the use of non-intrusive optical measuring methods to measure the temperature and the chemical species in the flame. To develop an optical measurement calibration burner that can be used at high pressure and temperature conditions, a new calibration burner which employed water-cooled multi-hole nozzle was developed in this study. Premixed $\text{CH}_4/\text{O}_2/\text{N}_2$ oxygen-enriched conditions were selected to investigate both the heat-resisting properties of the developed burner nozzle and the burner's flame characteristics. OH-Planar Laser-Induced Fluorescence (OH-PLIF) measurements were conducted on the flames to observe the OH distributions. The flame temperature at 0.10 MPa was derived using a Boltzmann-plot for the OH fluorescence excitations. To verify the variation of molecular concentration with equivalence ratio for the experimental flames qualitatively, the experimentally acquired OH and CH chemiluminescence intensities were compared with the simulated partial pressure of OH^* and CH^* , respectively. Experimental results showed that the $\text{CH}_4/\text{O}_2/\text{N}_2$ flames were stabilized on the burner nozzle in a wide range of oxygen-enrichment ratio, from 0.40 to 1.0 at atmospheric pressure. At an oxygen-enrichment ratio of 0.45, the flames were also stabilized in pressure conditions up to 0.49 MPa, while the inner nozzle temperature was lower than 400 K. The OH-PLIF images showed that the OH was distributed almost uniformly along the axial direction of the burner, and demonstrated similar characteristics to that of a flat flame. The derived maximum flame temperature at atmospheric pressure was approximately 2650 K at an oxygen-enrichment ratio of 0.80. The variation of the OH and CH chemiluminescence intensities with change of equivalence ratios corresponded roughly with the simulated partial pressures of OH^* and CH^* at each pressure condition.

Keywords : Oxygen-enriched flames, Burner design, High pressure combustion, Laser induced fluorescence, Chemiluminescence

1. Introduction

Pure oxygen combustion and oxygen enriched combustion are techniques that are widely used in application such as liquid bi-propellant rocket engines and industrial burners. Oxygen-enriched combustion has garnered significant attention due to its high calorific value and burning velocity which contributes to a reduction of exhaust gas (Nishimura et al., 2000, Shi et al., 2012), stabilization of mildly flammable fuels (Takeishi et al., 2015), high energy gains, and potential applications to low energy fuel combustion. The most notable characteristic of oxygen-enriched combustion is its high flame temperature. Compared with air-only combustion, an oxygen-enriched condition has substantially increased energy

efficiencies. Additionally, when methane is used for the fuel, the adiabatic flame temperature can reach as high as 2700 K under atmospheric pressure (Shi et al., 2012). In pure oxygen combustion, there are many fuels with adiabatic flame temperatures as high as 3000 K at maximum (Niioka et al., 2000).

This increased flame temperature creates problems for combustion measurement. High flame temperatures necessitate the use of non-intrusive optical measuring methods based on spectroscopy to measure the temperature and the chemical species in the flame. When an optical measurement is selected, which represents such non-intrusive measurement method, a calibration must be conducted for the method, because spectroscopic measurement handles spectroscopic variables that feature strong temperature and pressure dependences. To date, various non-intrusive measuring methods have been developed and applied for studies of combustion diagnostics. Moreover, two-dimensional combustion measuring methods such as Planar Laser-Induced Fluorescence (PLIF) have been also used frequently in recent years. Additionally, when a new combustion measurement technique is devised, it must be verified with results to confirm its accuracy. The most general method for calibrating a combustion measurement is to use a calibration burner, which creates a quasi-one-dimensional combustion field. Thus, a calibration burner is used in many combustion diagnostic studies.

There are many types of calibration burners, but the essential concept of all types is to create a uniform combustion field in the radial direction to assure one-dimensional properties of the field. There are two common methods to create this uniform field: use a porous material such as sintered metal or make many small holes or tubes as the shape of the exit for the unburnt gas. So-called McKenna burner (Holthuis & Associates) is a widely used calibration burner model that uses sintered metal, and experimental data, such as temperature measurements, have been reported via Coherent Anti-Stokes Raman Spectroscopy (CARS) at each combustion condition (Weigand et al., 2017, Prucker et al., 1994). It has been reported that it is possible to stabilize a stable laminar flat flame up to 60 bar via heat loss to the surface of the sintered metal (Bessler et al., 2002, Cheng et al., 2002). However, stabilizing a flat flame by heat loss causes a strong heat load on the sintered metal; thus, for conditions in which the flame temperature is higher than the temperature in above case, another burner type should be used according to Kojima et al (2003). Meanwhile, a nozzle shape with many small holes or tubes such as a Hencken burner and Meker burner must keep the injection velocity of the premixed gas faster than the burning velocity when the flame quenching diameter is smaller than the diameter of the burner exit. However, the heat load on the injection surface of the burners is estimated to be lower than sintered metal. As an example, stabilization of hydrogen-air rapid premixed flame at 10 atm, has been reported using a nozzle with non-cooling multiple small holes, but its gas outflow surface reached temperatures as high as 700 K (Kojima et al., 2003). Although there are many reports on calibration burners successfully operating in high pressure conditions, reports on their operation in oxygen-enriched conditions with high flame temperatures are scarce. The heat resistance of these burner is a cause of this problem. It is an urgent task to develop a calibration burner that can accurately realize a relatively wide quasi-one-dimensional uniform temperature and species field with actual flame temperatures associated with oxygen-enriched or pure oxygen combustion.

In this study, a new optical measurement calibration burner is presented that can be used for calibration and quantification of high flame temperatures such as oxygen-enriched flames in pressures ranging from atmospheric to highest pressure condition of 0.49 MPa. Oxygen-enriched methane/oxygen/nitrogen ($\text{CH}_4/\text{O}_2/\text{N}_2$) flames were formed with maximum chamber pressure up to 0.49 MPa, and the basic performance of the burner (e.g., flame stabilities and heat resistance of the nozzle) was verified. The emission distribution of OH radicals was acquired by an OH-Planar Laser-induced Fluorescence (OH-PLIF) measurement to examine the uniformity of OH distribution in region of downstream of the nozzle. Furthermore, a numerical simulation of the one-dimensional flame as well as an experiment using the Boltzmann plot method were conducted to examine the flame temperature. Moreover, the simulated partial pressure of excited chemical species OH^* and CH^* were compared with the corresponding OH and CH chemiluminescence intensities which were acquired in the experiments to verify the variation of molecular concentration with equivalence ratio for the experimental flames qualitatively.

2. Experimental and numerical method

2.1. Newly developed water-cooled multi-hole calibration burner

The newly-devised calibration burner designed and developed in this study is shown in Fig. 1. This burner was designed to be cooled by water considering its high heat load conditions, in contrast to so-called Hencken burner. The

Fig. 1 Schematic diagram of calibration burner using water-cooled multi-hole nozzle designed in this study.

Fig. 2 Schematic of high pressure combustion test facility.

burner was composed of only two parts: a nozzle made from oxygen-free copper, which has a high heat conductivity, and a supply tube made of stainless steel. Parallel pipe thread connected the nozzle and supply tube. The nozzle was so designed that it was easy to detach considering the increasing damage for the nozzle with these operating conditions. The center of the supply tube was used for supplying the premixed gas and there were four channels around the outer perimeter through which the cooling water could flow. This experiment used water for the coolant and the temperature and flow rate were approximately 293 K and 11 L/min, respectively. The bottom of the supply tube had a flange shape to match the interface with the high pressure combustion chamber (Takeuchi et al., 2017). The nozzle surface attached to the supply tube had a 3 mm wide circular coolant channel for flow on the outer perimeter. On the upper nozzle surface, 240 small holes with a diameter of 0.7 mm in a staggered arrangement were provided to fit inside a 17 mm diameter circumference to assure the formation of one-dimensional flame with the same way as so-called Hencken burner. The length of the holes was 5 mm, and the aspect ratio of the holes was 7.14. Furthermore, four insertion holes for a thermocouple were placed every 90 degrees around the 17 mm diameter as well as a single point in the center; thus, there were a total of five points to measure the radial temperature distribution of the injection surface during flame formation. The center hole for the thermocouple was named Point1, and two holes along the 17 mm diameter were named Point2 and Point3, as shown in Fig. 1. There was a 3 mm clearance between the nozzle and supply tube to insert sintered metal to prevent flame oscillation, flashback and to enhance mixing as well as so-called McKenna burner. By adopting these features, the burner can operate in the high pressure and temperature conditions.

2.2 Procedure of high pressure combustion and optical measurements

Combustion experiments were carried out using the high pressure combustion test facility in the Institute of Fluid Science, Tohoku University. As shown in Fig. 2, the burner was placed inside the chamber with a chamber pressure $P_c = 0.10 \sim 0.49$ MPa along with OH-PLIF measurement. The orifice or mass flow controller were used to measure each of the $\text{CH}_4/\text{O}_2/\text{N}_2$ gas flow rates. Compressed air was used to pressurize the chamber. The average premixed gas flow velocity of each hole was set to be above the laminar burning velocity. The largest Reynolds number for each hole was

approximately 1250 for $P_c=0.49$ MPa and an equivalence ratio $\phi=1.2$. Only the CH_4 flow rate was changed to adjust the equivalence ratio. Each gas flow rate was determined by the oxygen-enrichment ratio β and the equivalence ratio ϕ . By using volumetric flow rate Q of O_2 and N_2 , β is defined as given Eq. (1).

$$\beta = \frac{Q_{\text{O}_2}}{Q_{\text{O}_2} + Q_{\text{N}_2}} \quad (1)$$

According to this equation, $\beta = 0.21$ corresponds to air. In this study, the combustion experiment was carried out with $\beta = 0.40 \sim 1.0$ at atmospheric pressure and $\beta = 0.45$ at high pressure.

The OH-PLIF measurement was conducted to examine the flame formed above the burner as well as downstream of the flame. A Nd:YAG laser with an oscillation frequency of 10 Hz and a dye laser were used for the light sources to excite the OH in OH-PLIF measurement. The laser beam power was approximately 14 mJ/pulse at the dye laser outlet. The laser beam was formed into a sheet 40 mm in height above the nozzle surface and 0.1 mm in thickness using cylindrical silica lenses. The OH(2,0) band Q₁(9) branch (263.580 nm) was selected as the excitation line due to the relatively small temperature dependence of f_B / T for the predicted flame temperature range of 2500 ~ 3000 K. The temperature dependence of f_B / T is given in Eq. 2 (Sakiyama et al., 1999).

$$\frac{f_B}{T} = \frac{2J''+1}{T} \exp\{-B_V J''(J''+1)/(kT)\} \quad (2)$$

Here, f_B is the Boltzmann factor, T is the temperature [K], J'' is the total angular momentum quantum number of the vibrational ground state, B_V is the rotational constant=18.513 cm^{-1} at the vibrational ground state, and k is the Boltzmann constant. The variation range of f_B/T of the Q₁(9) branch is 0.1 % in the temperature range of 2500 ~ 3000 K.

The photon detector system is composed of an ICCD camera (Andor, USB-iStar), an ultraviolet lens (Nikon, UV-105 mm F4.5), and optical filters. The frame rate of the ICCD is approximately 4 Hz, and the gate duration of the image intensifier is approximately 25 ns. OH(2,1) band fluorescence was acquired by using a combined optical filter consisting of a color glass filter UG11 (SCHOTT, 325 nm centerd, FWHM of 110 nm) and an interference filter HQBP290-UV (Asahi spectra, 290 nm centered, 10 nm of FWHM).

Temperature measurements using the Boltzmann plot advocated by Anderson et al (1982) were conducted in the combustion condition with a chamber pressure $P_c = 0.10$ MPa and $\beta = 0.2, 0.4$, and 0.6 . This measurement technique is the standard method for obtaining the temperature from the slope by plotting each rotational and vibrational state of the molecule measured by Laser-Induced Fluorescence (LIF) to ground state of rotational energy $\omega'' = B_V J(J+1)$ [cm^{-1}]. The relationship between fluorescence intensity S_{FL} and rotational energy ω'' is shown in Eq. (3) (Anderson et al., 1982).

Table 1 Details of OH(2,0) band excitation lines.

Branch	Total angular momentum quantum number J''	Wavelength λ [nm]	Grond-State Energy ω'' [cm^{-1}]
Q1(1)	1.5	261.346	69.431
Q1(2)	2.5	261.507	162.006
Q1(3)	3.5	261.685	291.611
Q1(4)	4.5	261.902	458.246
Q1(5)	5.5	262.156	661.911
Q1(6)	6.5	262.449	902.606
Q1(7)	7.5	262.784	1180.331
Q1(8)	8.5	263.163	1495.086
Q1(9)	9.5	263.586	1846.871
Q1(10)	10.5	264.055	2235.686
Q1(11)	11.5	264.571	2661.531
Q1(12)	12.5	265.135	3124.406
Q1(13)	13.5	265.750	3624.311

$$\ln\left\{\frac{S_{\text{FL}}}{B_{12}(2J''+1)}\right\} = -\frac{\omega''}{kT} + C \quad (3)$$

Here, B_{12} is the stimulated absorption coefficient (Einstein's B coefficient) [$\text{m}^2/(\text{J} \cdot \text{s})$] which was acquired by using the reference from spectroscopic simulation software LIFBASE (2017). C is the arbitrary slope constant derived from the Boltzmann plot. In this study, the fluorescence intensity S_{FL} of each OH(2,0) band Q_1 branch rotational state was measured via the OH-PLIF equipment as explained above. The total angular momentum quantum number at ground state J'' , the wavelength λ and the rotational energy at ground state ω'' are shown in Table 1.

The flame temperature and the concentration field of the chemical species were also evaluated by measuring the chemiluminescence intensities of chemical species that have strong temperature dependences and by comparing them with simulated partial pressures of the chemical species. OH and CH were selected as the chemical species to be measured in this study. The same ICCD camera from the PLIF measurements was used to detect the chemiluminescence intensity. A filter combination of UG11 and HQBP310-UV (Asahi spectra, 310 nm centered, 10 nm of FWHM) was used to detect OH(0,0) band chemiluminescence, and a combination of UG11 and an interference filter (Optical Coating Japan, 432 nm centered, 17.4 nm of FWHM) was used to detect the CH(0,0) band chemiluminescence.

2.3 One-dimensional laminar flame numerical simulation

In addition to the experiment, the laminar flame velocity, mole fraction of each chemical species, and flame temperature at each combustion condition were evaluated by using a commercial reaction analysis software CHEMKIN-Pro (2017) with the Premixed Laminar Flame-Speed model. A CH_4/DME (Dimethyl ether) model composed of 113 chemical species and 710 elementary reactions (Burke et al., 2015) was used for the reaction kinetics. The radiation heat loss was modeled using Planck mean absorption coefficients [Barlow et al., 2001]. In this study, the unburnt premixed gas temperature and ambient temperature were considered to be 293 K by disregarding the heat loss to the burner. The excited chemical species of OH* and CH* were included to the reaction mechanism and their partial pressures were compared with the chemiluminescence intensities of the OH(0,0) band and CH(0,0) band obtained by the experiments.

3. Results and discussion

3.1 Heat resistance of burner nozzle

The oxygen-enrichment ratio and chamber pressure conditions were restricted by the heat resistance of the burner nozzle. The finite-element analysis conducted during the nozzle design stage indicated that the safety factor becomes less than 1 when the nozzle surface temperature reaches approximately 470 K. To ensure the safe operation of the burner, the inner nozzle temperature was evaluated. The variations of the inner nozzle temperature in Point 1 with equivalence ratio and net heat production rate at each pressure condition are shown in Fig. 3. The net heat production was calculated by

Fig. 3 Inner nozzle temperature measured at each pressure P_C . The temperatures measured at $P_C = 0.10, 0.28$ and 0.49 MPa are indicated by circle, triangles and squares, respectively. The oxygen-enrichment ratio β is 0.45.

the one-dimensional simulation and normalized by the chamber pressure. As shown in Fig. 3(a), both the inner nozzle temperature and the flame temperature had a peak value at approximately $\phi = 1.0$. The sintered metal was not inserted when the thermocouple was inserted, and the measurements at fuel enriched regions were not conducted at pressures of $P_C=0.28$ and 0.48 MPa because a loud vibration sound was released in the audible range, which was assumed to be flame oscillation. Numerical simulations also indicated that the nozzle inner temperature was around 380 K and the flame temperature was approximately 2900 K at the highest heat load condition in this study with $P_C=0.48$ MPa, $\beta=0.45$, and $\phi=1.0$ in this study. It can be concluded that the nozzle has a strong cooling performance and appropriate heat resistance for the experimental conditions. Moreover, the nozzle surface could be treated as an isothermal wall because the nozzle inner temperature history was almost steady at all flame conditions. From Fig. 3(b), it can be observed that there is a linear relationship between the inner temperature of the nozzle and the net heat production normalized by chamber pressure. From the linear relationship, the inner temperature of the nozzle at a certain pressure condition can be estimated by calculating the net heat production when the coolant temperature and flow velocity are constant.

3.2 Results of OH-PLIF measurements

Fig. 4 Multi-shot-averaged OH-PLIF images obtained from the output of image processing 100 single-shot images.

(a) shows the variation of oxygen-enrichment ratio β at $P_C=0.10$ MPa and $\phi=1.0$. (b), (c), and (d) show the variation of the equivalence ratio ϕ at $P_C=0.10$ MPa, 0.29 and 0.49 MPa, respectively.

The averaged OH-PLIF images acquired after processing 100 single-shot images for each flame condition are shown in Fig. 4. Figure 4 (a) shows the averaged OH-PLIF image with the conditions $P_C=0.10$ MPa, $\phi=1.0$ and $\beta=1.0, 0.80, 0.60$, and 0.40 . A steady flame was stabilized on the nozzle surface for all β conditions. It was also observed that the flame consisted of small conical flames on the outlet holes of the premixed gas instead of a flat flame. Small bumps were observed on the nozzle surface when $\beta=0.40$ where there was a big difference between the laminar burning velocity and the average premixed gas flow velocity $\bar{U}$. Meanwhile, attenuation of the fluorescence signal intensity was observed on the right side of the burner axial center which is the side of the laser sheet insertion. This attenuation was more noticeable for highly oxygen enriched conditions such as $\beta=1.0, 0.80$, and 0.60 . This is clearly caused by laser absorption becoming stronger when the OH concentration is high in oxygen enriched flames. Even for the OH(2,0) band excitation where the absorption intensity is weaker than the general OH(1,0) band excitation at atmospheric pressure, this effect should not be ignored and method such as Beer-Lambert's law (Daily, 1997) must be used to correct the laser-power degradation from OH absorption to accurately examine the radial fluorescence signal distribution of the flame. The non-uniformity of laser sheet intensity distribution can be identified as the cause of the axial intensity distribution but this will be evaluated in Figs. 6 later in this section.

The averaged OH-PLIF images for the conditions $\beta=0.45$ and $P_C=0.10, 0.29$, and 0.49 MPa are shown in Figs. 4(b) ~ (d). A uniformed OH distribution was observed for $P_C=0.10$ MPa, as shown in Fig. 4(b), similar to Fig. 4(a). With $P_C=0.29$ and 0.49 MPa, the fluorescence intensity attenuation in the radial direction is due to the increase in the OH number density. The OH fluorescence intensity was observed to be slightly higher for $\phi=0.80$ than for $\phi=1.00$ in all P_C conditions. One-dimensional numerical simulation indicated that for $\phi=0.80$ and $\phi=1.00$ at $P_C=0.10$ MPa, the flame temperatures 10 mm downstream of flame surface were 2769 K and 2685 K, respectively, and the OH mole fractions were 0.035 or 0.037, respectively. The difference in the flame temperature is approximately 80 K while the difference in the mole fraction was approximately 0.002. The results for $P_C=0.29$ and 0.49 MPa showed a similar trend. The fluctuation of f_B/T with the range of temperature differences was lower than 0.1%. However, there are other spectroscopic parameters with temperature dependences, such as the quenching rate or fluorescence lifetime of excited molecule (Bergano et al., 1983). It was evident that the fluorescence signal intensity decreases with increasing temperature, and the decrease of the fluorescence signal intensity is more dominant than the increase of the OH mole fraction for $\phi=0.80$ and $\phi=1.00$. The relevance of the equivalence ratio variation will be discussed later in chapter 3.3.

In higher pressure conditions of $P_C=0.29$ and 0.49 MPa, a disturbance in the outer burned gas surface began to be

Fig. 5 Images acquired at $P_C=0.10$ to 0.49 MPa, $\beta=0.45$, and $\phi=1.00$. (a) Single-shot OH-PLIF images. (b) Standard deviation distribution.

Fig. 6 Axial distributions of OH fluorescence intensity, S_{FL} , corrected by laser sheet intensity. The normalized laser sheet intensity is also shown in these figures.

Fig. 7 Axial distributions of flame temperature for $P_C = 0.10$ MPa and $\phi = 1.0$. (a) Boltzmann plot obtained at $Z = 10$ mm. (b) Axial temperature distributions at $\beta = 0.80, 0.60$ and 0.55 . In Fig. 7, the dashed lines represent the experimental results and the solid lines represent the 1-D flame simulation results.

observed where the burned gas and ambient air featured a large temperature gradient. To evaluate this disturbance, single-shot OH-PLIF images with $\beta = 0.45$ and $\phi = 1.0$ and the corresponding standard deviation distributions are shown in Fig. 5. The single shot OH-PLIF image was chosen randomly from the entire 100 images that were averaged in Fig. 4. As shown in Fig. 5, there were no disturbance in the outer surface of the burned gas at $P_C = 0.10$ MPa, and the standard deviation distribution matched the OH intensity distribution reasonably well. It can therefore be concluded that when $P_C = 0.10$ MPa, the standard deviation under 400 in arbitrary unit to systematic factor such as shot noise of the ICCD. On the other hand, when $P_C = 0.29$ and 0.49 MPa, the disturbance in the surface of burned gas can be observed in the single shot image, and the standard deviation quantity is high in the corresponding regions. However, the region near the axial center that was within 6 mm of radial distance had a standard deviation quantity close to that of the atmospheric pressure condition. In conclusion, when considering the distributions of quantities in the burned gas, the region near the axial center should be chosen to eliminate the surface disturbance of burned gas.

The OH fluorescence intensity in the axial direction along the burner's central axial for $\phi = 1.0$ at each P_C and β is shown in Figs. 6. The laser sheet intensity distribution was acquired using a quartz cell enclosed with acetone that was used to correct the fluorescence intensity distribution. The acquired laser sheet intensity is also shown in Figs. 6. Due to the quartz cell shape, the axial distance was corrected to $Z = 2 \sim 35$ mm. For each P_C and β condition, the region of $Z = 7 \sim 35$ mm region has a relatively uniform fluorescence intensity. In the $Z < 7.0$ mm region, the fluorescence intensity decreases due to the influence of heat loss to the nozzle surface. For $P_C = 0.49$ MPa, there were no significant intensity decreases compared with the case of $P_C = 0.10$ and 0.29 MPa due to the high heat release and thinning of the flame thickness.

The temperature distributions of the fuel in the radial direction at $P_C = 0.10$ MPa were evaluated by the temperature

measurement results of the Boltzmann plot and one-dimensional simulation results as shown in Figs. 7. The equivalence ratio was constant at $\phi = 1.0$ and oxygen-enrichment ratios of $\beta = 0.80, 0.60$, and 0.45 were evaluated. Figure 7(a) shows the Boltzmann plot taken at an axial distance of $Z = 10$ mm. The slope was calculated using least-squares fitting for each β condition. The results measured from $Q_1(1)$ to $Q_1(4)$ excitations were excluded in all the calculations, because the fluorescence intensities were much lower compared with higher J'' cases. Moreover, as J'' increases, the Boltzmann equilibrium by the rotational relaxation at the excited vibrational level is completed more certainly compared with the case of using lower J'' (Crosley, 1981). Thus, the results measured from $Q_1(5)$ to $Q_1(13)$ excitations were selected to calculate slopes of the fitting lines for the Boltzmann-plots. Figure 7(b) shows the axial distribution of the flame temperature T_f at positions $Z = 5, 7.5, 10, 12.5$ and 15 mm calculated from the Boltzmann plot and the one-dimensional simulated T_f distribution. It can be observed that the flame temperature was relatively constant around $Z = 7.5 \sim 15$ mm from Fig. 7(b). The temperature distribution can be assumed to be uniform similar to the fluorescence intensity distribution along the axial direction shown in Fig. 6. However, the experimental T_f was approximately 250 K lower than the one-dimensional simulated results which did not consider heat loss to the burner nozzle surface. In addition to heat loss, the half width of transmittance of the optical filter used for the fluorescence detection resulted in the temperature difference. The half width of the filter used in this study was 10 nm which is approximately two times larger than the half width of OH(2,1) band fluorescence. However, the acquiring fluorescence spectrum slightly changes by the difference of the excitation line J'' . When J'' is too small or too large, the filter is not able to transmit the fluorescence completely, because the filter transmittance is invariable. In other words, the detecting capability for the fluorescence will be variable in such case. This is a cause of underestimation of the flame temperature (Anderson et al., 1982). However, to prevent the strong OH chemiluminescence interference caused by high flame temperatures, a relatively narrow half width band pass filter was selected. Therefore, there was a possibility of the experimentally derived temperature being lower than the actual flame temperature in this study. Even though the experimental results differed from the numerical simulation results, when $P_c = 0.10$ MPa and $\beta = 0.80$ the flame temperature was higher than 2650 K and even when $\beta = 0.45$ the flame temperature was higher than 2450 K which is beyond temperature measurements by a thermocouple. It is rare to form such a high temperature flame for a calibration burner. The OH fluorescence intensity distribution at $Z = 7 \sim 35$ mm was uniform and the flame temperature was also uniform for a wide range of $Z = 7.5 \sim 15$ mm. The calibration burner makes it possible to efficiently quantify each physical parameter not only in one-dimensional measurements but also in two-dimensional measurement and withstands temperatures higher than 2650 K. Thus, it can be concluded that the proposed calibration burner has met the requirements for a spectroscopic measuring calibration burner.

3.3 Results of OH and CH chemiluminescence measurement

Figure 8 shows the OH and CH chemiluminescence acquired by the experiments for $\beta = 0.45$ at each pressure condition. The figure also shows the equivalence dependence of OH* and CH* partial pressures X which corresponds to

Fig. 8 Equivalence ratio dependence of acquired chemiluminescence intensity and simulated relative molar concentration of excited species. In Fig. 8, filled markers represent the experimental results and unfilled markers represent the simulated results.

Fig. 9 Relationships between chemiluminescence and relative molar concentration for each ϕ and P_C condition.

the chemical species partial pressure derived from the one-dimensional simulation. Because an outer flame was formed with the fuel enriched conditions, the results for $\phi = 0.60 \sim 1.0$ were examined. As mentioned above in chapter 3.2, position $Z = 10$ mm was selected for X_{OH^*} evaluation because the OH partial pressure and flame temperature in the axial direction can be regarded as uniform. Because CH only exists in the flame reaction zone, the peak intensity value near the nozzle surface was selected for X_{CH^*} . The burner center was selected as the radial position for both X_{OH^*} and X_{CH^*} evaluation. As shown in Fig. 8, the equivalence ratio dependence of OH* and CH* partial pressures corresponded well with the chemiluminescence results. Thus, it can be concluded that the experimental flame temperature and the variation of the corresponding chemical specie partial pressure with equivalence ratio are reasonable. In Fig. 4, the OH fluorescence intensity of $\phi = 0.80$ was originally thought to be higher than that of $\phi = 1.0$ from the PLIF measurement due to the decrease of OH concentration; however, the relationship of chemiluminescence and X_{OH^*} indicate that the flame temperature or OH concentration was actually higher at $\phi = 1.0$ than at $\phi = 0.8$. This confirms that the fluorescence intensity decreases due to the increased flame temperature.

To verify whether the chemiluminescence intensity and partial pressures of each chemical species qualitatively corresponded, the chemiluminescence versus partial pressures were plotted, as shown in Fig. 9. It can be confirmed from Fig. 9(a) that the relationship between the OH chemiluminescence intensity and X_{OH^*} has a slight convex curvature but is relatively linear. This curvature indicates that the rate of change of the simulated partial pressure of OH* was higher than that of experimentally acquired OH chemiluminescence intensity. In Fig. 9(b), it can be observed that relationship between the CH chemiluminescence intensity and X_{CH^*} has a stronger convex curvature than OH, because CH exists near the nozzle surface where the temperature is lower than that at downstream region due to the heat loss. Because the increase rate of the excited chemical species concentration rises exponentially, the difference in concentration between the experimental and numerical simulation results becomes larger than when the flame temperature increases at high pressures. Therefore, the heat loss of the burner surface must be considered in a similar way as a conventional calibration burner such as McKenna burner to calibrate the experimental results when targeting a chemical species located near the burner.

4. Conclusions

To develop a spectroscopic measurement calibration burner that can be used in pure oxygen or oxygen enriched conditions at high pressures, a new calibration burner which has a high heat resistance due to employ a water-cooled multi-hole nozzle was developed in this study. The basic performance of the burner (such as burner heat resistance and the flame characteristics) was evaluated based on both the experiments and numerical simulations. The following results were obtained.

1. At a chamber pressure $P_C = 0.10$ MPa and an oxygen enrichment $\beta = 0.40 \sim 1.0$, the spectroscopic measurement calibration burner designed in this study can form a remarkably stable $CH_4/O_2/N_2$ oxygen-enriched flame. Even with $P_C = 0.29$ and 0.49 MPa, when $\beta = 0.45$, a stable flame can be formed in a wide range of equivalence ratios $\phi = 0.6 \sim 1.2$.

2. The maximum inner temperature of the nozzle becomes higher than 380 K when $P_C=0.48$ MPa and $\phi = 1.0$, but it is well under the softening temperature of the oxygen-free copper used for the nozzle, which is designed to be 470 K at maximum, indicating that the burner can be used in higher heat load conditions.
3. OH-PLIF measurement results and the standard deviation at each pressure condition indicate there are disturbances in the outer surface of the burned gas at $P_C=0.29$ and 0.49 MPa but the effect of the disturbance is small in the region within 6 mm of the burner axial center. Moreover, the OH fluorescence intensity distribution is approximately uniform in a wide range of axial directions $Z = 7 \sim 35$ mm.
4. The flame temperature are distributed approximately uniformly along the axial direction for $Z = 7.5 \sim 15$ mm. This was derived from the temperature measurement result using a Boltzmann plot at $P_C=0.10$ MPa. The measured flame temperature was 250 K lower than the one-dimensional simulation which did not consider heat loss, but the flame temperature is still higher than 2450 K at $\beta=0.45$ and 2650 K at $\beta=0.80$.
5. The equivalence ratio dependence of OH(0,0) band and CH(0,0) band chemiluminescence relatively matched the equivalence ratio dependence of OH* and CH* partial pressure obtained by one-dimensional simulation.

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