Development of OH-PLIF Measurement Techniques for Application to High Pressure Rocket Combustion

著者	TAKEUCHI KIYONORI
学位授与機関	Tohoku University
学位授与番号	甲第18071号
URL	http://hdl.handle.net/10097/00125189

たけうち　きよのり
氏　　　　　名　竹　内　清　剛
研究科，専攻の名称　東北大学大学院工学研究科（博士課程）航空宇宙工学専攻
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論文審査委員　主査　東北大学教授　小林　秀昭　東北大学教授　浅井　圭介
東北大学教授　富岡　定毅　教授　出口　祥啓
（徳島大学）
東北大学准教授　中村　寿

論文内容要約

1. Introduction

Rocket combustion in typical bi-propellant liquefied rocket engines forms H_2/O_2 jet diffusion flames a is a combustion phenomenon that occurs under an extreme environment, which includes high-pressu high-flame temperature, and supercritical fluid combustion conditions. Under supercritical pressure conditio the flame characteristics have been expected to exhibit the phenomenon of gaseous propellant combustion unde subcritical pressure because the liquid propellant atomization process is no longer observed. However, it has al been necessary to make more detailed evaluations of what occurs in the region of the propellant mixing layer a reaction zone. Furthermore, high-frequency combustion oscillation can be sited as a representative combusti instability. The key factor for the oscillation exists in the region close to the injector exit. In addition, the criteria f flame stabilization have been proposed and include the reaction zone thickness of the flames. However, to date, few studies have evaluated the reaction zone thickness experimentally. Although OH-planar laser-induced fluorescence (OH-PLIF) is a reasonable measurement technique for the detailed flame structure, its application to rocket combustion has been scarce because of the arduousness of its measurements under high-pressure rocket combustion conditions.

The objective of the present study was to develop OH-PLIF measurement techniques that could be applied to high-pressure rocket combustion. In particular, a qualitative measurement technique for instantaneous two-dimensional OH distributions in the region close to propellant injector exit was developed and used to measure the distributions and reaction zones of gaseous H_2/O_2 jet diffusion flames under high-pressure rocket combustion conditions up to 7.0 MPa, which is greater than the pressures considered in previous OH-PLIF studies of rocket combustion. Furthermore, a new calibration burner for optical measurements of high-pressure and high-temperature flames was developed to realize the quantitative OH-PLIF measurements of flames under rocket combustion conditions.

To this end, a combination of several approaches was used and is described in Chapters 2–5. In Chapter 2, the OH-PLIF measurement principle and spectroscopic characteristics are presented. In addition, the interference of intense OH chemiluminescence is considered, and the development of the optimum excitation measurement method for high-pressure rocket combustion is discussed. Chapter 3 shows how the OH-PLIF developed measurement method discussed in Chapter 2 was applied to H_2/O_2 jet diffusion flame measurement under H_2/O_2 rocket combustion conditions up to 2.0 MPa, and its feasibility as a rocket combustion measurement method is evaluated. Chapter 4 shows how the OH-PLIF measurements of H_2/O_2 flames were performed under the unprecedented maximum pressure of 7.0 MPa for rocket combustion, and how the instantaneous flame structure under each pressure condition was qualitatively evaluated. In addition, the OH distribution in the injection axis direction and the change in flame thickness, which is represented by the OH distribution width with respect to a change in the Reynolds number, are clarified. In chapter 5, the basic performances of the newly developed calibration burner, including the heat resistance of the nozzle, two-dimensional OH distribution of the flame formed on the burner, and flame temperature measurement, are discussed to consider the temperature characteristics of the flame, along with its quasi-one-dimensional formation.

2. Construction of an optimal OH-PLIF method for rocket combustion measurement

This chapter deals with the OH-PLIF measurement principle and important parameters for high-pressure rocket combustion, a comparison of the OH excitation methods and their spectroscopic characteristics, and a consideration of the influence of OH chemiluminescence to develop an optimum OH-PLIF measurement method for rocket combustion. The laser-induced fluorescence (LIF) principle was described using a two-level model for the excitation/emission process, and then the spectroscopic parameters of interest under the high-pressure rocket combustion condition were considered. The absorbing line function, which depends on the pressure and temperature, was modeled and its variations with pressure and temperature were simulated. Furthermore, the temperature dependences for each OH absorption line were simulated from the Boltzmann fraction variation with temperature. Using these common parameters at each excited vibrational level, i.e., each band excitation method, the variations in the spectroscopic properties with the excited vibrational level were evaluated, including the fluorescence yield, absorption intensity, and fluorescence spectrum. This evaluation showed that the fluorescence yield of the OH(2,0)-band excitation method was lower than that of the OH(1,0)-band excitation method, which is typically used in studies of the application of OH-PLIF to rocket combustion. However, the OH(2,0)-band excitation method could effectively eliminate the interference of the OH(0,0)-band chemiluminescence. The elimination of chemiluminescence interference is feasible in the development of an optimal method for rocket combustion measurements, because intense chemiluminescence interference is a peculiar obstacle in rocket combustion measurements.

In summary, to achieve a high signal-to-noise ratio under the rocket combustion conditions by eliminating the chemiluminescence interference, the OH(2,0) excitation method was selected as the OH-PLIF measurement method under rocket combustion conditions.

3. A feasibility study of OH(2,0)-band excitation PLIF method to H_2/O_2 jet flames for rocket combustion up to 2.0 MPa

To realize an OH-PLIF method that eliminates the chemiluminescence of the OH(0,0) band, OH-PLIF measurements using the OH(2,0)-band excitation method were conducted to observe the OH fluorescence distributions and investigate the details of the fluorescence intensity of high-pressure H_2/O_2 jet diffusion flames by modeling the typical bi-propellant rocket combustion. In addition, numerical simulations of axisymmetric H_2/O_2 jet diffusion flames that modeled the experimental conditions were conducted to evaluate the consistency of the OH-PLIF imaging results and predict the flame temperature by simulating the OH* mole concentration.

The results showed that single-shot OH(2,0)-band excitation PLIF measurements were able to detect the OH(2,1)-band fluorescence by effectively eliminating the intensive interference of the OH(0,0) band chemiluminescence up to a pressure condition of 2.0 MPa. Furthermore, the local radial distributions of OH-PLIF corresponded well to those of the simulated OH molar concentration for each pressure condition, although the local signal-to-noise (S/N) ratio of the PLIF image, *SNR*, declined as the pressure rose because of the quenching and line broadening. However, it was predicted that measurements may be feasible under higher pressure conditions up to 7.0 MPa, which is greater than the pressures considered in previous OH-PLIF studies for rocket combustion. Meanwhile, the OH chemiluminescence intensity increased with the pressure, which indicated the need to eliminate the interference caused by intense chemiluminescence.

4. Measurements of 2-D instantaneous OH profiles of H_2/O_2 jet flames in high-pressure rocket combustion condition up to 7.0 MPa

To evaluate the flame characteristics and its instabilities under high-pressure rocket combustion conditions, the PLIF method was applied to measure the instantaneous OH profiles of H_2/O_2 jet diffusion flames under rocket combustion conditions up to 7.0 MPa. Furthermore, the full width at half maximum (FWHM) of the radial OH distributions δ_{OH} acquired under each H_2/O_2 injection condition was evaluated to examine the variation in the reaction zone thickness with the propellant injection conditions.

The results showed that the OH-PLIF measurements could detect the 2-D single-shot OH fluorescence distributions of the flames and eliminate the interference of OH chemiluminescence up to 7.0 MPa. In addition, the single-shot OH-PLIF images and standard deviation distributions showed that the OH distributions were almost steady and uniform in the region close to the injector face and fluctuated in the downstream region. The typical characteristics of the turbulent jet diffusion flames were observed under all chamber pressure P_C and injection Reynolds number Re conditions. The growth rate of δ_{OH} in the axial direction was almost the same to that under the P_C = 1.0–7.0 MPa conditions, because the velocity ratio and density ratio of the injected H_2/O_2 were almost constant in all P_C conditions. Moreover, the variations in the experimentally derived local δ_{OH} at Z = 1 mm with the Damköhler number qualitatively corresponded to the FWHM of the simulated mole fraction $\delta_{OH\text{-}SIM}$ under each P_C condition. The δ_{OH} in the region close to the injector face had a characteristic of the flame stretch and depended on the Damköhler number and pressure.

5. Development of a new calibration burner for optical measurements of high-pressure and high-temperature flames

A new optical measurement calibration burner was developed that can be used for the calibration and quantification of high flame temperatures such as those of oxygen-enriched flames under pressures ranging from atmospheric to the highest pressure condition of 1.0 MPa. Oxygen-enriched methane/oxygen/nitrogen ($CH_4/O_2/N_2$) flames were formed, and the basic performance of the burner (e.g., flame stabilities and heat resistance of the nozzle) was verified. The fluorescence distribution of the OH radicals was acquired using OH-PLIF measurements to examine the uniformity of the OH distribution in the region of downstream of the nozzle. Furthermore, a numerical simulation of the one-dimensional flame and an experiment using the Boltzmann plot method were conducted to examine the flame temperature.

The results showed that a major objective of this burner development, i.e., realizing a quasi-one-dimensional uniform flame temperature associated with oxygen-enriched combustion, was achieved under a high-pressure condition of up to 1.0 MPa. The developed type-N2 nozzle was capable of forming a $CH_4/O_2/N_2$ flame under the highest heat load condition of an oxygen enriched ratio β= 0.60 and a chamber pressure P_C = 1.0 MPa. The OH-PLIF measurement results and standard deviation under each pressure condition indicated that there were disturbances in the outer surface of the burned gas under high-pressure conditions, but the effect of these disturbances was small in the region within 6 mm of the burner's axial center. The temperature measurements using the Boltzmann-plot method showed that the acquired flame temperature was almost equal to or lower than the simulated flame temperature. However, under the β= 0.60 conditions, the maximum flame temperature reached almost 3000 K at P_C = 0.50 and 1.0 MPa, and the axial distributions of the flame temperature were almost constant under each flame condition. Furthermore, the equivalence ratio dependence of the OH(0,0)-band chemiluminescence relatively matched the equivalence ratio dependence of the OH* partial pressure obtained by the one-dimensional simulation. Thus, the experimental flame temperature and variation in the corresponding simulated OH* partial pressure with the equivalence ratio were considered reasonable.