Principle and Design of a Measuring System of Mixture Ratio and Combustion Species Concentration

ZHANG Meng-zheng[1], WANG Liang[1], YANG Guo-hua[2]
(1 *Northwestern Polytechnical University*, *Xi'an* 710082, *China*)
(2 *Xi'an Engining and Mechanics Design Institute*, *Xi'an* 710100, *China*)

Abstract: A new measuring system is developed. This system consists of YAG laser, dye laser, groups of crystals, CCD camera, synchronizer, light sheet unit, image analysis system and accessories. It is able to obtain the statistical average of parameter measured in specific area and specific period similar to systems of Coherent Anti-Stokes Raman Scattering, Laser-Induced Fluorescence, Degenerate Four Wave Mixing, Planar Laser-Induced Fluorescence and Spontaneous Raman scattering. The combustion species concentration, especially mixture ratio can be measured by the new system. The system has been successfully used to measure the mixture ratio of gas/gas, gas/liquid or liquid/liquid type injectors and concentration of combustion species including OH, CO, CO_2, NO, NO_2 and H_2O vapor. The system will be the powerful tool of liquid propellant rocket engine work process research.

Key words: Measuring system; Laser-induced fluorescence; Injector; Mixture ratio; Combustion species
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0 Background

The atomization, mixing and combustion characteristics of injectors are of great importance to combustion chamber design of the liquid rocket engine (LRE). Optical technology has been a powerful tool of LRE injector atomization characteristics research[1]. Coherent Anti-Stokes Raman Scattering (CARS), Rayleigh Scattering (RS), Mie Scattering, Laser-Induced Fluorescence (LIF), Degenerate Four Wave Mixing (DFWX), Planar Laser-Induced Fluorescence (PLIF) and Spontaneous Raman Scattering (SRS) have been successfully used for researching the combustion characteristics and refractive index[2-5]. The UV spectrum technology and LIF have been used in other research fields[6-7]. But don't have a available technology of measuring the spray mixture ratio distribution of oxidant to fuel for LRE injector so far, require a technology to provide quantitative information of planar temperature and concentration distribution of combustion species, such as OH, CO, CO_2, NO, NO_2 and H_2O(g) (vapor). A novel mixture ratio distribution and combustion species concentration measuring system is proposed in this paper.

1 System principle and composition

The system consists of 10 Hz Nd : YAG laser, dye laser, varied groups of crystals, light sheet unit, CCD camera, synchronizer, image analysis system and other accessories (Fig. 1). The YAG laser is equipped with a temperature stabilized 2nd harmonic generator. The dye laser is a single-modular tunable dye laser that enables to operate across a very large range of wavelengths (Direct tuning range: 420～750 nm). The light sheet unit was designed for all UV-type and visible applications that has a 0° - divergence , approx 40 mm height with adjustable focal point and sheet thickness. Two sets of optical filters were designed. One set is for OH, CO, NO and NO_2. The second set is for N_2, CO_2 and H_2O(g). System analysis and control software were used to control hardware configuration, timing sequences and parameter analysis. Acetone was used as tracer of gas-phase mixing, because it is with good signal level, low toxicity, a high vapor pressure, and accessible absorption (225 ～ 320 nm) and fluorescence (350～550 nm) features. Rhodamine was used as tracer of liquid-phase mixing, because

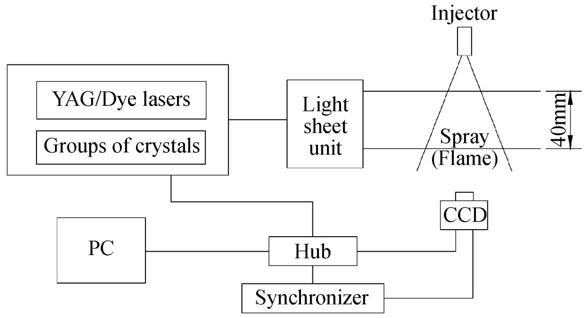

Fig. 1 Schematic of the measuring system

Tel: 029-85602167 Email: zhmzh1101@163.com
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it can absorb the laser light energy and re-emits light at a longer wavelength that can be detected by a photo detector. The tracer and combustion species of interest separately were excited at a given wavelength (shown in Table 1). The fluorescence with a well-defined emission peak is captured on to intensified CCD camera. The basic principle of laser-induced fluorescence was described in ref [8] and will not be repeated here.

Table. 1 Species excitation wavelengths

Excited Species /Compounds	Excitation wavelength	Laser energy available(approx)
NO_2	532 nm	400 mJ
OH	283-287 nm	25 mJ
N_2	283 nm	25 mJ
CO_2	283 nm	25 mJ
CO	230 nm	~13 mJ
NO	225 nm	4.5 mJ
H_2O(g)	248 nm	5 mJ
Acetone	283 nm	25 mJ
Rhodamine dye	532 nm	400 mJ

The excitation wavelength of a certain combustion species was achieved by selecting a suitable group of crystals in dry laser. Upgrade of the dye laser was done by means of non-linear optical processes in KDP or BBO crystals. It covers a spectral range from 200 nm to 420 nm. This extension of wavelengths is based on a modular frequency doubling and mixing system. The four techniques were used: 1) Frequency tripling of the dye laser frequency output (Output wavelength ranges from 200 nm to 217nm); 2) Frequency mixing of the frequency doubled of the dye laser output with the residual infrared from Nd:YAG laser (Output wavelength from 217 nm to 272 nm); 3) Frequency doubling of the dye laser fundamental output (Output wavelength from 267 nm to 365 nm); 4) Frequency mixing of the dye laser fundamental output with the residual infrared from the Nd:YAG laser (Output wavelength from 360 nm to 420 nm). The group of crystals and rhodamine concentration of laser were changed according to the species measured. The rhodamine firsthand was excited by the dye laser. The tracer acetone was excited by the 284 nm. Each species was excited by a specific wavelength and one emission peak was measured at a time. Images were processed according to the methodology featuring the system software to gain mixture ratio distribution (tracer comparative concentration) and combustion species concentration (number density) maps. Temperature was calculated from the OH data. The concentration parameter was based on the pixel-to-pixel mapping at known experimental conditions. All precision requirements of laser, camera and image were based on the concentration resolution. Accuracy of intensity variations in laser shot-to-shot was based on the set-up stability.

2 System functions and characteristics

The functions of this mixture ratio and combustion species measuring system are as follows: 1) Injector mixture ratio distribution measurement, including gas/gas, gas/liquid or liquid/liquid type injectors; 2) Combustion species measurement, including OH, CO, CO_2, NO, NO_2 and H_2O (g); 3) Combustion temperature measurement (T_{max}=2 500 K).

The system characteristics are as follows: 1) Record speed: 15frame/second; 2) Record area: Light sheet with 40 mm height; 3) Parameter type: Statistical average of measuring parameter in specific period and specific area.

The comparison of functions among different optical measuring systems is shown in Table . 2

Table. 2 Comparison among different optical systems

Optical system	Measuring parameters			easuring area	Measuring speed
	Combustion species	Temperature	Mixture ratio		
SRS	Yes	Yes	No	Sing-point	Instantaneous (10 ns)
RS	Yes	Yes	No	Sing-point	Instantaneous (10 ns)
LIF	Yes	Yes	No	Sing-point	Instantaneous (10 ns)
PLIF (commonly)	Yes	Yes	No	Plane	Instantaneous (10 ns)
CARS	Yes	Yes	No	Sing-point	Instantaneous (10 ns)
DFWM	Yes	Yes	No	Several mm long by 100 um	Instantaneous (10 ns)
This system	Yes	Yes	Gas/gas, gas/liquid, liquid/liquid; Mixture ratio distribution	Plane (Light sheet with 40mm height)	Succession(15 fps)

which shows the present system has integrated ability of LRE work process research.

3 Application examples

3.1 Mixture ratio measuring

Fig. 2 shows measuring result of the liquid/liquid impinging injector mixing process. The total mass flow rate of two jets is equal to 40 g/s. The rhodamine was mixing with one jet flow and concentration was defined as 100%(initial value). Fig. 2 (a) is mixture image. Mixture ratio distribution along given measurement line (shown in Fig. 2(a)) is shown in Fig. 2(b). The ordinate of Fig. 2(b) is rhodamine concentration ratio relative to initial value (%), the abscissa is distance along measuring line that is about 20 mm from the injector face location, and the coordinate origin is situated on left point of the line. The measurement line in Fig. 2(a) can be located anywhere of spray area depending on researcher, so we can get mixture ratio at any location of spraying jet. Fig. 2 (b) shows that mixture ratio distribution of oxidant to fuel of this injector at experimental condition is asymmetric along injector axis.

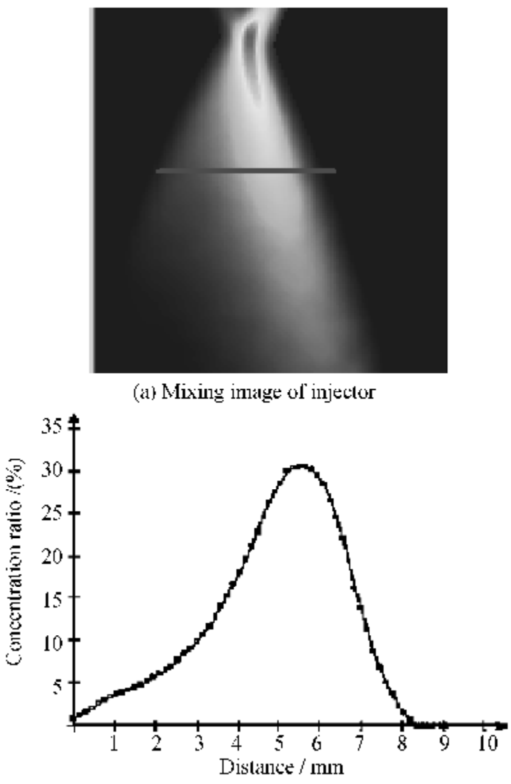


Fig. 2 Impinging injector mixing measurement

Fig. 3 shows the gas/gas coaxial injector mixing characteristics measuring. The inner injector is direct channel with exit diameter 12 mm, and outer injector is swirl one that has 8 circumambient orifices with 1.2 mm diameter. Mass flow rates of inner injector and outer injector equal 5.0 g/s and 4.0 g/s respectively. In Fig. 3(b), the measuring line is about 18mm from the injector face. The ordinate is acetone concentration ratio relative to initial value (%), the abscissa is distance, similar to that in Fig. 2(b). The Fig. 3(a) shows that mixing characteristics of injector on measuring position at experimental condition is asymmetric, the acetone concentration ratio along both sides of injector in Fig. 3(b) is asymmetric too.

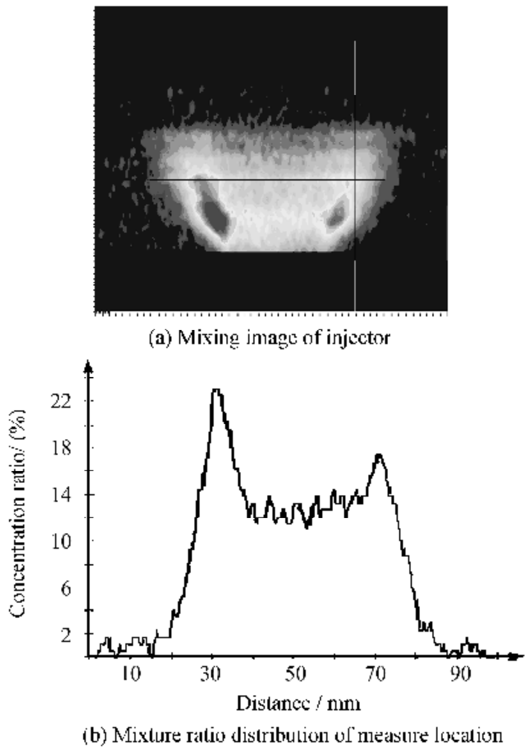
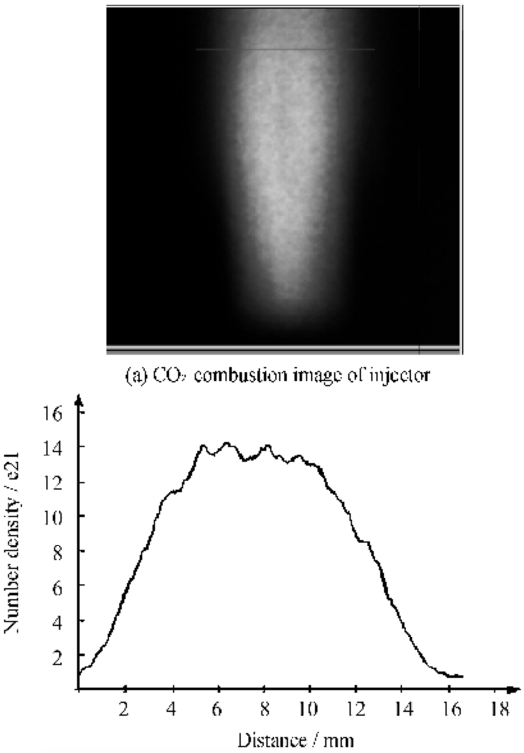


Fig. 3 Coaxial injector mixing measurement

From mixing measuring at different experimental conditions, the effect of injector configuration and work parameters on mixture ratio distribution can be understand and improving method can be presented.

3.2 Mixture ratio measuring

Fig. 4 shows combustion measurement of methane with air from the shear coaxial injector. The air mass flow rate of inner injector equals 0.5 g/s, methane mass flow rate of outer injector equals to 0.1 g/s at experimental condition. CO_2 combustion image is shown in Fig. 4(a), CO_2 concentration distribution (molecule number density) along measuring line located at 25 mm from injector is shown in Fig. 4 (b). The ordinate of Fig. 4(b) is CO_2 number density. The abscissa is similar to Fig. 2(b). The Fig. 4(b) shows the CO_2 concentration on injector center is bigger than that of both sides, exquisite combustion happens on center of flame.

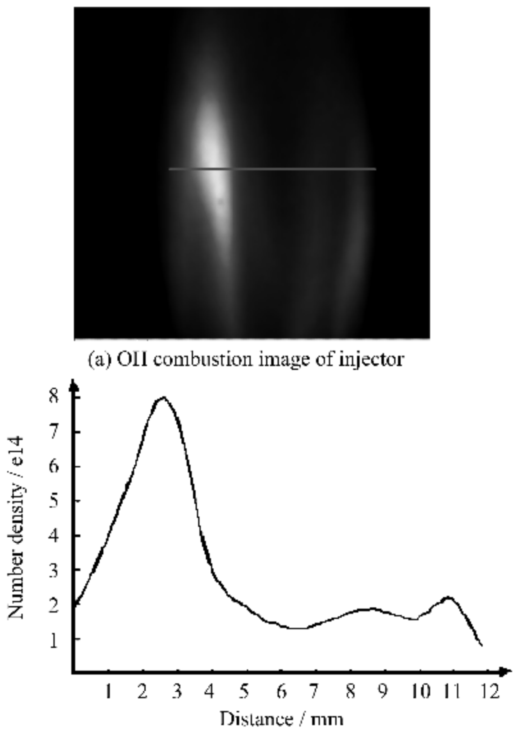


(a) CO_2 combustion image of injector

(b) CO_2 concentration distribution of measure location

Fig. 4 Combustion measuring of CO_2

Fig. 5 shows the OH concentration destruction from combustion of methane with air. Air mass flow rate of inner injector is equal to 0. 25 g/s. Fig. 5(a) shows the combustion image, Fig. 5(b) shows the OH concentration distribution (number density) along measuring line that is at 20 mm from injector exit. The OH calculation result shows maximal combustion temperature on measure line is about 2 300 K. We have found the mixing and combustion are dissymmetric in injector exit from Fig. 5.



(a) OH combustion image of injector

(b) OH concentration distribution of measure location

Fig. 5 Combustion measuring of OH

Analyzing the effects of injector configuration and work parameters on combustion species distribution and temperature, it is possible to make a optimum design of the injector.

4 Conclusion

A new measuring system of mixture ratio and combustion species is developed. The system can provide quantitative information of planar mixture ratio distribution , temperature and combustion specie such as CO_2 , CO , NO , NO_2 , OH and $H_2O(g)$. The system has the advantages of the temporal and dimensional statistics, and will also be a powerful analysis tool for mixture ratio distribution and combustion diagnosis research of LRE and other engines.

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混合比和燃烧组分浓度测量系统的原理和设计

张蒙正[1],汪亮[1],杨国华[2]
(1 西北工业大学,西安 710082)
(2 西安动力机械设计研究所,西安 710100)
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摘　要:研制了一套新型测量系统,系统由YGA激光器、染料激光器、晶体组、CCD摄像机、图像处理系统和附件等组成. 与反斯托克斯拉曼散射、激光诱导荧光、平面激光诱导荧光和拉曼散射系统相仿,该系统具有测量燃烧组分浓度的功能. 此外,它还可以测量喷嘴氧化剂和燃料的混合比分布,测量参数是给定时间内给定区域的统计值. 系统已经成功用于液体火箭发动机气/气喷嘴、气/液喷嘴和液/液喷嘴喷雾场混合比分布特性研究,并已用于CO、CO_2、NO、NO_2、OH和H_2O(g)等燃烧产物组分的浓度测量,这种新系统将成为液体火箭发动机工作过程研究的有力分析工具.
关键词:测量系统;激光诱导荧光;喷嘴;混合比;燃烧产物

ZHANG Meng-zheng was born in 1964, and graduated from Northwestern Polytechnical University in 1986 for his Bachelor's degree. Then he obtained his Master's degree from the National Defection Science and Technical University in 1989. Now he works in the Research and Develpment Center of Xi'an Engining and Mechanics Design Institute, and majors in spary and combustion research of liquid rocket engine.