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Research on Radiation Spectroscopy Thermometry of Plume of Solid Rocket Motor

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Abstract The plume of solid rocket motor has the characteristics of high temperature，high speed and intense radiation. The temperature of the plume is an essential parameter of condition and performance. The accurate temperature measurement of the plume of a solid rocket motor is important to provide a valuable reference for understanding the internal combustion condition and the overall performance of the motor. With the development of laser and spectroscopy，the laser spectroscopy technology is gradually applied to the measurement of combustion of solid propellant and plume temperature. Radiation spectroscopy thermometry can realize the non-intrusive and on-line measurement of temperature by measuring the radiation spectrum of flame. It has the advantages of wide temperature measuring range，fast response and high reliability. It can be applied to measure the temperature of the plume of the solid rocket motor. In this paper，the thermometry based on radiation spectroscopy was proposed to measure the temperature of the plume of the solid rocket motor. The measurement system of the radiation spectrum of the plume of the solid rocket motor was built using a 350～1 000 nm fiber spectrometer. Moreover，the spectral response coefficient was calibrated with a standard radiation blackbody furnace. The curve of response coefficient with wavelength was obtained to revise the measured radiation spectrums of the plume. Then the measurement system was applied to ground tests of standard ϕ118 solid rocket motors，the radiation spectrums of the plume of the solid rocket motor，which with a typical 12％ aluminum mass content propellant，were measured. The characteristics of radiation spectrums at different working times were analyzed. Furthermore，the graybody assumption was discussed based on the two-color gray judgment principle. The radiation of plume in a 675～745 nm spectral range can be considered as graybody. The maximum relative deviation of emissivity with wavelength was 4.01％，and the corresponding mean-variance was 1.53％. Therefore，the parameters of temperature and emissivity at the different working times were obtained by spectral fitting based on Planck radiation law. The maximum deviation between the temperature measurement and the theoretical thermodynamic calculation is 5.40％. Besides，the relationship between the measurement results and conditions were discussed，the radiation spectrums of the plume of the solid rocket motors with 12％，15％，and 19％ aluminum mass content propellants were measured，and the characteristics of radiation spectrums with different aluminum mass content were discussed. In addition，the influences of aluminum mass content on radiation spectrums，temperature，and emissivity of the plume were analyzed with the measurement results. This research on radiation spectroscopy thermometry of the plume of

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the solid rocket motor can provide the tool for performance evaluation and formulation optimization of the solid rocket motor. The influences of aluminum mass content of propellant on radiation spectrums, temperature, and emissivity of the plume can provide the experimental data support for reducing the characteristic signal of the plume of the solid rocket motor.

Keywords Radiation spectrum; Combustion diagnostics; Thermometry; Solid rocket motor; Plume temperature

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Introduction

The plume temperature of a solid rocket motor is one of the critical parameters to characterize the condition and the combustion state of solid propellant. Accurately measuring the plume temperature of the solid rocket motor is vital to the reference value for understanding the internal combustion condition and the overall performance of the motor[1]. However, solid propellant combustion is a complicated physical and chemical process with high-temperature high pressure, heterogeneous, and multiple field coupling[2]. Besides, the exhaust plume has the characteristics of high temperature, high speed and intense radiation, and its temperature is far beyond the temperature measurement range of contact means such as a thermocouple. In this way, a huge obstacle can be given to solid propellant combustion and exhaust plume temperature measurement.

With the development of laser and spectroscopy, the laser spectroscopy technology is gradually applied to the measurement of the combustion of solid propellant and exhaust plume temperature. For example, the coherent anti-stokes Raman scattering technique (CARS), the temperature of solid propellant can be determined by measuring the anti-stokes light generated by incident excitation laser and stokes laser that through the region[3]. This kind of active laser spectroscopy has effectively raised the upper limit of temperature measurement, making it possible to measure the combustion temperature of solid propellant and the temperature of the exhaust plume. However, there are still some problems for the multi-phase combustion of solid propellant. For example, the effects of high-temperature radiation and scattering attenuation caused by a large number of particles from solid propellant combustion and the influence of high temperature and high pressure on the spectral lines will affect the accuracy of temperature measurement results.

For measuring of multi-phase combustion, a strong self-radiation plume of the solid rocket motor, there exists a temperature measurement named radiation thermometry. This method can be realized based on the analysis of the flame radiation varying with temperature and composition and characteristics. It is a passive measurement method showing the advantages of wide temperature range, fast response, high reliability and so on. Notably, it has the characteristics of a high signal-to-noise ratio for the spontaneous emission from propellant combustion[4], which is more suitable for temperature measurement of the solid propellant combustion and exhaust plume of the solid rocket motor. In order to improve the measurement accuracy of a single wavelength and dual-wavelength radiation method, the multi-wavelength method and spectroscopy method has been developed for the radiation thermometry method. FU et al. developed a multi-wavelength radiation temperature measurement method based on the least square method, which effectively eliminated the influence of ambient radiation and improved the accuracy of temperature measurement[5]. Liang et al. and Wang Chang-hui et al. developed a multi-objective multi-spectral pyrometer and realized the measurement of true plume temperature of solid rocket motor[6-7]. With the development of optical fiber spectrometer, the detection array receiving after grating splitting makes it easier to obtain the high-resolution spectrum of flame radiation, and the resolution can be up to 0.1 nm. Thus, radiation spectroscopy thermometry has been developed rapidly due to its higher measurement accuracy and richer information of radiation spectrum[8-10].

In this paper, firstly, the radiation spectroscopy thermometry was used for solid rocket motor plume temperature measurement based on the above research. Secondly, the exhaust plume flame radiation spectrum measurement system was built to carry out the standard ϕ118 solid rocket motor ground test plume radiation spectrum measurement. Thirdly, the solid rocket motor plume radiation spectrum characteristics were analyzed, and the plume flame gray body characteristics were discussed. Finally, the online measurement of solid rocket motor plume temperature was realized, and the related experimental research was carried out.

1 Principle of measurement

The basic principle of radiation spectroscopy thermometry measurement method is Planck's radiation law, which describes the variation of radiation intensity with wavelength[11]. As shown in Fig. 1, the high-temperature flame radiation is collected by the lens, and the flame radiation spectrum is measured by optical fiber spectrometer. As the plume flame radiation is mainly manifested as solid radiation, the basic theory of radiation heat transfer can be known that the emissivity of solid particles in the range of visible waveband does not change much with the wavelength. Thus, the plume flame can be assumed to gray body. According to Planck's radiation law, the emissive power of an actual object is E_{λ_i}:

$$E_{\lambda_i} = \varepsilon C_1 \lambda_i^{-5}\left(\exp\left(\frac{-C_2}{\lambda_i T}\right) - 1\right) \tag{1}$$

where ε is the average blackness of high-temperature particles in the detection band, T is the average temperature of the field of view in the detection area, $C_1 = 3.742\times10^{-16}$ W · m^2 is the first radiation constant, $C_2 = 1.438\,8\times10^{-2}$ m · K is the second radiation constant. When $\lambda T \leqslant 2\,000$ μm · K, Planck's law can be simplified into Wien's relation

$$E_{\lambda_i} = \varepsilon\lambda_i^{-5}\exp\left(\frac{-C_2}{\lambda_i T}\right) \tag{2}$$

Therefore, according to the least square method, the optimal function matching of data is found by minimizing the sum of squares of errors, and the objective function $f(\varepsilon', t)$ is established

$$f(\varepsilon', t) = \sum_{i=1}^{n}(\ln E_{\lambda_i} - y_i)^2 = \sum_{i=1}^{n}\left(\ln k + \varepsilon' - 5\ln\lambda_i - \frac{C_2}{\lambda_i}t - y_i\right)^2 \tag{3}$$

where $\varepsilon' = \ln\varepsilon$, $t = 1/T$, y_i is the logarithm of the radiation intensity corresponding to wavelength measured in the experiment. When $f(\varepsilon', t)$ reaches the minimum value, the value of ε' and t is the parameter to be obtained by using the curve fitting of the least square method. Therefore, ε and T the average blackness of the field of view and the average temperature of the field of view can be obtained.

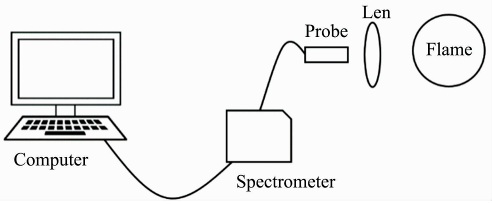

Fig. 1 Schematic of radiation spectroscopy thermometry

2 Experimental calibration of spectrometer response coefficient

Optical fiber spectrometer (ISUZU OPTICS, SE1040, 350～1 000 nm, 0.4 nm)is used to measure the plume radiation spectrum of solid rocket motors. Since the spectrometer uses silicon as the photosensitive detection element, the response of the radiant light to the flame of different wavelengths is different to some extent. Therefore, it is necessary to calibrate the response coefficient of the spectrometer by using the standard radiation blackbody furnace to obtain the curve of the response coefficient changing with the wavelength. This curve can be used as the plume radiation spectral data correction, so as to obtain a more accurate plume radiation spectrum.

Assuming that the response intensity value of each pixel of the photosensitive element in the optical fiber spectrometer is linear to the radiant light flux of any single wavelength, it can be found that the actual response intensity value of the photosensitive element to the radiant light

$$I_\lambda = k_\lambda A_\lambda \tag{4}$$

Where I_λ is the actual response strength walue of the photosensitive element, A_λ is the radiant flux of a single wavelength detected by a photosensitive element, k_λ is wavelength response coefficient.

The standard blackbody radiation furnace can be approximated as blackbody radiation. Through the Planck radiation law, temperature blackbody radiation with the change of wavelength can be determined through theoretical calculation. Based on this standard, the change of the spectral response coefficient with the wavelength can be obtained by comparing the experimental spectrum with the theoretical spectrum of blackbody radiation. The response coefficient characteristics of the spectrometer were obtained by using the blackbody furnace. (FuYuan Optoelectronics, HFY-203b, 0.99, 1 423 K). The response coefficient characteristics of the spectrometer are shown in Fig. 2. It can be seen that the response value of the spectrometer is not linear with the wavelength, which is mainly influenced by the characteristics of the factory standard light source. The selection of response coefficient and parameter fitting wavelength range is mainly based on the spectral signal-to-noise ratio, spectral linear response and spectral characteristics. In the wavelength range of 675～745 nm, the wavelength response coefficient is relatively stable, and the linearity is good. Therefore , this spectral range is

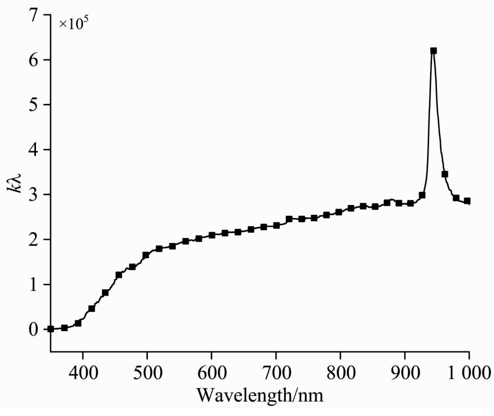

Fig. 2 Spectrometer wavelength response curve

selected as the parameter fitting range of the radiation spectral temperature measurement method. Through the modification of the above standard radiation calibration, a more accurate high-temperature flame radiation spectrum can be obtained and the temperature measurement accuracy of radiation spectroscopy can be effectively improved.

3 Experimental measurement system and experimental conditions

Fig. 3 shows the schematic diagram of the experimental system for measuring the temperature of the solid rocket plume radiation spectrum. The system consists of the standard ϕ118 solid rocket motor, focusing lens, optical fiber probe, and optical fiber spectrometer. The radiation spectrum of the exhaust plume is gathered to the optical fiber probe by a concentrator lens, and the optical fiber probe receives the flame radiation light and transmits it to the optical fiber spectrometer through the optical fiber. After the analog-to-digital conversion, the data is input into the computer for data analysis and processing. In the experiment, the integral time of the spectrometer was set 1 ms, and the flame radiation spectrum of the propellant combustion process was recorded continuously (time interval 100 ms).

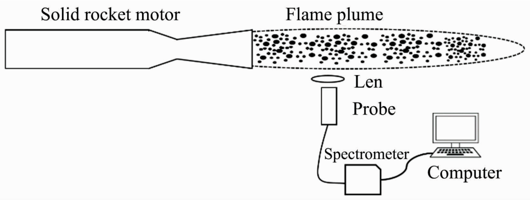

Fig. 3 Experiment system

The standard ϕ118 solid rocket motor used in the experiment isused primarily to study and evaluate the propellant formula and the burning rate of the propellant. Composite solid propellants are used in the experiment and the main formulations are ammonium perchlorate and aluminum. In order to study the influence of aluminum content of solid propellant on radiation spectrum, plume temperature and emissivity, the propellant with an aluminum mass fraction of 12%, 15% and 19% are selected for experimental study.

4 Experimental results and analysis

4.1 Typical exhaust plume flame radiation spectrum

In the experiment, a measuring system of exhaust plume flame radiation spectrum is built to measure the exhaust plume radiation spectrum of propellants with different aluminum content. The radiation spectrum of exhaust plume with 12% aluminum content at different time ranges of 350～1 000 nm is obtained. As shown in Fig. 4, it can be seen that the exhaust plume radiation spectra at the different time have the characteristics of a continuous spectrum of solid radiation and dispersion of metal atomic characteristic spectrum. In solid rocket motors, the propellant combustion produces a high-temperature gas containing a large number of aluminum oxide condensate particles from the nozzle to produce thrust. These high-temperature condensate particles exhibit the continuous radiation spectral characteristics of solids in the band range. Besides, the propellant contains metal elements such as aluminum and sodium, which are ionized by heat to form gaseous free atoms and ions, and these free atoms and ions emit strong atomic characteristic lines. These discrete atomic characteristic lines are superimposed with the solid continuous radiation spectrum to form the plume flame radiation spectrum.

As shown in Fig. 4, according to the atomic spectra database of the National Institute of Standards and Technology (NIST)[12], USA, the atomic characteristic lines, which near 589.9 nm is sodium atomic lines. The atomic characteristic lines of potassium are found near 766.8 and 770.1 nm. The atomic line of calcium salt radical is near 620 nm. There are atomic aluminum lines near 380 nm. The appearance of these atomic lines and their intensity changes are related to the combustion temperature. Among them, calcium salt radical represents the combustion product of the energetic material in the propellant, while sodium and potassium are the main sources of propellant catalyst.

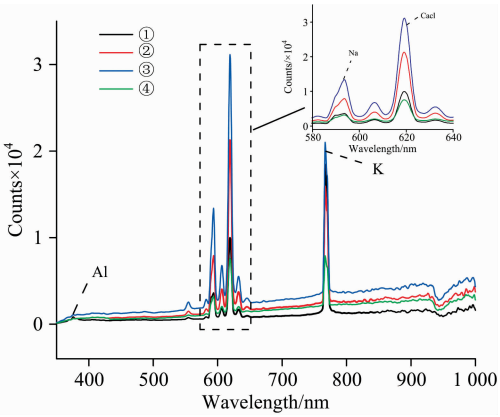

Fig. 4 Typical plume radiation spectrums

It can be seen from Fig. 4 that after the ignition of the solid rocket motor, for the time from ① to ③, the solid propellant continues to burn, the plume temperature continues to rise, and the continuous radiation spectrum and the atomic characteristic spectrum are continuously enhanced. However, at time ④, the propellant gradually burns out, the combustion temperature and particle concentration decrease, and the plume continuous radiation spectrum and atomic characteristic spectrum are weakened. The spectral characteristics of plume radiation can reflect the internal combustion of the motor. The intensity of continuous radiation spectrum and atomic characteristic spectrum is closely related to combustion.

4.2 Plume flame ash hypothesis discussion

According to the above-mentioned principle of radiation spectral temperature measurement, the flame ash hypothesis is the basis of accurate temperature measurement. Therefore, this paper comprehensively considers factors including spectral signal-to-noise ratio, linear spectral response and spectral characteristics et al. Then the band range of 675～745 nm is selected as the range of radiation spectral parameters to fit the temperature data, and the change of exhaust plume flame emissivity with wavelength is mainly discussed.

Based on the gray judging principle of the two-color method[13], the gray analysis is carried out on the radiation spectrum of 675～745 nm band obtained from the experiment. Among them, the dual-wavelength interval selects 6 wavelength intervals, about 3 nm. The emissivity of the plume flame is considered to be constant in the shorter wavelength range. The dual-color gray-color analysis is performed on the data of the band range of 675～745 nm at time ② in Fig. 4, and the variation of emissivity with wavelength is obtained in Fig. 5. As shown in Table 1, it can be seen that in this band range, plume flame emissivity changes little with wavelength. The maximum relative deviation of emissivity varying with wavelength is 4.01%, and the corresponding mean-variance is 1.53%, all of which are less than 5%. Therefore, it can be considered that the plume of solid rocket motor with a large number of solid particles is a gray body in the band range of 675～745 nm, which lays a foundation for temperature measurement using the radiation spectral parameter fitting method.

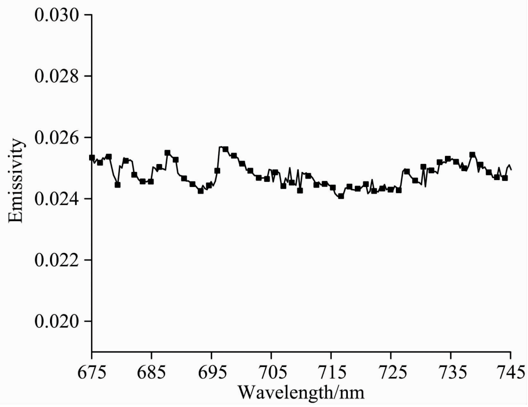

Fig. 5 Emissivity varies with wavelength

Table 1 Analysis of fluctuations of emissivity

Parameter	Means	Max relative deviation/%	Relative variance/%
Result	0.024 8	4.01	1.53

4.3 Plume temperature and emissivity measurements

On the basis of the above assumption of exhaust plume flame ash body and Planck radiation law, a range of 675～745 nm band was selected. This range of band can perform parameter fitting on the plume radiation spectrum of 12% aluminum-containing solid rocket motor to get results of plume temperature and emissivity during motor working time. As shown in Fig. 6, after the ignition of the motor, the overall trend of plume temperature and emissivity kept increasing. However, both of them had an inverse correlation to some extent in the adjacent in a short time. As the temperature decreased, the emissivity increases. In the band range of 675～745 nm, plume emissivity is related to such parameters as particle size, surface radiation characteristics, the concentration of condensate particles in the plume. Therefore, the inverse correlation between temperature and emissivity performance in the adjacent near the short time is related to the combustion of propellant aluminum particles. In a short time, the burning conditions are closed, when aluminum burning more fully, the combustion temperature is higher, product condensed phase particle size smaller that leads to reducing the emissivity.

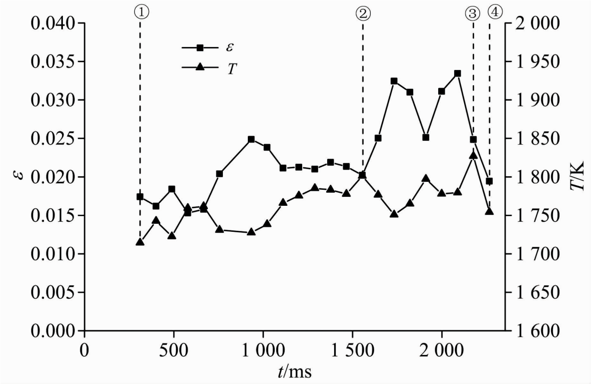

Fig. 6 Temperature and emissivity *vs*. time

Table 2 Measurement result of temperature and emissivity at typical times

No.	T/K	ε
1	1 732.15	0.015
2	1 805.15	0.020
3	1 829.59	0.025
4	1 754.81	0.019

In Fig. 6, ① to ④ are the typical moments of Fig. 4. Corresponding to Fig. 4, the measurement results of these four typical moments are shown in Table 2. Fig. 4 shows the typical moment of the radiation spectrum. After the motor ignition, the plume radiation intensity increases, the temperature and emissivity overall show a rising trend. When nearly burnt out, although the plume temperature is slightly decreased (around 50 k), the aluminum combustion form of condensed phase particle concentration has fallen that reduced the radiation rate quickly is about 20%.

4.4 Radiation spectrum and temperature analysis of motor under different working conditions

The plume flame radiation spectrum of solid rocket motor with an aluminum content of 12%, 15% and 19% are measured. The average time treated radiation spectrum of the motor during the working period is taken. As shown in Fig. 7, with the increase of aluminum content, the concentration of condensate particles in exhaust plume is higher, and the solid radiation is substantial. Therefore, the corresponding radiation spectral intensity increases significantly, and the amplitude of the radiation intensity increases with the increase of aluminum content. Taking 725.29 nm as an example, the spectral intensity of plume flame radiation of 19% aluminum-containing propellant is 9.6 times that of 15% aluminum-containing propellant. The spectral intensity of the plume flame radiation of the 15% aluminum-containing propellant is 2.0 times higher than that of the 12% aluminum-containing propellant.

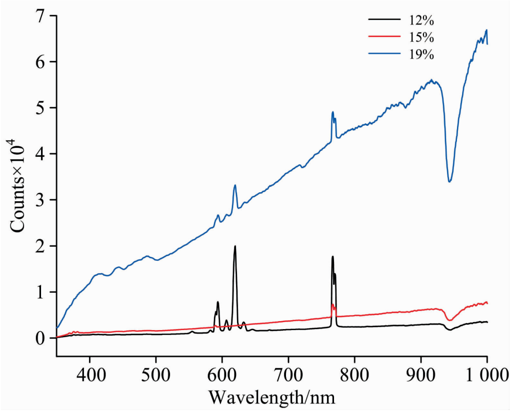

Fig. 7 Radiation spectrums of the plume of different propellants with aluminum mass contents of 12%, 15%, and 19%

The wavelength range of 675～745 nm is selected as the parameter fitting range. The radiation spectrum in Fig. 7 is carried out the parameter fitting based on Planck's radiation law to obtain the plume temperature and emissivity parameters. Meanwhile, the minimum free energy method of thermodynamic calculation method is carried out for the experimental solid rocket motor. Under the experiment condition, plume equilibrium flow temperature of propellant with different aluminum content is calculated, and the results are taken as reference. In Table 2, it can be seen that the maximum deviation between the measurement result and the thermal calculation result is 5.40%, which verifies the accuracy of the measurement of plume temperature of solid rocket motor by the radiation spectrum method.

In addition, the influence of propellant aluminum content on exhaust plume temperature and emissivity parameters can also be analyzed from Table 3. With the increase of the content of the propellant aluminum, the combustion temperature and emissivity both increased significantly. This is because, in the solid rocket propellant combustion, aluminum as the primary fuel component of the propellant combustion provides heat energy. The higher the aluminum content, the greater the power contained in the propellant, and the higher the temperature of the plume produced by combustion. The radiation in the band range of 675～745 nm is mainly reflected in the solid radiation of condensate particles generated by the combustion of aluminum particles, and its emissivity is related mostly to the concentration of condensate particles and the surface radiation characteristics. For the exhaust plume, most of the aluminum is completely burned, and the condensate particles are mainly aluminum oxide, and the surface radiation characteristics of the condensate particles are similar. Therefore, the plume radiation of the motor is determined primarily by the concentration of the condensate particles.

Table 3 Measurement results and comparison of different Aluminum content

Aluminum content/%	Temperature T/K	Emissivity ε	Thermodynamic calculation/K	Relative error/%
12	1 821.50	0.022	1 730.19	5.28
15	2 075.79	0.052	1 969.39	5.40
19	2 833.83	0.181	2 701.63	4.89

5 Conclusion

In this paper, the plume radiation spectral temperature measurement method of a solid rocket motor is mainly studied; the following findings are obtained:

(1) A method for measuring plume temperature of solid rocket motor based on flame radiation spectrum is proposed. Calibration of the response coefficient of the spectrometer is carried out with standard radiation blackbody furnace, and the curve of response coefficient with wavelength is obtained, which is used as plume radiation spectral data correction. The method is applied to the ground test of standard 118 solid rocket motor to carry out spectral measurement of plume radiation of solid rocket motor with different propellant formulations with 12%, 15% and 19% aluminum mass contents, and obtain plume temperature and emissivity parameters. The maximum deviation between the temperature measurement and the theoretical thermodynamic calculation is 5.40%.

(2) The graybody characteristics of solid rocket exhaust plume flame in the band range of 675～745 nm are discussed by using the gray property judgment principle of the two-color method. The changes in flame emissivity with wavelength are obtained. The maximum relative deviation of emissivity with wavelength is 4.01%, and the corresponding mean-variance is

1.53%, both of which are less than 5%. It can be considered that the plume of solid rocket motor with a large number of solid particles is a gray body in the band range of 675～745 nm, which lays a foundation for temperature measurement by using the radiation spectral parameter fitting method.

(3) The spectral analysis of solid rocket motor plume radiation in the band range of 350～1 000 nm has the characteristics of the continuous spectrum of solid radiation and dispersion of metal atomic characteristic spectral lines. By combining the measurement results of temperature and emissivity, the spectral characteristics of plume radiation of solid rocket motor with different aluminum content are discussed, and the effects of aluminum content of solid propellant on the radiation spectrum, plume temperature and emissivity are analyzed. It provides important experimental data support for reducing the characteristic plume signal of the solid motor.

References

[1] Zhao W, Zhu S, Li Y, et al. Journal of Thermophysics and Heat Transfer, 2004, 18(3): 404.

[2] Dennis C, Bojko B. Fuel, 2019, 254: 115646.

[3] Boyarshinov B F, Fedorov S Y. Journal of Applied Mechanics and Technical Physics, 2002, 43(6): 925.

[4] Yang R, Li Y, Zhang J, et al. Combustion and Flame, 2006, 145: 836.

[5] Fu T, Liu J, Duan M, et al. Review of Scientific Instruments, 2014, 85(4): 044901.

[6] Liang M, Sun B, Sun X, et al. Measurement, 2017, 95: 239.

[7] Wang Changhui, Liang Mei, Liang Lei, et al. Spectroscopy and Spectral Analysis, 2018, 38(9): 2860.

[8] Yan W, Zhou H, Lou C, et al. Energy & Fuels, 2013, 27(11): 6754.

[9] Yan W, Li K, Huang X, et al. Energy & Fuels, 2020, 34(1): 907.

[10] Yang Bin, Guo Haoran, Gui Xinyang, et al. Spectroscopy and Spectral Analysis, 2018, 38(6): 1958.

[11] Modest M F. Radiative Heat Transfer. Academic Press, 2003.

[12] National institute of Standards and Technology. NIST Atomic Spectra Database[EB/OL]. http://www.nist.gov/pml/data/asd.cfm.

[13] Sun Yipeng, Lou Chun, Zhou Haichun. Proceedings of the Combustion Institute, 2011, 33: 735.

固体火箭发动机羽流辐射光谱测温方法研究

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摘　要　固体火箭发动机羽流具有高温、高速与强辐射特征，羽流温度是发动机工作状态与性能的重要表征参数。准确测量固体火箭发动机羽流温度对了解发动机内部燃烧情况以及发动机综合性能具有重要的参考价值。随着激光与光谱学的发展，激光光谱技术逐步应用于固体推进剂燃烧及发动机羽流温度测量。辐射光谱测温法通过测量火焰辐射光谱来实现温度的非接触在线测量，具有测温范围宽、响应快及可靠性高等优点，可应用于固体火箭发动机羽流温度测量。在此提出了基于火焰辐射光谱的固体火箭发动机羽流温度测量方法，采用350～1 000 nm波段光纤光谱仪搭建了发动机羽流火焰辐射光谱测量系统，利用标准辐射黑体炉开展光谱仪响应系数标定，获得响应系数随波长的变化曲线，并以此用作羽流辐射光谱数据修正。之后将该测量系统应用于标准ϕ118固体火箭发动机地面试验，开展典型12%铝质量含量推进剂发动机羽流辐射光谱实验测量，选取不同时刻羽流辐射光谱分析了发动机羽流辐射光谱特征，并利用双色法灰性判断原理对羽流火焰灰体特性进行讨论，验证在675～745 nm波段发动机羽流火焰辐射可近似认为灰体，该波段辐射率随波长变化最大相对偏差为4.01%，相对均方差为1.53%。因此，基于普朗克辐射定律开展辐射光谱拟合参数获得不同时刻羽流温度与辐射率参数，并讨论测量结果与发动机工作状态的关系。最后，开展12%，15%与19%铝质量含量的不同推进剂配方固体火箭发动机羽流辐射光谱测量，将辐射光谱法温度测量值与理论热力计算值进行比较，两者最大偏差值为5.40%，讨论了不同铝含量推进剂发动机羽流辐射光谱特征，并结合温度与辐射率测量结果，分析了固体推进剂铝含量对辐射光谱、羽流温度及辐射率的影响。通过固体火箭发动机羽流辐射光谱测温方法研究，为固体火箭发动机性能评估及推进剂配方优化等研究提供了有效的羽流参数测量手段。分析获得的推进剂铝含量对发动机羽流辐射光谱、温度及辐射率参数的影响，为降低固体发动机羽流特征信号提供了重要的实验数据支撑。

关键词　辐射光谱；燃烧诊断；测温方法；固体火箭发动机；羽流温度

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