Development of infrared spectral radiation measurement system of a non-luminous flame

Zhao Jin (金 钊)[1], Maohua Yang (杨茂华)[2], Guibin Yuan (原桂彬)[1], and Jingmin Dai (戴景民)[1]

[1]*Department of Automation Measurement and Control, Harbin Institute of Technology, Harbin 150001*

[2]*Department of Electronic Science and Technology, Harbin Institute of Technology, Harbin 150001*

Received January 14, 2005

The spectral radiation characteristic of a non-luminous flame is analyzed. The apparatus and the calibration procedure based on infrared emission spectrometry for measurements of the flame are introduced. The influence of background radiation and stray light on the measurement results could be reduced and suppressed by the design of thermolator and digital lock-in technique. A blackbody cavity was used as reference emission source to calibrate the system that completed absolute measurement. The spectral measurement range is 1—20 μm. The least measuring distance and the lowest power detected at the entrance pupil are 550 mm and 10^{-9} W/cm^2, respectively. The experimental results show that the measure error is less than 10%.

OCIS codes: 280.2470, 120.4570, 300.6340, 000.3110.

Flame radiation is an important parameter in combustion diagnostics. From the investigation of flame radiation, quantitative flame parameters, such as local temperatures and species concentrations along the path of rays, can be derived. Thereby one can improve fuel performance, combustion engine efficiency, and the chemical reaction process[1,2].

According to the difference between the radiation spectra of the flame, all flame is divided into luminous flame and non-luminous flame, the former radiates continuous spectra, and the latter radiates only stronger at some characteristic bands, with non-continuous spectra. Usually continuous radiation is from glowing soot particles and non-continuous one from gases species in the flame. The plume of solid rocket motor, burning pulverized coal, and incomplete flame with gas as combustible are luminous. The plume of liquid rocket motor, jet of exhaust gases, and complete flame with gas as combustible are non-luminous. For non-luminous flame, the ultraviolet (UV) and visible radiation energy is smaller than 0.4% of the total radiation energy. Its visible radiation is basically from the inner cones in the flame. Moreover, its infrared (IR) radiation is from the combustion products[3]. Many species are created in the combustion products of hydrocarbon fuels, but H_2O and CO_2 have a particularly strong effect on the thermal radiation. In IR region, the 2.7- and 4.3-μm bands show the highest intensity. This is due to the asymmetric stretch vibration of water and carbon dioxide molecules, respectively. Thus the measurement of non-luminous flame radiation intensity can be performed near 2.7- and 4.3-μm bands[4]. The trend of a non-luminous flame spectral radiation at 1—20 μm was rarely studied.

We used the IR emission spectrometry to measure non-luminous flame radiation. The apparatus consists of an optical system, a photoelectric detection system, and a data acquisition system. The technical indicators are as follows: measurement distance is 550 mm, spectral range is 1—20 μm, resolution is 0.2 nm, minimum target is ϕ5 mm and scanning rate can be adjusted in the larger range. An arrangement of the measurement system is shown in Fig. 1.

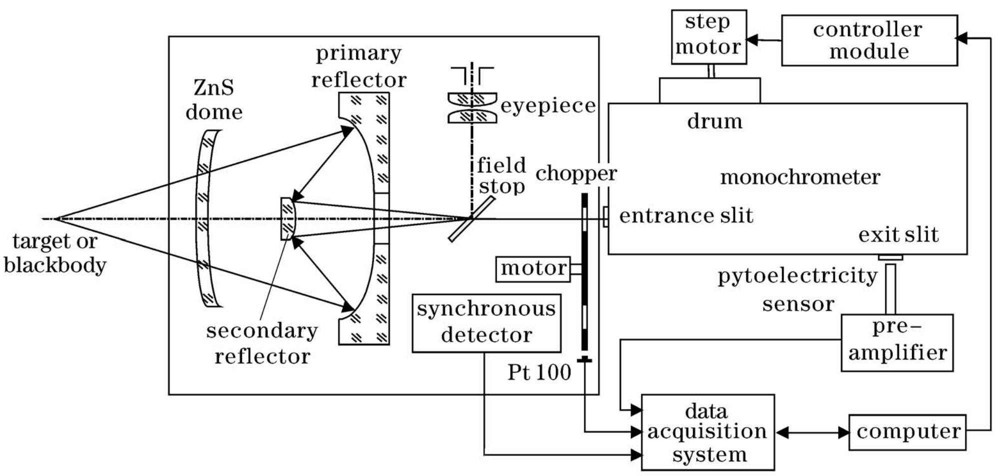

Fig. 1. Arrangement of the measurement system.

The optical part is composed of a WDG30 grating monochrometer, a system of automatic scanning wavelength and an optical collection system. The optical collection system is placed in a small dark room located in front of the entrance slit of the monochrometer. The monochrometer is a typical C-T horizontal symmetrical optical system. The structure of this system is simple and its resolution is high. Moreover, the stray light of instrument is small and signal-to-noise ratio (SNR) is high. The system of automatic scanning wavelength is composed of a 4-phase step motor with power of 20 W and a MONOpack LT-2500 mA step motor controller/driver module. The step motor and the drum of the monochrometer are synchronistically rotated.

The optical collection system is the combined Cassegrainian-type system. The radiation flux emitted from the flame is focused on the entrance slit of the monochrometer by the objective lens composed of a ZnS dome with antireflection coating, a primary reflector, and a secondary reflector. Chromatic aberration and monochromatic aberration can be eliminated very well if the thickness of the ZnS dome is properly chosen. As visible light can pass through ZnS, aiming and focusing in visible light and IR ranges simultaneously are realized by the aiming system. The focal distance of the objective lens is 80 mm and the object distance is 550 mm. The field stop gives a narrow field that can reduce and suppress the background radiation and the stray light radiation. To reduce the effects of stray radiation on the radiation measurement, the temperatures of several core optical components must be controlled. In our apparatus, the temperature of field stop is controlled at 10 °C by heat pipe with cold buffers. Therefore the sensitivity and stability of the instrument are improved[5]. Photoelectric detection system is composed of a chopper, a pyroeletricity sensor, and a low-noise pre-amplifier. To get the best performance from the infrared sensor, the chopper frequency is set to 80 Hz, because the $1/f$ noise is reduced to a minimum value in this frequency range. A pyroeletricity sensor is used as a photodetector which needs no refrigeration and has not selectivity for the wavelength. The range of spectral sensitivity of the detector is 1—20 μm. The diameter of the active element of the detector is 1 mm. The detector has the sensitivity $D^* \geq 10^{10}$ $\mathrm{W^{-1}{\cdot}cm{\cdot}Hz^{1/2}}$ at total spectral response. The pre-amplifier unit has automatic zero adjustment of the dark signal of the diode. In radiation measurement of a non-luminous flame, because the stray radiation inside the instrument will drift with environment temperature, output of the detector will accordingly change, and result in the measurement error. In order to reduce this error, a small precision thermolator has been developed whose design is nearly identical to that of Ref. [6]. Thereafter, the signal enters the AD976A, a 16-bit successive approximation A/D converter produced by the Analog Devices Company. The data acquisition system stores the results of measurement, and sends them to a personal computer via an ISA bus.

The signal received by the computer contains many noises. Digital lock-in technique is introduced to extract the effective signal from the noise[7]. The correlative modem of the digital lock-in technique consists of the digital-multiplication and digital-average, namely is achieved by the software. Compared with conventional analog lock-in technique, digital lock-in amplifier has the time constant with larger changing range, high linearity, and good flexibility. Other errors are not introduced except the rounding error in processing data.

To calibrate the apparatus, a heated tube blackbody cavity is used as reference emission source. Its temperature is controlled by the photoelectric cell feedback temperature control system. The range of the working temperature is 1500—2000 °C and the effective spectral emissivity is 0.995. Since the field stop with very small caliber is used in the optical collection system, the background radiation is not considered in the calibration. The temperature of the chopper is constant, therefore the incident radiation part absorbed by the chopper is also not considered. Firstly, when no signal is inputted, the output signal is measured to adjust zero for the instrument. Secondly, when the blackbody cavity opening is placed at the flame axisymmetrical plane, then the output signal of the radiometer is given by

$$V_{\mathrm{b}}(\lambda_i) = G(\lambda_i)\cdot\tau(\lambda_i)\cdot\sigma(\lambda_i)\cdot I_{\mathrm{b}}(\lambda_i, T_{\mathrm{ref}}), \tag{1}$$

where $G(\lambda_i)$ is the geometry factor involving the target area and the solid angle subtended by the entrance pupil of the instrument, $\tau(\lambda_i)$ is the transmittance of the optical system, $\sigma(\lambda_i)$ is the spectral responsivity of the detector, $I_{\mathrm{b}}(\lambda_i, T_{\mathrm{ref}})$ is the radiation intensity of the blackbody at wavelength λ and temperature T_{ref}. After calibration, the apparatus completes absolute measurements. The measurement signal of the target is

$$V(\lambda_i) = G(\lambda_i)\cdot\tau(\lambda_i)\cdot\sigma(\lambda_i)\cdot I(\lambda_i). \tag{2}$$

Rearranging Eqs. (1) and (2) can get

$$I(\lambda_i) = \frac{V(\lambda_i)}{V_{\mathrm{b}}(\lambda_i)} I_{\mathrm{b}}(\lambda_i, T_{\mathrm{ref}}). \tag{3}$$

Measurements of IR spectral radiation intensity were performed for an axisymmetric non-luminous flame, produced with acetylene as combustible. A brass tube burner with 10-mm diameter and 150-mm height was used. Measurement was performed at 20-mm above burner exit, so that flame is perfect combustion. The measurement range is 1—5 μm and spectral interval is 10 nm. The measured values are in good agreement with those obtained by a Fourier transform infrared (FTIR) spectrometry. The repetitious experiments show that

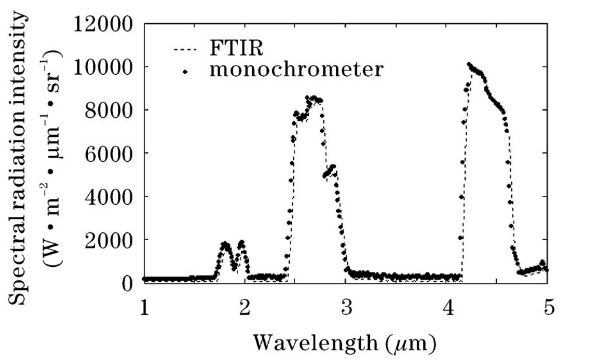

Fig. 2. Measurement of spectral radiation intensity of an acetylene flame.

the measurement error is less than 10%. A spectral radiation intensity of an acetylene flame is shown in Fig. 2.

An infrared measurement system has been developed to acquire high resolution radiation spectra in a non-luminous flame. The experimental instrument has the following advantages. 1) The measurement is non-intrusive. It will not disturb the flow field and it allows investigation of inaccessible objects (hazardous fires). 2) Using ZnS dome, focusing on the visible light and IR ranges simultaneously is realized by the aiming system. 3) The temperature of field stop controlled by a heat pipe and the design of the precision thermolator reduce the influence of background radiation and stray radiation on measurement results. 4) Digital lock-in technique can extract the effective signal from the noise and reduce the measurement error. 5) Using a blackbody cavity as the reference source to calibrate the system, the experimental instrument completes absolute measurements. However, this instrument still has some disadvantages: light barrier of the Cassegrainian-type optical system is larger; since measurement of flame radiation properties is performed by a single detector and a monochrometer, the measurement can provide information only one wavelength at one time. These disadvantages will be reformed in future investigation.

Z. Jin's e-mail address is hitjinzhao@hit.edu.cn.

References

1. E. Vitkin, O. Zhdanovich, V. Tamanovich, V. Senchenko, V. Dozhdikov, M. Ignatier, and I. Smuror, J. Heat and Mass Transfer **45,** 1983(2002).
2. J. Spelman, T. E. Parker, and C. D. Carter, J. Quantitative Spectrosc. Radiative Transfer **76,** 309 (2003).
3. A. G. Gaydon, *Spectroscopy and Combustion Theory* (Chapman, London, 1949).
4. J.-M. Char and J.-H. Yeh, J. Quantitative Spectrosc. Radiative Transfer **56,** 133 (1996).
5. D. Cong, J. Dai, X. Sun, and Z. Chu, J. Infrared and Millimeter Waves **19,** 407 (2000).
6. J. Dai, X. Sun, X. Lu, and D. Cong, *Theory and Practice of Multi-Spectral Thermometry* (Higher Eeducation Press, Bengjing, 2002) pp.101—103.
7. C. Qi, C. Yang, W. Li, and J. Dai, Chin. Opt. Lett. **1,** 398 (2003).