Two-Dimensional Flame Temperature and Emissivity Distribution Measurement Based on Element Doping and Energy Spectrum Analysis

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ABSTRACT Most of the existing non-contact flame temperature measurement methods rely on the ideal thermal-optical excitation model, which has a great influence on temperature measurement accuracy. Therefore, based on element doping and energy spectrum analysis, this study proposes a novel two-dimensional (2-D) estimation method for flame temperature and emissivity distribution. The element doping method and laser-induced breakdown spectroscopy (LIBS) are introduced into the temperature field test. The external doped element whose spectral radiation characteristics are easy to be analyzed, is regarded as the measured particles to describe the flame temperature distribution from the side. And LIBS is used to analyze and select the doped element, and further determine the effective working wavelength of the optical camera. Besides, the relationship between spectral radiance and emissivity \((L - \varepsilon)\) of doped samples is obtained by the emissivity calibration experiment. Then, the 2-D temperature and emissivity distributions can be estimated. Infrared thermograph is used to verify the accuracy of temperature measurement, the measurement error between calculated and standard values is not more than 5%. The experimental results of the oxygen-ethanol combustion flame show that this method can be well applied to the similar temperature measurement.

INDEX TERMS Temperature measurement, spectral emissivity, element doping, spectral analysis.

I. INTRODUCTION

High temperature combustion reaction is common in military, metallurgy, thermal power generation, engine manufacturing, and other industrial production industries. In the state measurement of the combustion reaction, the temperature is one of the significant parameters, which can be used for feedbacking the combustion state to facilitate the diagnosis and optimization of the combustion process [1]–[3].

Traditional temperature testing methods are divided into contact [4], [5] and non-contact [6]–[8] methods. Compared to contact methods, non-contact methods have some advantages such as no disturbance to the temperature field, wider measurement range, and temperature measurement continuity.

As the main form of non-contact temperature measurement, optical temperature measurement methods include laser spectroscopy and radiation spectroscopy method. Laser spectroscopy methods, such as laser interferometric holography [9], [10], planar laser-induced fluorescence (PLIF) [11] and coherent anti-Stokes Raman scattering spectroscopy (CARS) [12]–[15], rely on complex, high-precision optical instruments which are expensive and difficult to meet the testing requirements in extreme industrial environments. On the contrary, the radiation spectral method with better environmental adaptability is widely used in industry. For example, the traditional radiation spectral imaging both in infrared [7], [16]–[19] and visible light band [20]–[22] have
been widely used to test the surface temperature projective information of high-temperature targets.

After achieving the projection of high-temperature targets by using the above radiation spectral methods, resolving the temperature field is one of the important demands in the temperature testing area at present.

In the calculation and reconstruction of the temperature field, a more accurate radiation transmission model is needed. Most of the existing temperature field reconstruction methods are based on the simplified radiation transfer model. Nowadays, common temperature field reconstruction methods such as the two-color temperature measurement method [23], hyperspectral imaging and multi-wavelength thermography method [24] and light field imaging technology which combined with optical tomography reconstruction algorithm [25]. However, these methods work by regarding the flame as a grey body or assuming a particular form of flame emissivity which ignore the radiation spectrum properties of the different elements inside the flame. And it may affect the accuracy of temperature measurement. On that basis, Yuan et al. [26] and Sun et al. [27] give a method for determining the properties of a medium by using spectral analysis, but it was not applicable to all types of flame.

In this study, we present a 2-D flame temperature and emissivity distribution test based on element doping and energy spectrum analysis. Firstly, we use element doping and spectral analysis methods based on laser-induced breakdown spectroscopy (LIBS) to explore the intrinsic excitation characteristics of flame. The effective working wavelength of the detection module is selected accordingly. Furthermore, an emissivity calibration method of doped elements in the flame is put forward. Through the calibration experiment of imaging system, the thermal-optical coupling transmission model of nodes in flame is obtained. Then, the high precision sCMOS science camera is used for optical detection of doped flame. The 2-D temperature and emissivity distribution of flame can be calculated by combining the image processing technology and calibration results. Finally, the accuracy of temperature measurement results and the effectiveness of this method are verified by infrared thermal imaging technology and thermocouple contact point temperature measurement technology.

II. MODELS AND METHODS

A. THERMAL-OPTICAL COUPLING TRANSMISSION MODEL

It is necessary to construct a suitable quantitative model of thermal-optical radiation energy spectrum transmission in the reconstruction process of the flame temperature field. The combustion reaction of flame is an extremely complex process accompanied by energy conversion. As shown in Fig. 1, the complete forward thermal-optical radiation energy transfer model of a single temperature node includes:

- (a) Energy spectrum excitation of thermal-optical radiation;
- (b) Attenuation of thermal radiation in a spatial transmission medium;
- (c) Thermal radiation reception and imaging of optical device. The quantitative correlation model of thermal-optical coupling transfer between the temperature inside the flame and the gathered projection can be expressed by the optical transfer function shown in formula (1).

$$G_{\text{intensity}} = f_{\text{reception}}(f_{\text{attenuation}}(f_{\text{excitation}}(T_{\text{node}(x,y,z)})))$$

where $T_{\text{node}(x,y,z)}$ represents the node temperature value with the space coordinate $(x, y, z)$ inside the flame. The camera projection intensity value $G_{\text{intensity}}$ of the corresponding position can be calculated by the three sub-functions which are $f_{\text{excitation}}, f_{\text{attenuation}}$ and $f_{\text{reception}}$. The following is a detailed description of each sub-model in the process of thermal-optical radiation energy spectrum transmission.

1) ENERGY SPECTRAL EXCITATION MODEL

The medium in the flame is a gas-solid mixed dispersion medium of combustion particles and fuel products at high temperature. Anything above 0 K can emit thermal radiation accompanied by energy transfer between the ground state and the excited state. The fuel and combustion product particles originally in the ground state inside the flame are subjected to local high temperature, they jump from the ground state to the excited state and generate excited atoms or ions. The energy level transition from the high energy state to the low energy state will occur in a short time, and the spectral radiation with its own properties is excited to release energy to the outside space in the form of light. Therefore, various elements of high temperature dispersion medium will emit a series of detectable characteristic emission spectrum.

Since the influence of gas medium particle radiation inside the flame can be ignored within the wavelength range of 650 nm-1100 nm, only the spectral excitation characteristics of solid particles need to be considered [28]. Moreover, the main elements corresponding to the original solid particles in the flame have a weak spectral response in the visible detection band of the camera. In order to improve the detection accuracy, the flame can be doped with elements with a strong spectral response in the visible band.

Ni et al. [29] and Guo et al. [30] mixed a small amount of copper (Cu) powder into energy-containing materials, Yang and others [31] put a small amount of CuSO₄ powder into...
emits energy to the outside in the form of electromagnetic waves [35]. This thermal radiation excitation process can be described by the relevant theories of thermal radiation. According to Planck’s blackbody radiation law and Wien’s law, the relationship between the high temperature of a single node and the excited radiation satisfies equations (2) and (3):

\[
L(\lambda, T) = L_b(\lambda, T) \cdot \varepsilon(\lambda, T)
\]  

where \( c_1 \) and \( c_2 \) are radiation constants; \( L_b(\lambda, T) \) and \( L(\lambda, T) \) are the spectral radiance of ideal blackbody and non-ideal blackbody; \( T \) is temperature value at wavelength \( \lambda \); the spectral emissivity of non-ideal blackbody can be represented by \( \varepsilon(\lambda, T) \).

2) ATTENUATION MODEL OF THERMAL RADIATION TRANSMISSION

The thermal radiation generated by the excitation of the flame internal nodes needs to pass through two transmission environments before reaching the lens of the optical camera: (a) Dispersion medium environment inside the flame; (b) Atmospheric medium environment outside the flame.

Firstly, the temperature node at any position in the flame is regarded as a single point radiation source. Due to the small particle size of the doped particles and the original medium particles, and the high spectral emissivity of doped particles at the detection wavelength, the scattering capacity of the particles is far lower than the absorption capacity according to Mie scattering theory. Therefore, it is assumed that the scattering effect of the medium can be ignored [36], and the attenuation is entirely due to the absorption of the medium. In the short sampling time of the camera, the interior of the flame is considered as the thermodynamic equilibrium state. According to Kirchhoff’s law of thermodynamics, the emissivity and absorptivity of the medium are equal at thermal equilibrium \( (\varepsilon = \alpha) \), can be represented as [37]:

\[
\varepsilon = 1 - \exp \left[ - \int_{s_e}^{s_d} k_{\lambda \varepsilon} (s') ds' \right] \\
\alpha = 1 - \exp \left[ - \int_{s_0}^{s_d} k_{\lambda \alpha} (s') ds' \right]
\]  

where \( k_{\lambda \varepsilon} \) and \( k_{\lambda \alpha} \) are respectively the emission coefficient and absorption coefficient of the medium, \( k_{\lambda \varepsilon} = k_{\lambda \alpha} = k \) can be regarded as the total attenuation coefficient of the medium inside the flame; \( s_e \) and \( s_d \) are the length of the emission and absorption paths of thermal radiation in the direction of detection. The thermal-optical radiation attenuation process of a point source to the flame surface can be given by Beer-Lambert law:

\[
L_S = L_V \times \exp \left[ - \int_{0}^{s_d} k_{\lambda \varepsilon} (s') ds' \right]
\]  

Therefore, the spectral emissivity or emission coefficient is the key to build the model accurately. However, it is difficult to study the properties of intrinsic particles inside the flame and measure their spectral emissivity in the visible band. Therefore, it is feasible to use particles with known spectral...
characteristics and little influence on the temperature field as external dopants, and then solve their spectral emissivity to describe the internal radiation model and temperature of the flame.

By means of elements doping in section 1), the high temperature box furnace is used as the heat source to heat the doped samples. In the case of uniform doping, the spectral emissivity distribution of doped elements at the detection wavelength can be obtained from the ratio of radiance between the samples and the ideal blackbody at the same temperature as formula (6):

$$\varepsilon_{\text{node}} = \varepsilon_{\text{sample}} = \frac{L_{\text{sample}}(\lambda_0, T)}{L_b(\lambda_0, T)}$$

Among them, the spectral emissivity of the point source $\varepsilon_{\text{node}}$ is replaced by that of the sample $\varepsilon_{\text{sample}}$; $L_{\text{sample}}(\lambda_0, T)$ and $L_b(\lambda_0, T)$ are the spectral radiance of doped sample and standard blackbody respectively, the emissivity of doped sample is related to its spectral radiance.

Secondly, the attenuation of heat radiation in the atmosphere is mainly caused by a variety of absorbing gas molecules. Because of the close detection distance, the less environmental background radiation, and the low absorption efficiency of gas molecules at the detection wavelength, so we can ignore the attenuation of the thermal radiation in the external environment.

3) IMAGING AND RECEIVING MODEL OF THERMAL RADIATION

After the attenuation of the transmission medium, the thermal radiation from the flame node radiation source finally achieves the receiving and imaging of optical information in the camera.

The receiving property of the optical camera is the last step of constructing the model of thermal-optical radiation spectrum transmission. The 2-D projection image obtained from the camera pixel plane is actually the integral of the flame internal radiance in the detection band [38]. Based on the spectral analysis method in section 1), the corresponding narrow-band filter system was designed, the calibration was carried out only for the imaging model with a single wavelength.

Calibration of optical camera can be carried out according to the method of small light source in a short distance. As is shown in Fig. 3, taking the high temperature blackbody furnace as the standard thermal radiation source, the short-distance blackbody radiation source with the radiance of $L_b$ can be equivalent to the surface radiation source with the area of $A_c$ and the radiation brightness of $L_b$. Combining camera optical parameters and integral mean value theorem, the calibration model of monochrome camera grayscale value ($G$) as shown in (7) can be obtained finally.

$$G = A \cdot \int_{\lambda_1}^{\lambda_2} L(\lambda, T) R(\lambda) d \lambda + G_p = AL(\lambda, T) + B$$

where the calibration coefficient $A$ represents the optical parameters of the camera, which includes transmittance of filters and lens, relative aperture, exposure time, gain of camera; $R(\lambda)$ is the spectral response of camera; $G_p$ is the gray offset of the pixel. The calibration constants $A$ and $B$ can be obtained through the calibration experiment.

To sum up, after obtaining the relation between the spectral emissivity of the doped samples and their radiance ($\varepsilon - L$), and the imaging receiver model of the detection module ($G - L$), 2-D temperature distribution based on detection imaging can be determined according to Plank’s law:

$$T_{\text{cal}} = \frac{c_2}{\lambda \ln \left( 1 + \frac{c_1 \varepsilon}{\pi k^5 L} \right)}$$

where $L$ and $\varepsilon$ can be obtained under characteristic wavelength by detection module and spectral emissivity calibration experiment. To evaluate the accuracy of the temperature measurement results, thermocouples and infrared thermograph are used as standard temperature verification devices. The relative error $\delta_T$ between the calculated temperature value $T_{\text{cal}}$ and the standard value $T_{\text{act}}$ is:

$$\delta_T = \frac{|T_{\text{cal}} - T_{\text{act}}|}{T_{\text{act}}} \times 100\%$$

B. DETECTION IMAGE POST-PROCESSING

The optical camera is required to have high sensitivity due to the filter detection of specific doped element flame, and the higher sensitivity will affect the imaging quality. Therefore, the wavelet denoising method is used to process the collected image, and the image processing quality is evaluated by analyzing the peak signal-to-noise ratio (PSNR) and multi-scale-structural similarity index (MS-SSIM). The PSNR of denoised image can be calculated by MSE between image before processing $x$ and after processing $y$, which is given by

$$\text{MSE} = \frac{1}{mn} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} [x(i, j) - y(i, j)]^2$$

$$\text{PSNR} = 10 \cdot \log_{10} \left( \frac{\text{max}^2}{\text{MSE}} \right)$$

where $m \times n$ is the size of image; $\text{max}$ is the maximum pixel value of the image. The MS-SSIM can be calculated by [39]

$$\text{MS-SSIM}(x, y) = \left[ L_m(x, y) \right]^{\beta} \prod_{i=1}^{M} \left[ C_i(x, y) \right]^{\gamma_i}$$

FIGURE 3. Schematic diagram of calibration principle.
where $L(x, y)$ is the luminance contrast factor; $C(x, y)$ and $S(x, y)$ are contrast factor and structural contrast factor, respectively. $\alpha$, $\beta$, $\gamma$ are the weighting factor of the three components, which can be replaced by constants; $M$ is the scale factor of image.

The effective area is extracted by the gray threshold segmentation of the denoised image. At this point, the image can be used to calculate the temperature and emissivity distribution.

### III. RESULTS

#### A. SPECTRAL ANALYSIS EXPERIMENT

Experiments were conducted on ChemReveal LIBS Desktop Elemental Analyzer from TSI USA, which combines a Nd:YAG laser, a complex optical system, a spectrometer and a sample platform.

1) SELECTION OF DOPED SAMPLES

According to the selection principle, refer to the NIST spectra database [40], we can find the wavelength corresponding to the strong spectral peak of Cu (510.5 nm, 521.8 nm) and K (404.4 nm, 691.1 nm, 693.8 nm, 766.5 nm, 769.9 nm) in the visible range. The Cu filter (with central wavelength of 515 nm and bandwidth of 20 nm) and K filter (with central wavelength of 768 nm and bandwidth of 20 nm) was installed in front of the camera lens and the contrast experiment was carried out.

The Cu powder and CuSO$_4$ powder were doped into the flame respectively, and the optical camera (with Cu filter) was used for detection. The K$_2$SO$_4$ powder was doped into the flame and the optical camera (with K filter) was used for detection. In the case of fixed camera parameters, the comparison of the flame images before and after element doping is shown in Fig. 4. It can be seen that compared with Cu doping, the imaging grayscale of the flame part after K doping is much higher.

Therefore, we finally selected potassium (K) as the doping element which is easy to transit from low energy level to high. And the solid compound potassium sulfate (K$_2$SO$_4$) is selected as the doping element due to its high melting point and stable physicochemical properties. Physical properties and spectral features are shown in Table 1 and Table 2 respectively.

The sample of potassium sulfate(K$_2$SO$_4$) is ground in a grinding bowl in order to ensure the uniformity size of particles, and then put the powder sample in a PMG steel ring die with an inner diameter of 32mm. The spectral analysis sample was made by PP-30S automatic tablet press. The tablet preparation process and the molding sample are shown in Fig. 5.

2) DETERMINATION OF DETECTION WAVELENGTH

The molded K$_2$SO$_4$ sample was placed in the center of the sample platform. In order to ensure the stability of laser energy and availability of spectral data, 20mJ laser energy was used to hit the multi-point matrix on the sample surface, the ideal data was selected and fitted, the full excitation spectrum of each shot was obtained. As shown in Fig. 6, it can be found that the trend of the full spectrum obtained by the laser hitting the sample surface for multiple times is consistent, and the spectral intensity after multiple hits is different due to the unstable laser energy of the instrument. Regardless of the impurity elements, the strong spectral line of element K (404.4 nm, 691.1 nm, 693.8 nm, 766.5 nm, 769.9 nm) was extracted from it. Lorentz fitting was performed on the characteristic spectral lines to eliminate the effects of self-absorption and self-erosion. As shown in Fig. 7, the spectral intensity of element K and the quantum efficiency of the camera are both lower than others at 404.4nm. In addition, the spectral intensity of K varies dramatically in the band

| TABLE 1. Physical Properties of Potassium Sulfate (K$_2$SO$_4$) Samples. |
|------------------------|-----------------|
| **Properties**          | **Parameters**   |
| MW (molecular weight)   | 174.26           |
| Content (K$_2$SO$_4$)   | $\geq$ 99.0%     |
| Melting Point           | 1341 K           |
| Boiling Point           | 1963 K           |
| Appearance              | White crystalline powder |

| TABLE 2. Spectral Features of Potassium (K) from the NIST database. |
|------------------------|-----------------|------------------|-----------------|
| **Observed Wavelength**| **Emission Transition Probability ($10^8$ s$^{-1}$) | **Accuracy** | **Transition Level (eV)** |
| (nm)                   |                  |                  |                  |
| 766.489913             | 3.779e-01        | $\leq$ 0.3%      | 0.00000000 - 1.617112996 |
| 769.896456             | 3.734e-01        | $\leq$ 0.3%      | 0.00000000 - 1.609957830 |

FIGURE 5. (a) Sample preparation process; (b) Mold-release process; (c) The molding sample of K$_2$SO$_4$. 

VOLUME 8, 2020
691.1 nm - 693.8 nm, and the average spectral intensity is limited. By contrast, it can be seen that the relative spectral intensity of the main element K at 765.5 nm - 769.9 nm is extremely strong even saturated. Meanwhile, the camera has strong quantum efficiency at this band. So, this wavelength band was selected as the effective wavelength for optical detection. Therefore, we only need to use a K filter (with a central wavelength of 768 nm and bandwidth of 20 nm) and camera to detect the thermal-optical radiation information at the effective characteristic wavelength of potassium (K).

B. CALIBRATION EXPERIMENT OF DETECTION SYSTEM

The test of the high temperature field was carried out by DHYANA 400BSI sCMOS high sensitivity monochrome camera with the front filter module. Technical parameters of the camera are shown in Table. 3.

1) CALIBRATION OF DETECTION MODULE

The calibration of imaging system is needed for obtaining calibration constants and constructing the relationship between thermal radiance $L$ and grayscale intensity $G$ in (8). The experiment was completed by using SR20-32 medium temperature black furnace from CI. Fig. 8 shows the experimental setup. The furnace has an isothermal black cavity with 25.4 mm inner diameter and 100 mm length. The temperature range of cavity is 50°C-1000°C and the spectral emissivity is 0.99. The experiment was conducted in a dark room to ensure that there was no background light. In the process, the imaging system was placed at 0.5m from the black body furnace. The images of blackbody were captured multiply from 700°C to 1000°C with an interval of 25°C. Fig. 9 shows the monochrome images of the blackbody cavity at different temperatures.

After repeated experiments and image processing, the relationship between spectral radiance $L_b$ of blackbody and

| Categories | Parameter          | Quality       |
|------------|-------------------|---------------|
| Sensor     | Sensor size       | 1.2"          |
|            | Sensor model      | Backside-illuminated sCMOS |
|            | Effective no. of pixels | 2048(H)×2048(V) |
|            | Pixel size        | 6.5 μm×6.5 μm |
|            | Frame rate        | 74fps@4.2MP   |
|            | Exposure time     | 6.6 μs-10 s   |
| Filter     | Wavelength        | 768 nm        |
|            | Transmittance     | 90%           |
|            | Bandwidth         | 20 nm         |
imaging grayscale $G$ is shown in Fig. 10. According to function (7), the fitted relationship can be expressed as:

$$\begin{align*}
G_{\lambda}(T) & = \left(1.032 \times 10^{-2}\right)L_{b}(T) + 11.889
\end{align*}$$

(13)

It can be seen that the above formula is consistent with the theoretical calibration function (7), so the fitted relationship is effective.

Then, the relationship between blackbody temperature $T_{b}$ and grayscale $G$ can be acquired, as is shown in Fig. 11. The cubic polynomial function is suitable for fitting these data according to [41], which can be expressed as:

$$\begin{align*}
G_{\lambda}(T) & = \left(9.913 \times 10^{-6}\right)T_{b}^{3} - 0.03055T_{b}^{2} + 31.498T_{b} - 1.085 \times 10^{4}
\end{align*}$$

(14)

2) CALIBRATION OF SPECTRAL EMISSIVITY

Assume that the doped sample fills the flame region, the spectral emissivity of doped sample is used to represent the emissivity of each node inside the flame. The calibration of sample spectral emissivity was completed by using high temperature box furnace as high temperature heating source which temperature range is 50°C-1700°C. A thermocouple was used to calibrate the furnace temperature. A small amount of K$_2$SO$_4$ powder was placed and tiled on the bottom of the self-made graphite simulated blackbody cavity and heated in box furnace. DHYANA 400BSI sCMOS camera was used to collect the small area image of samples under different temperatures in order to avoid the effects of background light.

Since samples(K$_2$SO$_4$) can emit different spectral radiation when heated to different temperatures, combined with the spectral radiation characteristics of ideal blackbody at different temperatures and the calibration function of the imaging system, the spectral emissivity of samples can be easily measured. Schematic diagram of the experiment is shown in Fig. 12.

After repeated experiments, image collection, segmentation and extraction, the square feature area of the sample in the image was extracted. The gray values of extracted image groups at the same temperature were averaged. The radiance $L_{sample}$ of doped sample can be determined by camera calibration function (13) firstly. Combined with the emissivity calculation formula (6), the relationship between sample emissivity $\varepsilon$ and its radiance $L$ was approximately fitted by ExpAssoc function as shown in Fig. 13. The fitted
formula can be expressed as:

\[
\varepsilon(L) = -0.95226 + 0.63573 \times \left[ 1 - \exp\left( -\frac{L}{37037} \right) \right] \\
+ 1.0752 \times \left[ 1 - \exp\left( -\frac{L}{49537} \right) \right]
\]  

(15)

It can be seen from the fitted results that the spectral emissivity of the sample changed little after its radiance reached \(1.3210 \times 10^8\,\text{W/(sr}\times\text{m}^2)\). At this point, the spectral emissivity of doping sample is stable around 0.76. Before that, the emissivity varies significantly with the radiance.

### C. FLAME IMAGE ACQUISITION AND POST-PROCESSING

The oxygen-alcohol diffusion flame with a relatively stable form was used as the detection target, which had a height of 70mm and a diameter of 15mm. The sCMOS high sensitivity science camera was used to capture raw image data of the flame to be measured. In order to reduce the potential influence of solution doping on the flame temperature field, the powder feeding device is directly used to spray a small amount of doped solid powder (K\(_2\)SO\(_4\)) intermittently along the direction of the flame gas, which can ensure that the doped particles move and burn with the flame gas.

Several flame images were captured continuously at the moment of element sample doping, and the images with uniform grayscale distribution high intensity were selected to calculate temperature. The flame image before and after element doping is shown in Fig. 14. Due to the use of filters, the flame image before element doping is very dark. The results show that the element doping method can realize the obvious enhancement of flame brightness under this wavelength, among which the average enhancement multiple is 3.4, and the maximum enhancement multiple of grayscale can reach 11.875.

### D. 2-D EMISSIVITY AND TEMPERATURE DISTRIBUTION OF FLAME

The effective region of the flame at a certain moment after the element doping was extracted by the image threshold segmentation method. By observing the histogram of the gray image, the gray threshold of the image is dynamically searched to eliminate the invalid area of the flame [42]. According to the imaging system calibration function \((G - L)\) and emissivity calibration function \((L - \varepsilon)\), the 2-D spectral emissivity distribution of high temperature flame was acquired based on element energy spectrum detection, as shown in Fig. 16(a). Finally, the flame 2-D emissivity matrix and the radiation luminance matrix are put into the temperature back-projection function (9). Then, the 2-D temperature distribution of flame can be calculated. Fig. 16(b) shows the temperature distribution of the flame effective region. The calculated flame temperature varies from 1007 K to 1227 K. We observed that the local temperature result is too high in the middle of the flame, which may be caused by the nonuniformity distribution of doping elements.

### E. EXPERIMENTAL VERIFICATION AND ERROR ANALYSIS

The accuracy of flame temperature distribution was verified by thermocouples and infrared thermograph. Firstly, thermocouples (K-type Pt-Rh thermocouples, which have a diameter of 3 mm with a temperature upper limit of 1600 K), were used to calibrate the infrared emissivity which can be adjusted manually. Secondly, the DL-700 infrared thermograph (with 673.2 K-2273.2 K temperature range and 8-14 \(\mu\)m detecting
TABLE 4. Temperature and emissivity of the flame sampling points.

| Points | #01  | #02  | #03  | #04  | #05  | #06  | #07  | #08  | #09  | #10  |
|--------|------|------|------|------|------|------|------|------|------|------|
| $T_{\text{calculated}}$ (K) | 1045 | 1088 | 1127 | 1141 | 1160 | 1174 | 1149 | 1146 | 1142 | 1166 |
| $T_{\text{standard}}$ (K)  | 1000 | 1043 | 1074 | 1096 | 1106 | 1127 | 1115 | 1115 | 1119 | 1123 |
| $\delta_T$ (%) | 4.50 | 4.31 | 4.93 | 4.11 | 4.88 | 4.17 | 3.05 | 2.78 | 2.06 | 4.36 |
| $\epsilon_{\text{calculated}}$ | 0.542 | 0.724 | 0.756 | 0.758 | 0.759 | 0.759 | 0.758 | 0.758 | 0.758 | 0.759 |

FIGURE 16. 2-D measurement results of flame with element doping.

FIGURE 17. 2-D unfiltered and undoped flame: (a) division of original image; (b) division of filtered and doped flame; and (c) infrared thermal image.

Because of the integral effect inside the flame, thermocouple temperature of the outermost part of the flame is closest to the infrared thermal imaging temperature. As shown in Fig. 17(a), the unfiltered and undoped flame image was divided longitudinally, and thermocouples were arranged on the outer layer at 10 heights in the direction of flame diffusion. When the thermal imaging temperature of a certain point is equal to the thermocouple test temperature, the infrared emissivity of the flame can be approximated to the emissivity of thermograph. Combined with the conclusion in [43], after several tests at different heights, the average infrared emissivity was determined at 0.19. Fig. 17(c) shows the infrared thermal image at emissivity of 0.19. The standard temperature of infrared thermograph varies from 983.3 K to 1151.3 K, which is close to the calculated results in Fig. 17(b).

The average temperature of each sampling point in multiple imaging results were used as the final calculated value and the thermal imaging results were regarded as the final standard value. The standard temperature values of the points along the flame diffusion direction in Fig. 17(b) were taken out for comparison with the calculated results at the same position. The comparison results and relative error of temperature values are shown in Fig. 18(a) and (b) respectively.
It can be seen that there is a good agreement between the two types of temperature results at most sampling points, and the maximum relative error on the sampling line is no more than 5%. The comparison data are shown in Table 4. One of the reasons for the measurement error is the integral effect in the calculation of the 2-D temperature field. In addition, even if the flame is regarded as a stable temperature field, the element doping method and the inherent limitations of the powder feeding device will inevitably disturb the flame temperature field and fluid field, which can affect the flame form and element distribution. This is another reason for the inaccurate calculation of the flame local temperature.

IV. CONCLUSION

In this study, based on the element energy spectral excitation model and the element doping method, appropriate flame doping element is selected via LIBS technology, and a narrow wavelength band filter detection system is designed. Combined with the imaging system, spectral emissivity calibration experiment and image processing technology, the flame 2-D temperature and emissivity distribution are calculated. The final flame temperature description is achieved only by studying the radiation characteristics of the doped samples (K$_2$SO$_4$). The experimental results are verified by thermocouple and infrared thermography. According to the research results of this article, the following conclusions are drawn:

(a) LIBS analysis can be used for flame temperature field detection. Potassium (K) and its compound potassium sulfate (K$_2$SO$_4$) are selected as characteristic element and doping sample through spectral analysis. The wavelength band of 766.5 nm - 769.9 nm, which corresponds to the strong spectral peak of K, can be used to design a filter detection system.

(b) The relationship between the image grayscale and the temperature / radiance of the black body can be obtained by the calibration experiment of the imaging system. According to the spectral emissivity calibration experiment, the emissivity of the doped sample can be estimated from its corresponding radiance. When the radiance reaches a threshold value, the emissivity fluctuates around 0.76.

(c) The element doping method enhances the flame radiance at a specific wavelength (766.5 nm - 769.9 nm), and the maximum enhancement multiple is 11.875. It can be used for flame temperature field measurement under a single wavelength. It is appropriate to use Sym5 wavelet base for image denoising, and MS-SSIM can be used to evaluate the image quality.

(d) The thermocouple is placed at different heights of the flame, the point temperature of the outermost flame can be measured, and the emissivity of the infrared thermal imager is calibrated to be 0.19. In a series of sampling points in the direction of flame diffusion, and the calculated temperature range (1045 K - 1174 K) is close to the standard temperature range (1000 K - 1127 K) of thermal imaging. The maximum temperature relative error between the two is less than 5%.

It is obvious that the proposed method provides a new scheme for the high temperature flame temperature field test and a new idea for solving the complex temperature field emissivity problem.

By installing the element doping mechanism at the flame nozzle, the method of this study can be extended to similar stable flame testing. Combined with the flame flow field simulation experiment, it can also be used to measure the unstable temperature field in the future, such as the combustion of biomass fuel, the detonation of energy-containing materials. And this is very useful for subsequent reconstruction of the flame 3-D temperature field.

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[42] B. Xue and X. Hao, “Enhancement for high-luminance objects by a false-color-depth method,” in *Proc. SPIE*, vol. 10964, Nov. 2018, Art. no. 109644Q.

[43] W. W. Yuen and C. L. Tien, “A simple calculation scheme for the luminous-flame emissivity,” *Symp. (Int.) Combustion*, vol. 16, no. 1, pp. 1481–1487, Jan. 1977.

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