Multi-Focus Microlens Array Light Field Imaging for Three-Dimensional Flame Temperature Field Measurement Postprint

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Abstract

Multi-focus microlens arrays can improve the depth resolution of focused light field cameras. To investigate the influence of multi-focus microlens arrays on three-dimensional temperature field measurement of flames via light field imaging, this paper, based on a flame radiation light field imaging model, analyzes the flame radiation light field imaging characteristics of single-focus and multi-focus microlens arrays, calculates flame radiation images under two different microlens arrays, and reconstructs the three-dimensional temperature field of the flame from the flame light field images. Experimental research on three-dimensional temperature field reconstruction of flames using a multi-focus microlens array focused light field camera was conducted, and the numerical calculation and experimental results were analyzed.

Full Text

Three-dimensional Temperature Field Measurement of Flames Using Light Field Imaging with a Multiple-Focus Microlens Array

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Abstract: Multiple-focus microlens arrays can improve the depth resolution of focused light field cameras. To investigate the effect of multiple-focus microlens arrays on three-dimensional temperature field measurement of flames using light field imaging, this paper analyzes the light field imaging characteristics of flame radiation for both single-focus and multiple-focus microlens arrays based on a flame radiation light field imaging model. Flame radiation images are numerically calculated for these two different microlens arrays, and three-dimensional temperature fields are reconstructed from the flame light field images. Experimental studies on three-dimensional flame temperature field reconstruction are conducted using a focused light field camera with a multiple-focus microlens array, and both numerical and experimental results are analyzed in detail.

Keywords: focused light field camera; multiple-focus microlens array; radiative transfer equation; inverse problem; temperature

Combustion flames are widely present in industrial processes such as gas turbines, power station boilers, and aero-engines. Combustion is a complex, intense multiphase reaction process accompanied by continuous heat and mass transfer, generating various combustion products and releasing substantial heat. Since temperature is a crucial parameter characterizing combustion conditions, effective measurement of flame temperature fields is essential for improving combustion efficiency and stability while controlling combustion products, particularly pollutant gases.

Existing flame temperature field measurement techniques can be categorized into laser spectroscopy-based methods and flame image-based methods. Laser spectroscopy techniques can measure not only flame temperature fields but also intermediate species concentrations during combustion. For instance, Ma et al. used a hyperspectral detector to capture absorption spectra after laser transmission through flames and reconstructed flame temperature fields and absorptive species concentrations using tomographic inversion algorithms. However, laser thermometry suffers from complex systems, high costs, and demanding operational requirements, limiting its application primarily to laboratory flame diagnostics. Flame image-based thermometry methods, which do not require external laser sources, use conventional imaging detectors (cameras) to capture flame self-radiation images and reconstruct temperature fields through inversion algorithms. This approach reduces system complexity and facilitates installation and operation, offering advantages for industrial flame temperature measurement where laser techniques cannot be applied due to measurement condition constraints. Hossain et al. used conventional cameras to capture flame images and applied tomographic reconstruction techniques such as filtered backprojection (FBP) algorithms to obtain cross-sectional images of flame interiors, then calculated temperature distributions using two-color pyrometry, with applications in industrial flame monitoring. Li et al. similarly established a radiative transfer model correlating flame radiation with image intensity based on conventional camera imaging processes, then reconstructed flame temperature fields using inversion algorithms such as Tikhonov regularization, with successful applications to large industrial flames like power station boiler combustion. However, since conventional cameras cannot resolve flame radiation directionality, image-based thermometry requires multiple cameras to acquire multi-view radiation information for three-dimensional temperature field reconstruction of non-axisymmetric flames, demanding high camera coupling and synchronization precision.

Light field cameras serve as flame radiation sampling devices by installing a microlens array between the imaging detector and main lens. Compared with conventional cameras, light field cameras can record flame radiation intensity with higher accuracy and resolve radiation directionality in a single exposure. Combined with inversion algorithms such as the least squares method based on QR decomposition (LSQR), three-dimensional flame temperature field reconstruction can be achieved with a single light field camera, significantly reducing measurement system complexity. Building upon conventional light field cameras, Lumsdaine proposed the focused light field camera design where the imaging detector is positioned on the defocused plane of the microlens array. This configuration reduces directional sampling while increasing spatial sampling, effectively improving the resolution of refocused images. Perwass et al. further employed a triple-focus microlens array with three different focal lengths uniformly distributed, enabling spatial points at different depths to be refocused on the same image and enhancing depth resolution. However, no research has yet investigated flame temperature field reconstruction using triple-focus microlens array focused light field cameras.

To investigate whether adopting a triple-focus microlens array in focused light field cameras can improve measurement accuracy for three-dimensional flame temperature based on light field imaging, this paper studies flame three-dimensional temperature field measurement methods using light field imaging technology with focused light field cameras as flame radiation detectors. The distribution of sampled radiation rays is analyzed for both single-focus and triple-focus microlens array focused light field cameras, and the effects of these two microlens arrays on flame three-dimensional temperature field reconstruction results are investigated. Finally, experimental studies on three-dimensional temperature field reconstruction of ethylene diffusion flames are conducted using a triple-focus microlens array focused light field camera.

1. Flame Radiation Light Field Imaging Model

Light field cameras install a microlens array between the imaging detector and main lens. In conventional light field cameras, the detector plane is located at the focal plane of the microlens array, whereas in focused light field cameras, the detector plane is offset from the microlens array focal plane, reducing directional sampling dimension while increasing spatial sampling dimension, thereby overcoming the redundancy in directional sampling of conventional light field cameras. This paper employs a focused light field camera as the flame temperature field measurement device, as shown in Figure 1(a). The object-side conjugate plane of the camera detector plane relative to the imaging system is defined as the virtual object plane, where the detector plane and virtual image plane are conjugate with respect to the microlens array, and the virtual image plane and virtual object plane are conjugate with respect to the main lens.

Points on the virtual object plane are called virtual source points, while points on the virtual image plane are called virtual image points. When the microlens array contains three focal lengths, three corresponding virtual image planes and three virtual object planes exist, as illustrated in Figure 1(c).

The flame radiation received by each pixel on the detector can be considered as a beam of imaging rays originating from a virtual source point. As shown in Figure 1(a), for focused light field cameras where the distance between the microlens array and detector plane is less than the microlens focal length, the virtual image plane and detector plane lie on the same side of the microlens array. A flame radiation imaging beam from the same virtual source point is divided into multiple beams by the microlens before being converged to the virtual image point by the main lens. Each beam is then projected onto different pixels on the detector through the converging action of the corresponding microlens. The direction of each pixel' s beam can be determined from the pixel position and its corresponding microlens location, simultaneously recording both intensity and directionality of flame radiation. For each detector pixel, since the aperture angle of the received radiation imaging beam is small, the principal ray passing through the microlens center can represent this beam based on the pinhole imaging model. The intensity and direction of this principal ray represent the intensity and direction of flame radiation detected by the pixel. This principal ray is termed the sampling ray of the pixel. The spatial distribution of all sampling rays from detector pixels characterizes the flame radiation sampling pattern of the light field camera. Therefore, analyzing the sampling ray distributions of single-focus and triple-focus microlens array focused light field cameras enables comparative analysis of their flame radiation sampling characteristics.

For single-focus microlens array focused light field cameras, all microlenses have identical focal lengths, and the sampling ray distribution on the detector plane is shown in Figure 1(b). For triple-focus microlens array focused light field cameras, the microlens array contains three focal lengths uniformly arranged such that no two adjacent microlenses share the same focal length. Microlenses of the same focal length can focus object points at a specific depth in object space, while three focal lengths facilitate simultaneous focusing of object points at different depths onto the detector plane, improving depth resolution. The sampling ray distribution on the detector plane for triple-focus microlens array focused light field cameras is shown in Figure 1(c).

In Figures 1(b) and 1(c), microlenses with three different focal lengths are represented by red, green, and blue colors. Comparing these figures reveals that compared with the triple-focus microlens array, the single-focus microlens array exhibits more uniform virtual source point distribution and more uniform sampling ray distribution within the flame interior space, with higher independence among sampling rays. In contrast, the triple-focus microlens array shows non-uniform distribution of flame radiation sampling rays within the flame interior space with higher overlap. With comparable numbers of sampling rays, the single-focus microlens array demonstrates lower overlap of sampling rays within the flame interior space, acquiring more effective flame radiation information and thus being more advantageous for flame three-dimensional temperature field reconstruction.

Based on geometric optics thin lens formulas (1) and (2), ray tracing is performed for flame radiation sampling rays of each detector pixel to determine their positions and directions in object space (flame).

Soot particles in flames are absorptive with small diameters. According to Mie theory, soot particle scattering is far weaker than absorption. This paper considers only absorption to simplify flame radiation transfer processes. Using the apparent ray method, the intensity of flame radiation sampling rays for each detector pixel is calculated through equation (3) to obtain flame radiation images.

$$I_n = I_{b1}(1 - e^{-\tau_1}) + I_{b2}(e^{-\tau_1} - e^{-(\tau_1+\tau_2)}) + \cdots + I_{bn}e^{-(\tau_1+\tau_2+\cdots+\tau_{n-1})}$$

where I_n is the ray intensity detected by the detector, I_{bi} and τ_i are the blackbody radiation intensity and optical path of the ith control volume along the ray path, and I_{bn} and τ_n are the blackbody radiation intensity and optical path of the last control volume along the ray path.

2. Three-dimensional Temperature Field Reconstruction

To reconstruct the flame three-dimensional temperature field, a linear equation system is established based on equation (3) for the intensities of all sampling rays on the detector plane:

$$\mathbf{I}_{ccd} = \mathbf{A}\mathbf{I}_B$$

where $\mathbf{I}_{ccd}$ is the vector of flame radiation intensities detected by camera imaging pixels, $\mathbf{I}_B$ is the vector of blackbody radiation intensities of all flame control volumes, and $\mathbf{A}$ is the corresponding coefficient matrix.

The coefficient matrix $\mathbf{A}$ is a large sparse matrix. The least squares method based on QR decomposition (LSQR) can solve least squares problems for large sparse matrices. Similar to the conjugate gradient method, LSQR exhibits higher stability when $\mathbf{A}$ is ill-conditioned. Solving equation (4) involves solving the least squares problem shown in equation (5):

$$\min \|\mathbf{A}\mathbf{x} - \mathbf{b}\|$$

where $\mathbf{x}$ equals $\mathbf{I}_B$ and $\mathbf{b}$ equals $\mathbf{I}_{ccd}$. Assuming k bidiagonalization processes have been performed, the $m \times (k+1)$ orthogonal matrix $\mathbf{U}_{k+1}$, $n \times k$ orthogonal matrix $\mathbf{V}_k$, and $(k+1) \times k$ bidiagonal matrix $\mathbf{B}_k$ are obtained:

$$\mathbf{B}_k = \begin{pmatrix} \alpha_1 & & & \\ \beta_2 & \alpha_2 & & \\ & \ddots & \ddots & \\ & & \beta_k & \alpha_k \\ & & & \beta_{k+1} \end{pmatrix}$$

where $\alpha_1, \alpha_2, \cdots, \alpha_k \in \mathbb{R}$ and $\beta_1, \beta_2, \cdots, \beta_{k+1} \in \mathbb{R}$.

The bidiagonalization process yields:

$$\mathbf{A}\mathbf{V}_k = \mathbf{U}_{k+1}\mathbf{B}_k$$

$$\mathbf{x}_k = \mathbf{V}_k\mathbf{y}_k$$

From equations (8) and (9), we obtain:

$$\|\mathbf{A}\mathbf{x}_k - \mathbf{b}\| = \|\mathbf{U}_{k+1}\mathbf{B}_k\mathbf{y}_k - \mathbf{b}\| = \|\mathbf{B}_k\mathbf{y}_k - \mathbf{U}_{k+1}^T\mathbf{b}\| + \|\mathbf{U}_{k+1}^{\perp}\mathbf{b}\|$$

Since $\mathbf{U}_{k+1}$ is an orthogonal matrix and orthogonal transformations preserve matrix norms, the original problem becomes:

$$\min \|\mathbf{B}_k\mathbf{y}_k - \mathbf{U}_{k+1}^T\mathbf{b}\|$$

Thus, the complex least squares problem is transformed into a simpler one, which is solved using standard QR decomposition. After obtaining the blackbody radiation intensity I_{bi} of the ith flame control volume, the flame temperature of each control volume is calculated using the Stefan-Boltzmann law:

$$I_b = \pi\sigma T^4$$

where the Stefan-Boltzmann constant σ is $5.670373 \times 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$.

3. Numerical Simulation and Experimental Study

To compare the accuracy of three-dimensional flame temperature field reconstruction between single-focus and triple-focus microlens array focused light field cameras, numerical simulations were conducted. Calculation parameters were set according to the commercial focused light field camera Raytrix R29, as listed in Table 1. Here, d_m and d_p are the microlens diameter and pixel side length, respectively; N_m and N_s are the number of pixels covered by the diameter of each sub-image (a group of pixels covered by a microlens) and the number of microlenses in the vertical (or horizontal) direction of the microlens array, respectively; f_m and f are the focal lengths of microlenses and the main lens, respectively; L_{ix}, L_{ux}, and L_{xp} are the distances between the microlens array and virtual image plane, main lens plane, and camera detector plane, respectively; and L_{ou} is the distance between the main lens plane and virtual object plane.

For both microlens arrays, parameters d_m, d_p, N_m, N_s, f, L_{ux}, and L_{xp} are identical. The microlens focal length f_m for the single-focus microlens array is 600 m. For the triple-focus microlens array, the three microlens types (A, B, and C) have focal lengths f_m of 650 m, 600 m, and 550 m, respectively, all greater than the distance L_{xp} between the microlens array and detector plane (440 mm). The three focal length microlenses are arranged alternately in the horizontal (or vertical) direction such that no two adjacent microlenses share the same focal length. Parameters L_{ix} and L_{ou} are calculated based on the conjugate relationships described in Section 1.

The flame is configured as a cylinder with radius $L = 80$ mm and height $H = 300$ mm, with an absorption coefficient of 8 m^{-1}. The flame is divided into $10 \times 10 \times 1$ control volumes in the axial, radial, and circumferential directions. The flame temperature is set as symmetric about the cylinder central axis according to the distribution function $T(r, z)$:

$$T(r, z) = 1800 \sin\left(\frac{\pi z}{H}\right)\left[1 - 0.8\left(\frac{r}{L}\right)^2\right] + 300$$

where r and z are the radial and axial coordinates (in mm) of the control volume center relative to the flame bottom center. For the single-focus microlens array, the flame central plane is located on the virtual object plane. For the triple-focus microlens array, the flame central plane is located on the virtual object plane corresponding to microlens (B). Since the flame radius is 80 mm, the distances L_{ou} between the three virtual object planes (for A, B, and C) and the main lens plane are 505 mm, 482 mm, and 444 mm, respectively, ensuring all three virtual object planes lie within the flame interior and the flame remains in focus for all three microlens focal lengths.

3.1 Numerical Simulation

Flame radiation images were calculated using equation (3), as shown in Figure 2. Figure 2(a) shows the flame image from the single-focus microlens array focused light field camera, while Figure 2(b) shows the image from the triple-focus microlens array focused light field camera. Macroscopically, the two images are essentially consistent, with bright regions corresponding to high temperatures and dark regions corresponding to low temperatures, following the temperature distribution characteristics of equation (13).

Comparing sub-images reveals that the single-focus microlens array produces uniform sub-image sizes, whereas the triple-focus microlens array generates sub-images of varying diameters despite identical microlens diameters d_m. Larger microlens focal lengths ($C \to B \to A$) correspond to smaller sub-image diameters, as shown in Figure 2(b). This occurs because with constant detector-to-microlens array distance L_{xp}, larger microlens focal length f_m increases defocusing of the pupil image on the detector, resulting in blurrier imaging contours and smaller sub-image diameters.

Gaussian noise was superimposed on flame images to simulate measurement errors with signal-to-noise ratios of 30 dB and 20 dB. Three-dimensional flame temperature fields were reconstructed using the method described in Section 2, and the relative temperature reconstruction errors for all control volumes ($10 \times 10 \times 1$) were calculated and averaged. The results are shown in Figure 3. As noise increases, relative temperature reconstruction errors increase for both microlens arrays. However, at either noise level (30 dB or 20 dB), the single-focus microlens array yields smaller relative temperature reconstruction errors than the triple-focus microlens array. This is because the single-focus microlens array focused light field camera exhibits more uniform distribution of flame radiation sampling rays within the flame interior space with higher ray independence, acquiring more effective flame radiation information and thus achieving higher temperature measurement accuracy.

3.2 Experimental Study

An experimental study was conducted on ethylene diffusion flame temperature measurement using a triple-focus microlens array focused light field camera (Raytrix R29). The captured flame light field image is shown in Figure 4(a). The fuel flow rate was 3 mL/s, with flame radius and height of 10 mm and 90 mm, respectively. Using this image, the three-dimensional temperature field of the ethylene diffusion flame was reconstructed. Six cross-sections were uniformly selected along the flame height direction from $Z = 5$ mm to $Z = 90$ mm, as shown in Figure 4(a). The reconstructed temperature distributions for each cross-section are presented in Figure 4(b). The flame temperature ranges from 700 K to 1400 K. In diffusion flames, fuel (ethylene) diffuses outward while air diffuses inward. When the fuel-air mixture reaches the stoichiometric ratio, complete combustion occurs, releasing substantial heat and forming high-temperature regions with temperatures exceeding other flame regions. Consequently, temperature distributions across flame cross-sections show a radial trend of initially increasing then decreasing from inner to outer layers. For the topmost flame cross-section (90 mm), fuel and air can mix sufficiently at the center, resulting in a radial temperature decrease from inner to outer layers. The temperature distributions shown in Figure 4(b) are consistent with these characteristics.

Thermocouple (Type R) measurements were performed at different radial positions ($R = 0$ mm, $R = 5$ mm, $R = 10$ mm) on two flame cross-sections ($Z = 30$ mm, $Z = 60$ mm). Since thermocouples experience radiative heat loss to the cooler surrounding environment during flame temperature measurement, the results were corrected according to literature [19]. The corrected thermocouple temperatures were compared with the reconstructed temperatures from the triple-focus focused light field camera, as shown in Figure 5. The temperature distribution trends are consistent at both heights, showing initial increase then decrease with increasing radius. The maximum temperature difference of 182 K occurs at height $Z = 60$ mm and radius $R = 5$ mm, while other locations show differences less than 85 K, with a minimum difference of 8 K. Relative to the flame temperature reaching 1400 K, these results demonstrate reasonable reconstruction accuracy.

To further improve the accuracy of three-dimensional flame temperature field reconstruction, based on numerical simulation results, a single-focus microlens array focused light field camera can be designed and assembled for flame three-dimensional temperature field reconstruction to enhance temperature reconstruction precision.

Conclusion

This paper analyzed the light field imaging characteristics of single-focus and triple-focus microlens arrays and compared the distribution properties of flame radiation sampling rays for both arrays. Apparent ray methods were used to calculate flame radiation images for both microlens arrays, with different noise levels superimposed to simulate measurement errors, based on which three-dimensional flame temperature fields were reconstructed. Finally, experimental studies on three-dimensional temperature measurement of ethylene diffusion flames were conducted using a multiple-focus microlens array focused light field camera. The results indicate that for triple-focus focused light field cameras, sub-image contours in flame light field images decrease with increasing microlens focal length. The single-focus microlens array exhibits more uniform distribution of flame radiation sampling rays within the flame interior space with higher ray independence, yielding smaller temperature field reconstruction errors than the triple-focus microlens array. Experimental temperature field reconstruction results for ethylene diffusion flames show consistent trends with thermocouple measurements and good numerical agreement. Future work will focus on designing and implementing a single-focus microlens array focused light field camera for three-dimensional flame temperature field reconstruction to improve temperature reconstruction accuracy.

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Note: Figure translations are in progress. See original paper for figures.