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Light field imaging analysis of flame radiative properties based on Monte Carlo method

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ABSTRACT

Light field imaging, which is one of the noncontact flame measurement methods, can capture and record multiangle radiative intensity information of a flame through a single shot. After the postprocessing and integration of the flame information, the three-dimensional reconstruction of the temperature and radiative properties can be achieved. However, the diversity and universality of the reconstruction parameters make the reconstruction process complex and redundant. Therefore, the order of priority in which the radiative properties (attenuation coefficient, scattering albedo, and scattering phase function) of a flame influence light field imaging should be analyzed by simulation. This study aims to simplify the reconstruction process by simulating the light field imaging of nonuniform temperature distribution using a previously developed multifocus plenoptic camera model. In addition, a quality evaluation system is established to quantitatively analyze the optical influence of different radiative properties in the flame medium on the light field imaging process. The following conclusions are drawn by analyzing the aperture image of the flame with different radiative properties: (1) The attenuation coefficient should be the first priority for the reconstruction of the radiative characteristic parameters of the flame. (2) The scattering albedo should be the next consideration for ensuring high reconstruction precision. (3) For the scattering phase function, the only consideration is whether it is more affected by either isotropy or anisotropy.

1. Introduction

In fields such as aerospace and energy production, high temperature combustion always occurs in equipment such as combustion engines, power station boilers, and coal gasification reactors [1,2]. Theoretical and experimental research on the burning phenomenon of a flame has focused on the design optimization of the combustion system [3,4]. Therefore, to obtain the distribution of the temperature, soot formation, and radiative properties in the flame medium, contact [5] and noncontact [6,7] methods have been introduced. Compared to contact methods, noncontact methods such as the radiative spectrum method [8] and the laser spectroscopy method [9] have some advantages; for example, noncontact methods can provide continuous measurements in a largescale space. However, they also have some disadvantages. For example, the instruments used for laser spectroscopic analysis are sophisticated; hence, they are unsuitable for use under severe conditions such as those encountered in a boiler plant. A more sustainable method is to use a camera to capture pictures and then analyze the radiative spectrum. Because an ordinary camera can capture only one picture at a time and record information from only a specific angle, several cameras need to operate simultaneously to obtain the entire flame distribution, which increases the cost of the experiment and the difficulty of realizing simultaneous shooting. In contrast, a plenoptic camera (light field camera) [10] can record multiangle light field information of a flame from a single shot. This camera has a microlens array between the main lens and the photoreceptor (e.g., charge-coupled device (CCD)). Each microlens transmits light intensity from a certain direction, which is received by the CCD. In this manner, light field information can be captured [11], and a three-dimensional (3D) model of the flame can be reconstructed [12]; in addition, the distribution of the physical parameters of the flame can be analyzed. Since the value range of the properties in the medium [13–15] is difficult to determine, the choices obtained for the reconstructed parameters are redundant and diverse [16–19]. Therefore, to provide a reference for flame reconstruction, it is important to analyze the influence of the radiative properties on light field imaging by simulation.

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In recent years, some researchers have begun to use the light field camera for flame detection. By using the light field imaging technique, Chen et al. [20] studied the combustion process inside a complex 3D engine and realized the direct visualization of liquid fuel spray atomization through optical diagnosis. By utilizing optical field imaging technology, Danehy et al. [21] developed a three-color pyrometer, using which spectral information can be calibrated in the form of spatial coding on the pyrometer sensor. Klemkowsky et al. [22] integrated the background-oriented texture technique with the light field imaging technique and presented a new method of 3D qualitative visualization to determine the density gradient produced by simple flames at different depths in a given scenario. In addition to using light field imaging techniques to visualize a flame, researchers have used optical diagnostic methods to conduct research on flame properties such as temperature, soot formation, and radiative properties. Hossain et al. [23] performed a 3D reconstruction of the flame temperature and emission by using optical tomography and two-color high temperature measurement techniques. Ayrancı et al. [24] developed an inversion scheme based on the emission tomography reconstruction of a flame. Using the spectrum gradient of emission, they extracted characteristic information pertaining to the soot refractive index to characterize the temperature and soot volume fraction of a rough optically thin axisymmetric flame in the field. Iyer et al. [25] determined the total scattering coefficient using three polygonal scattering measurements at different heights above the smoke-free laminar flow of an ethylene diffusion flame burner. Liu et al. [26] proposed a reverse radiative analysis aimed at simultaneously estimate the distribution of the temperature and the radiative properties, including the absorption and scattering coefficients, in a two-dimensional gray medium. A camera with CCD captures the emergent radiative energy. Xu et al. [27] developed a novel tomographic scanning technique to measure the 3D temperature distribution of a flame by integrating a camera and a variable-focus liquid lens based on ionic electro-wetting. Huang et al. [28] developed a method based on multispectral light field imaging to simultaneously reconstruct the multidimensional nonuniform temperature distribution and the radiative properties (scattering and absorption coefficients) of participating media.

However, so far, although the effect of the radiative properties of different flame media on light field imaging has been analyzed, it has mainly been verified for qualitative research and to a much lesser extent for quantitative analysis. On the other hand, the number of radiative properties that effectively influence the imaging is large and these properties have a wide range; these factors make the reconstruction process tedious and subjective to user choices. Therefore, for improving the accuracy of the reconstruction of the flame temperature, it is crucial to correctly analyze the influence of different radiative properties on the light field imaging process. Accordingly, based on the physical simulation of the optical transmission process of the developed light field camera [29–33], this study develops a simulation model for the light field imaging of the flame and uses this model to simulate the radiative properties (attenuation coefficient, scattering albedo, and phase function) of the flame medium in a nonuniform temperature field. To investigate the order of priority in which the parameters with different radiative properties influence light field imaging and to carry out quantitative analysis on the most influential parameter, four quality evaluation functions are introduced: mean square error (MSE), peak signal-to-noise ratio (PSNR), structural similarity (SSIM), and edge quality. Using these functions, the priority of the parameters can be selected in the reconstruction process of the flame temperature. The study results are expected to serve as a reference for improving the accuracy and efficiency of the reconstruction process of the flame temperature.

2. Model and methods

2.1. Flame–plenoptic camera model

The focused plenoptic camera [34,35] is designed based on the plenoptic camera [10]. The CCD in the imaging model of the camera is not at the focal plane of the microlens array; thus, this camera has a lower angular resolution but a higher spatial resolution than a light field camera. By using the focused light field camera, Georgiev and Lumsdaine [36] proposed the multifocus plenoptic camera. By using a staggered microlens array with different focal lengths, the camera can focus on incoming light beams from two or more different object planes and the depth of the field can be extended.

According to the previously designed simulation model of the multifocus plenoptic camera [33] and the study of Georgiev and Lumsdaine [36], this study utilizes the Monte Carlo method (MCM) to physically simulate the light field imaging process. Fig. 1 shows a diagram of the flame–plenoptic camera model. For the sake of simulating the light field imaging of the flame captured by the plenoptic camera, it is necessary to build a light transmission model, i.e., a model of the light rays traveling from the flame to the plenoptic camera (traveling through the main lens and across the microlens array and reaching the CCD). The flame is set 1 m away from the main lens. Suppose that the outside of the flame is located in a transparent medium without attenuation and that no additional light source exists. The entire energy of the light rays is the radiant energy emitted by the flame itself. The parameters of the plenoptic camera is obtained by calibrating the Raytrix R29 camera [37], and the diameter and focal length of the main lens and three types of microlenses are obtained from a previous work [33].

2.2. Applications of MCM in flame–plenoptic camera model

In this study, a flame is regarded as a participating medium [32]. Using an MCM-based model based on geometrical optics [38], the radiative transfer in the flame is divided into emission and attenuation (including absorption and scattering), and the corresponding random model is established. To establish a logical sequence for the light energy, the entire light ray transfer until its arrival at the CCD is simulated, after which the simulation of the next ray begins.

2.2.1. Particle emission within medium

To analyze the energy carried by light rays under a single spectral condition, the wavelength of light is set as $\lambda = 610$ nm. According to Planck's law, a photon's own blackbody spectral radiative force $E_{b\lambda}$ $[\mathrm{W/(m^2\ \mu m)}]$ at any location is

$$E_{\mathrm{b}\lambda} = \frac{c_1\lambda^{-5}}{[\exp(c_2/(\lambda T)) - 1]} \tag{1}$$

where c_1 is Planck's first radiative constant ($c_1 = 3.7418\times 10^{-16} W\,\mathrm{m}^2$), c_2 is Planck's second radiative constant ($c_2 = 1.4388 \times 10^4\ \mu\mathrm{m\,K}$), and T is the temperature of a certain position (K). Thus, the blackbody spectral radiative intensity $I_{\lambda,0}$ $[\mathrm{W/(m^2\ \mu m\ sr)}]$ is expressed as

$$I_{\lambda,0} = \frac{E_{b\lambda}}{\mathrm{d}\Omega\cos\theta} \tag{2}$$

where Ω is the solid angle (sr) and θ is the zenith angle. Using the temperature distribution (Eq. (3)) reconstructed by Sun et al. [37], the flame is supposed to be burning in a cylindrical, transparent (without attenuation) chamber.