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Light-field-camera imaging simulation of participatory media using Monte Carlo method

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ABSTRACT

In this study, we use the Monte Carlo method to analyze the light-field camera imaging of various participating media (absorbing, scattering and emitting media), along with refocused and sub-aperture images, during the process of reconstructing the temperature field of a high-temperature combustion flame. Hence, the optical field of the participating medium is analyzed. We found that if the participating medium does not have active emission capability, the absorptive and scattering capacity can be regarded as attenuation capacity. However, if the medium has active emission capability, it is difficult to obtain the emission characteristics corresponding to the depth of field through refocusing, and the medium's temperature field can only be reconstructed using sub-aperture images.

1. Introduction

High-temperature combustion is widely employed in aerospace technology, power and energy generation, ferrous metallurgy, and the chemical industry, in applications such as rocket engines, gas turbines, engines, station boilers, coal gasification rectors, and other high-temperature devices [1–4]. The mechanism and apparent characteristics of the combustion of fuel have been investigated through both theoretical and experimental research; this has helped in revealing the core parameters of combustion phenomena and the laws governing the combustion process. Such research can also help in developing and facilitating the optimized design and operation of combustion systems.

The measurement of a flame's three-dimensional (3D) radiant energy field [5] is primarily based on readings from a single camera and a polyphaser. Such a one-camera measuring system is simple, inexpensive, and easy to install. This system can be used to reconstruct the flame cross section directly and three dimensions. However, single-camera image measurement systems are generally limited and can only be applied to stable, axially symmetric flames [6]. This prevents their application to unsteady and turbulent flame measurement.

An increasing number of studies on polyphasers have been conducted in recent years. The polyphaser system is derived from the computed tomography (CT) measurement method, through which a combustion flame is imaged using a number of cameras at different positions and angles. Hence, flame images at different projections are obtained. This approach can yield better spatial resolution compared to that yielded by single-camera techniques; the greater the projection, the better is the resolution [7]. However, an increased number of cameras results in greater system complexity and cost. Further, as strict centering of the spatial position of the optical axis of the polyphaser system is required, along with synchronization and calibration of more than one camera, the installation and operation of such systems is technically difficult [7]. In contrast, light-field imaging technology can theoretically achieve the synchronous acquisition of optical-field information at large projection angles [8]. Therefore, light-field imaging is more suitable than a polyphaser system for detecting the temperature of an exhaust plume, as it virtually divides the main aperture into many sub-apertures, each one of which can obtain the radiation intensity image at its specific view angle. However, because of various limitations related to imaging mechanisms, arithmetic, and other factors, existing light-field imaging techniques are limited to the acquisition of light-field information under surface radiation conditions, and radiated light-field information cannot be obtained for participating media with complex anisotropy (such as an exhaust-plume flow field) [9–11].

To realize the precise reconstruction of the 3D temperature field of a large-scale combustion flame, the flame temperature must be obtained, and a reconstruction algorithm for optical radiation information that can be applied to participatory flame media with

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complex anisotropy must be constructed. The latter step is very important. In establishing the reconstruction algorithm to yield the effective light-field radiation information, the aim is to facilitate the accurate imaging of the characteristics of the participating medium. Since the publication of Ren's study in 2005 [12], light-field camera research has primarily been focused on the imaging of non-participating media (i.e., media without absorption, scattering, or active emission). For example, Su et al. [13] utilized the characteristics of a light-field camera to obtain the spatial information of rays, used the light-field camera theory to develop a snapshot imaging spectrometer, and proved that a camera based on a microlens array shows superior performance compared to a device based on a pinhole array. Further, Liang et al. [14] constructed the ray transmission model of a light-field camera to analyze the fundamental limitations of the camera resolution and, thereby, evaluated design concepts of light-field cameras. Apelt et al. [15] used focus and depth-of-field images obtained using a light-field camera to observe the morphology of plant growth and to acquire related information. Further, Kim et al. [16] used a light-field camera to detect facial activity, while Marwah et al. [17] proposed a compression light-field camera structure, which can extract a light field with a better resolution from a single image as well as compress and de-noise a 4D light field.

The nonlinear attenuation of radiation intensity in participating media makes it difficult to reconstruct the radiation intensity of medium elements. Therefore, the influence of the radiative characteristics of the medium needs to be clarified. However, very few studies have been published on the light-field imaging of participating media, and therefore, further study is required. Focusing on this problem, in this study, we use a Monte Carlo method (MCM) to construct a computer simulation model, and we simulate a microlens-array imaging process for a high-temperature participating medium. We analyze the imaging performance for light-field information for a pure absorbent medium, a scattering medium, and a medium with active emission ability. In addition, we analyze the differences between sub-aperture and refocus imaging using the obtained imaging results to identify the appropriate imaging technique for reconstructing the temperature-field of the medium. Finally, we simulate a physical model of a typical flame.

2. Model and algorithm

In a previous study, we constructed a simulation calculation model [18,19] that can be used for light-field camera imaging simulations employing an MCM [20–22]. Related information can be found in reference [12]. In the previous study, only the surface radiation of objects was imaged, and participating media were not considered [23]. Therefore, we will briefly introduce the light-field camera simulation model below, before discussing the model facilitating the imaging of the participating medium that was developed in the present study.

2.1. Light-field camera model

The common light-field camera caliber is not sufficiently large to cause small distance changes between various sub-apertures, and the perspective changes of the objects are not significant. In addition to factors such as insufficient numbers of pixels, insufficient distance between the objects, and the objects being substantially located within the depth of field, a significant factor also led to the small differences in the refocusing results. This paper considered the use of a lens of larger caliber to increase the distance between the main lens and the objects to simulate the perspective changes and refocusing more accurately. The reflecting telescope caliber is easy to modify while maintaining a constant focal length.

Fig. 1 shows a model of the camera structure. The hook faces on the two sides of the main lens are spherical surfaces with radius $R = 0.2$ m. The lens thickness along the optical axis is $L = 0.02$ m, the main lens diameter is $D = 120$ mm, the focal length of each main lens is $f = 304.0987$ mm, and the corresponding minimum aperture F-number is $F = 2.534$. The distance between the adjacent microlens centers is 0.5 mm, the diameter of each microlens is $d = 0.48$ mm, the hook faces on the two sides of the microlens are spherical surfaces with radius $r = 1.15$ mm, the microlens thickness is 0.1 mm, and the refractive index of the microlens medium is $n = 1.5$. For these microlens parameters, the focal length of each microlens is $f = 1.1669$ m, as calculated from

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)L}{nR_1R_2}\right]. \tag{1}$$

Therefore, the minimum aperture of the microlens is $F = 2.431$ for a microlens array located outside the focal length of the main lens. Further, the F of the microlens and main lens meet the requirements of Eq. (2), where

$$(L+f)/D \geqslant f/d. \tag{2}$$

A single lens, rather than a group of lenses, is used as the main lens as this yields superior imaging performance. In general, the aperture is reduced in order to reduce lens aberration. In this example, the aperture diameter is 100 mm and $F \approx 3.04$.

A total of 60×60 microlenses are employed, the pixel size of the charge-coupled device (CCD) camera is 0.05 mm, and the number of pixels is 600×600. Therefore, each microlens corresponds to 10×10 pixels, each of which records the directional information of the light.

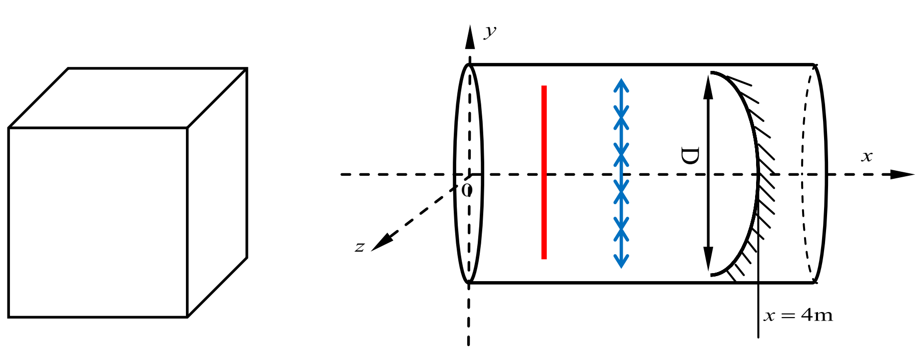

Fig. 1. Camera structure.