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Influence analysis of radiative properties and flame temperature reconstruction based on optical tomography

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ABSTRACT

The flame temperature measurement is significant to study flame structure. However, during the detection process using light field imaging technology, the influence of radiative properties on flame distribution at different positions is hard to evaluate. Therefore, this study simulates the light field imaging of section flames to analyze the influence of radiative properties on flame distribution. A tomographic image is reconstructed from three-dimensional light field imaging, which is evaluated as similar to the section flame images. Then the temperature reconstructed from the tomographic image is compared to the known temperature, with a small relative error, under 10%. In addition, the influence of radiative properties on the accuracy of reconstructed temperature is also analyzed.

1. Introduction

When conducting theoretical and experimental analysis on the different combustion states of a fire, on engine operating conditions, power generation, or heating conditions, it is very important to study the distribution of the three-dimensional (3D) temperature field inside the flame. At present, there are many ways to detect flame temperature, soot volume fraction, and radiative properties. These methods can be divided into two types: contact [1,2] and non-contact [3–5]. The disadvantages of contact detection methods, such as thermocouples, are slow response speed, large error, and interference in the detected object. Non-contact detection methods mainly utilize optical methods, such as radiative spectroscopy, which is widely used and well-suited for long-distance targets and moving objects. Photosensors such as charge-coupled devices (CCDs) can respond quickly and detect a relatively wide range of temperature. Optical computed tomography [6,7] is a new technology based on the technology of computer information process, and its most outstanding feature is that it can precisely measure a certain level of transient physical distribution without disturbing the distribution of the measured field. A combination of radiative spectroscopy and optical tomography can be used to reconstruct the structure of a flame in a section manner to achieve the goal of detecting its 3D interior structure.

At present, several researchers have introduced optical tomography to detect the flame, based on the radiative spectroscopy using traditional cameras. Zhou et al. [8] designed a 3D imaging system using optical sectioning tomography to reconstruct the temperature distribution of candlelight. Xu et al. [9] used a high-speed focusing liquid lens to detect the 3D temperature of a flame based on the optical sectioning tomography method. Hossain et al. [10] presented an experimental investigation of the 3D reconstruction of flame temperature and emissivity distributions by using optical tomography and two-colour pyrometric technique. Li et al. [11] presented an experimental investigation on the estimation of radiative properties and temperature distributions in a coal-fired boiler furnace by a portable imaging processing system. Liu et al. [12] used hyperspectral imaging equipment to capture an axisymmetric laminar ethylene flame in various environments, and to perform tomography at different wavelengths. The temperature of the flame and the soot volume fraction were also reconstructed. He et al. [13] presented a cone beam tomography to reconstruct an axisymmetric flame, and verified the methods through simulation and experiments. Liu et al. [14] proposed an inverse radiation analysis for simultaneous estimation of temperature field and radiative properties by CCD cameras at boundary surfaces.

However, different from traditional camera used by above mentioned researches, light field camera [15] is a novel example of radiative spectral imaging technology. It can record multi-angle light field information through a single shot, while traditional cameras only collect one angle information of one shot. A number of

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microlenses are set between the main lens and the photosensor inside the light field camera. Wherein, the photosensor is set to receive the radiative information of the light rays transferred from each microlens after travelling through the main lens. Then, the multi-angle light field information is collected [16] and the 3D model of the detected object can be reconstructed from the post-processing refocused images [17].

Therefore, light field camera can simultaneously record multi-angle light field information from the target flame (to reconstruct the 3D model of the flame) and analyze the internal distribution of characteristics such as temperature and radiative properties. Sun et al. [18] used light field camera to reconstruct the three-dimensional temperature distribution. Huang et al. [19] simultaneously reconstructed the multi-dimensional inhomogeneous temperature distribution and radiative properties of participating media, based on multi-spectral light-field imaging technique. However, only few researchers have used light field camera to apply optical tomography to flame detection, such as, Zhao et al. [20] proposed the optical sectioning tomographic technique for three-dimensional flame temperature measurement combined with light field imaging.

There are many uncertainties in the optical imaging process of flame, some of which have been studied by our research group, such as, (1) the influence of radiative properties on flame light field imaging [21]; (2) the attenuation process of light emanating from the flame in a transitive medium like air [22]; (3) the distortion and other optical phenomena generated by the microlenses inside the camera [23,24]; (4) the photoelectric conversion process corresponding to the energy received by the sensor, and the output of the detection signal [25]. However, during the experimental process of detecting flame temperature using light field camera, the real-time measurement of temperature distribution at the specific location inside the flame is restricted to the high-speed reaction and fluctuation. Thus, it is important to investigate the real-time influence of radiative properties on flame distribution, and the influence of radiative properties on the accuracy of reconstructed temperature.

In this study, based on the established physical simulation model of the light field camera [22,26,27] using Monte Carlo method with ray splitting technique, a section flame model is presented to capture the radiative information of different sections in the flame using light field camera. Comparing tomographic flame images with the section flame images at the same position, the similarities are evaluated. Reconstruct temperature from the tomographic images, the relative deviation from the actual temperature is obtained. Meanwhile, the influence of flame radiative properties on the precision of reconstructed temperature is analyzed. Then, the outermost flame sections are reconstructed using the adjacent inside flame sections with higher accuracy. The realization of the above work provides the data support for experimental research of actual flame detection, using light field camera.

2. Models and methods

2.1. Flame-light field camera model

To simulate the light field imaging of a flame through light field camera, it is necessary to establish light transfer model from the flame to the light field camera (with particular attention to the process from the main lens to the microlens array to the CCD). The Monte Carlo method, based on ray splitting technique, can be used to simulate an optical path and maximally fit the results of an actual experiment based on probability, thus, meeting the objective of the simulation [26]. This study uses the established multi-focus microlens-based light field camera model [27]. Fig. 1 presents a diagram of the flame-light field camera model, and the flame section method. Assuming that the area outside the flame is in a transparent medium (i.e., no attenuation occurs and there is no external light source), all of the light energy is radiative energy emitted by the combustion flame. Parameter information of the Raytrix (R29) light field camera, are shown in Table 1 and the detail description refers to the previous work [18,27].

2.1.1. Flame temperature distribution

According to the temperature fitting formula experimentally measured and fitted by Sun et al. [18], the simulated temperature distribution is:

$$T_{exa}(r,z) = 1200 + 600 \times \exp\left\{-\left[3 \times \left(\left(\frac{r}{R}\right)^2 + \left(\frac{z}{Z}\right)^2\right) - 0.9\right]^2\right\} \tag{1}$$

where $R = 0.04$ m is the max radius, $Z = 0.4$ m is the max height, r and z are the axial and radius coordinates. In addition, $r = \sqrt{x^2 + y^2}$ allows in the Cartesian coordinate system shown in Fig. 1. Based on the premise of the known temperature distribution, the true structure of the flame can be reconstructed based on the information captured by CCD. Fig. 2 shows the actual temperature distribution. The flame is stratified along the x-axis into seven sections and are named as such in the following order: $x = 0.03$ m, 0.02 m, 0.01 m, 0.0 m, -0.01 m, -0.02 m and -0.03 m. Each section is assigned a thickness of (-0.005 m, 0.005 m). Within this thickness, the temperature is still distributed as the section position, that is, independent of the x coordinate. The flame temperature distribution of each section follows Eq. (1), and thus, the temperature distributions of different sections are different from each other; the farther the sections are from the center of the flame, the lower is the height of each flame.

Judging from the relatively low temperature of first and seventh sections, which may be difficult to reconstruct from the 3D imaging of the flame. It is considered that, only the outer four sections (first, second, sixth and seventh sections) are simulated to reconstruct the outermost sections. In this way, the influence of the central sections, with larger temperature distribution, is eliminated; the analysis is detailed in Section 3.5.

2.1.2. Simulation method of section flame

The section flame imaging process considers only the attenuation of emitted energy in the medium, and assumes that the sections do not affect each other. By simulating section flames, the effects of different sections of the flame on the light field imaging process can be analyzed. On the premise of the temperature and radiative properties distribution, the flame is simulated in sections and the images are captured by light field camera.

When analyzing the radiative properties of each section independently, the medium plays an important role in the attenuation of light energy. To exclude the temperature influence of other sections, only the temperature distribution of the certain flame section and the effect of medium field are considered.

The simulated flame is divided into N sections, and each is assigned a certain thickness. Light rays are uniformly emitted in this thickness range. Note that in the process of using the Monte Carlo method to stratify the flame, the sampled light density, n_r, is introduced as the amount of sampled light per unit area of a blackbody surface at a given temperature [28]. Thus, all the light rays can have the same energy as it does in the 3D imaging process E. The energy of each sampled light beam, e_i, is

$$e_i = E/n_r \tag{2}$$