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Liquid lens-based optical sectioning tomography for three-dimensional flame temperature measurement

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A B S T R A C T

Measurement of three-dimensional temperature field of a flame plays a significant role in in-depth insight into combustion process. This paper proposes a novel optical sectioning tomography for the measurement of three-dimensional temperature of flame through a single camera in combination with an ionic electrowetting-based variable focus liquid lens. Firstly, the optical sectioning imaging principle is introduced based on a variable focus liquid lens. Secondly, the calibration works are carried out on a liquid lens-based optical sectioning tomography system for three-dimensional flame temperature measurement to determine the relationship between the working voltages of the liquid lens and its focal planes in combination with entropy function. Further Gaussian model is taken as the defocused model to calibrate the point spread function of the system through edge method, and the CCD sensor is calibrated by a black body furnace to find out the relationship between the image gray and the received radiation energy. The reconstruction algorithms for three-dimensional flame luminosity distribution of the combustion flame are also developed. Finally experimental works are undertaken to evaluate the optical sectioning tomography system. Preliminary experimental results on an ethylene-air co-flow burner verified the feasibility of the optical sectioning tomography for the three-dimensional temperature distribution of a diffusion flame. The developed optical sectioning tomography system is capable of characterizing the structure and combustion characteristics of the diffusion flame.

1. Introduction

Combustion is a high-temperature exothermic redox chemical reaction between a fuel and an oxidant, which is the world's major source of energy used in various industrial processes such as gas turbine, internal combustion engine, coal-fired boiler and gasifier. Temperature is one of the key quantities in these combustion processes. It governs reaction chemistry (reaction rates and equilibrium states), influences the structure and stability of flame, and pollutant formation processes. However, the flame field inside the combustion equipment is inherently unstable and fluctuating due to the wide ranging fuel properties and variations in load [1]. In order to achieve an insight into the flame structure, fuel mixing and combustion mechanism, it is desirable to deploy three-dimensional monitoring techniques to obtain the critical information of the flame field such as three-dimensional temperature distribution [2]. The accurate and precise determination of temperature is further useful for the development of combustion equipment with better performance, lower environmental impact, and greater flexibility [2,3]. Additionally, in order to optimize and control combustion processes it is of crucial importance to have techniques which are able to measure critical temperature [3].

Tremendous progress has recently been made with regards to flame measurement. Non-intrusive diagnostic technique has the advantage of non-interfering with the combustion, which is categorized as laser-based diagnostic technique and non-laser diagnostic technique (radiation imaging, ultrasonic method) [2,4]. The laser-based combustion diagnostics technologies such as Rayleigh scattering spectroscopy, Raman scattering spectroscopy, Coherent anti-stokes Raman scattering, and tunable laser absorption spectroscopy have made a great development, and become important measurement methods for combustion research [2,4,5]. These methods can accurately measure the temperature, species concentration, speed and other parameters of combustion and flame. However, the laser-based diagnostic technique is almost based on the point or line measurement method. Through a variety of mechanical or optical actuators these techniques can be extended for two-dimensional and three-dimensional field measurements of flame. However, the extended two- or three-dimensional

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temperature measurement systems are complicated and expensive, which limits the practical application of these systems in industrial fields [2].

Radiation imaging is a very promising technology for two or three dimensional flame temperature measurement through the use of flame radiation and image processing technique. It features high accuracy, non-intrusiveness and real-time continuous measurement. Hossain MM and Yan Y developed various instrumentation systems for the flame temperature, soot concentration and flame shape through a single camera and digital imaging techniques, and performed lots of experimental works in lab-scale and industrial scale burners [6,7]. Liu D and Wang F performed the in-depth study of the simultaneous reconstruction of the temperature field and soot concentration of inhomogeneous, anisotropically scattering media using the color images of flame [8,9]. Zhou HC arranged multi-CCD cameras as flame detectors to receive flame radiation information from the internal combustion flame on a coal-fired boiler of power plant, and successfully achieved the 3D flame temperature distribution of the absorption and scattering medium of coal-fired flame [10–13]. Radiation imaging technology is generally divided into single camera and multi-camera system. The single camera system is simple in structure, low in cost and easy to be installed in industrial field. However the single camera system is only used for stable axisymmetric flame measurement, which greatly limits its application in unsteady turbulent flame. A multi-camera system is derived from computed tomography (CT) technology. In this system multi-cameras are arranged around flame in different positions and angles, so the projection images of flame from multiple perspectives are used to reconstruct the flame temperature based on Radon theory. It has advantages of high resolution and high accuracy [14]. But the complexity and cost of system increase with increasing number of cameras. More seriously, the complex calibration, alignment and synchronization of multi-camera system make it difficult in installation and application in industrial burners [14–16].

In 1971, Weinstein AM reconstructed the structure of 3-D specimens from a series of 2-D section images [17]. In 1983, Agard DA proposed an optical sectioning tomography (OST) system using chromosome fluorescence microscope with high numerical aperture and small depth of field, and successfully achieved the reconstruction of different sections of biological samples [18]. Since then, the optical sectioning tomography has attracted much attention in flame monitoring field [19–21]. A 3-D luminous combustion flame can be regarded as a combination of a series of two dimensional luminous sections of the flame. The focused image of each section of the flame caught by a single CCD camera is the superposition of the luminosity from the focused and defocused sections of the flame. Hence based on superposition theorem the original luminosity distribution in each section can be reconstructed from the captured section images of flame. From Plank's law, the 3-D distribution of flame temperature can further be achieved. Lu YG and Wang SM investigated the optical sectioning tomography for flame temperature measurement in combination with digital image processing technique and realized the reconstruction of the three-dimensional temperature field of a candle flame [19,20]. Gong combined optical sectioning tomography with two-color method to measure three-dimensional flame temperature distribution in an opposed multi-burners gasifier, and the measured results have good agreement with those of thermocouples [21]. Compared with CT system, the optical sectioning tomography system utilizes a single camera and single lens, and so it has advantages of being simple and reliable in equipment, and low in cost. But in traditional optical sectioning tomography system, a stepping motor was used to move the optical system to focus each section of flame. The imaging speed is slow, and it is difficult to realize the transient 3-D temperature field measurement of flame.

Variable focus liquid lens is one of novel optical elements developed in recent years. In the liquid lens, there are two kinds of equidensity liquids: conductive electrolyte and insulating oil. The interface shape between the electrolyte and the insulating oil is controllable by regulating the voltage applied to the electrodes [22]. This is because the applied voltage changes the shape of liquid droplets due to the electrowetting effect. The liquid lens has no moving parts, and is simply capable of changing its focal length by regulating working voltage instead of complicated mechanical actuator [23]. So the response speed of variable focus liquid lens is fast, and fast focus can be achieved to meet the requirements of real-time imaging. The variable focus liquid lens is introduced into the optical sectioning system for flame measurement, which is useful for the dynamic measurement of flame.

This paper aims to investigate a novel optical sectioning tomography for the continuous measurement of three-dimensional temperature of flame through a single camera in combination with a variable focus liquid lens. An improved matrix model is proposed to transform the matrix convolution between the CCD images and flame to a set of linear algebraic equations, and the van Citter iteration method with constraints is then used to solve the linear algebraic equations and retrieve the original luminosity distribution in each section of the three-dimensional flame. A series of calibration experiments are performed to determine the relationship between the focal planes of liquid lens and its working voltage, the point spread function (PSF) of liquid lens-based optical system, and relationship between the gray of flame image and its luminosity. Finally experiments are carried out on the ethylene-air co-flow burner to evaluate the liquid lens-based optical sectioning tomography system, and experimental results on the three-dimensional temperature distribution of a diffusion flame are presented and analyzed in details.

2. Fundamental measurement principles

By regulating the working voltage of the liquid lens, the liquid lens-based imaging system is capable of focusing on different sections of a flame. A 3-D luminous flame can be regarded as a combination of a series of two dimensional luminous sections of the flame. The focused image of each section of the flame can be captured by the liquid lens-based imaging system. Flame is transparent or translucent, so the captured image is the superposition of the luminosity from the focused and defocused sections of the flame. Fig. 1 shows a schematic diagram of OST system. The

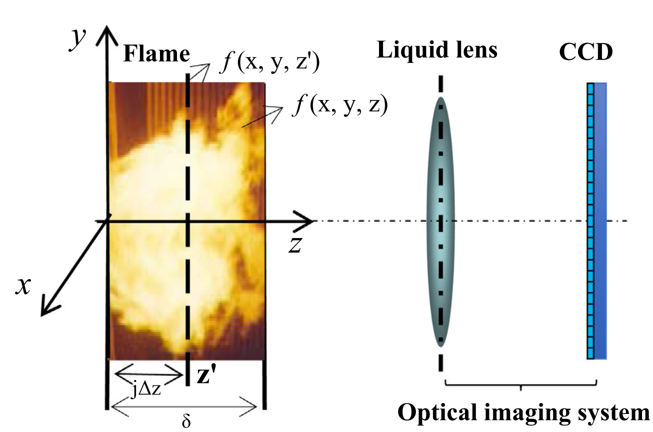

Fig. 1. Schematic of OST system.