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Experimental investigation on gas-phase temperature of axisymmetric ethylene flames by large lateral shearing interferometry

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ABSTRACT

The gas temperature fields of axisymmetric co-annular laminar diffusion ethylene flame jets in air and oxygen-enriched atmospheres were measured and visualized using large lateral shearing interferometry technique. Seven cases of reconstructed temperature fields were investigated using various compositions of fuel/oxidant with an average correction factor. The phase difference field were obtained using a fringe trace algorithm. A discrete Abel inversion process was adopted to resolve the refractive index distribution from the line-of-sight integrated data. The peak temperatures of the flame varied between 1980 K and 2050 K using air as the oxidant and increased to more than 2150 K when oxygen was added. Two separate high temperature zones, one located at the side edge of the flame, the other in the upper part of the flame around the centerline of the burner were observed in four of the seven instances of high mixture stoichiometry. The proposed methodology was verified to be suitable for the reconstruction of temperature distributions from the experimental measurement results.

1. Introduction

A diffusion flame is one of the most common and fundamental types of flames and is widely used in both domestic and industrial applications. Diffusion flames have also become the object of investigation to better understand reaction flow and combustion devices. Air is traditionally used as the oxidizer of a diffusion flame, on the basis of low cost and abundance. However, pollutants such as NO_x and soot particles are emitted from hydrocarbon/air combustion reactions. Consequently, combustion with different concentration of oxygen has been studied as a means for producing cleaner combustion without the emission of unwanted products [1,2]. In these studies, the measurement of temperature distribution in the flame, which strongly affects the chemical reaction rate and energy transfer process in flames, is important for modeling chemical reactions [3] and soot formation [4]. This is because flame structure, which significantly influences the residence time of soot particles, plays an important role in the study of soot formation [5,6]. A map of flame temperature distribution is one of the most intuitive approaches for analyzing flame structures.

Non-intrusive optical flame measurement methods have been studied extensively by a number of investigators [7–12], including the Tunable Diode Laser Absorption Spectroscopy (TDLAS) [7], laser-induced incandescence [13,14], emission-based tomography [9,11] and others. These optical approaches were commonly used to study the structure, shape and extinction of the flames [15]. Laser interferometry is one such technique that can be utilized as a method for revealing the gas phase temperature distribution over an entire flame, where measurement of the refractive index of the gas phase can be used to deduce the flame temperature. Many different interferometric methods have been adopted to study the temperature distribution of the flame objects, such as the double-exposure holographic interferometry system [16,17], Mach-Zehnder [18,19], Michelson [20] and single-exposure holographic interferometer systems [21] and the speckle pattern interferometry [22]. These techniques have shown great performance to measure a dynamic flame and provide simple fringe patterns. However, they are usually difficult to build and very sensitive to vibration, because the object and reference beams are widely separated from each

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other.

Shearing interferometry is a more attractive real time temperature measurement method due to its simple structure and vibration tolerance [23]. Shakher's group has focused on the shearing type interferometry techniques to study different kinds of gaseous flames [24–29]. A double aperture [24], a shearing plate [26] or grating and ground glass [28] was used to generate small shearing displacements to obtain the distribution of the gradient of refractive index inside the flame object. Liu and Feng [30] used a lateral shearing interferometry system to measure the temperature distribution in an engine during a high speed combustion process. However, many types of shearing interferometry systems provide complex fringe pattern corresponding to the self-referencing of a distorted wave-front, which could not directly reflect the phase difference distribution characteristics and may need reduction operations [31,32].

To avoid these drawbacks, Lv et al. [33,34] proposed a large lateral shearing interferometry system which maintains the advantages of shearing interferometry while providing simple holographic fringe patterns. Thus the temperature field of a flame can be sampled without the need for complex optics configuration or extra computation in data processing. Zhu et al. [35] used this large lateral shearing interferometry to measure the temperature field around a heated cylinder, in order to study the natural convection phenomenon. However, limited case of laminar jet flame in air atmosphere has been examined by this approach. The effects of different configurations and different atmospheres, such as different concentration of oxygen, are still to be tested. Besides, the application and data processing of large lateral shearing interferometry in oxygen-enriched atmospheres is to be developed.

In this reported study, axisymmetric diffusion flames utilizing either air or oxygen were experimentally investigated employing large lateral shearing interferometry. Diffusion flames with various flow conditions were established to study the flame shapes, structures and temperature distribution. First, the theory of the interferometry, Abel inversion and the relationship between the local refractive index and gas temperature will be briefly described. Second, the experimental apparatus, data post-processing procedures and corresponding uncertainty analysis will be introduced. Then the measured temperature fields and corresponding discussions will be provided. Finally, the study conclusions will be summarized.

2. Theory

2.1. Large lateral shearing interferometry

When a plane wave front passes through a phase object such as gas flame, it is distorted by the non-uniform refractive index in the flame. In a lateral shearing interferometer system, a parallel-sided interferometer plate is placed behind the flame. The incident beam is partly reflected by the front surface and partly by the back surface of the plate. These two reflected wave fronts remain in the same direction, but have experienced a certain lateral displacement s in the horizontal direction. In the overlap zone of these two wave fronts, a lateral shearing fringe pattern Θ can be observed in real-time, as shown in Fig. 1.

The phase difference Θ can be expressed as

$$\Theta(x,h) = \theta(x,h) - \theta(x-s,h) + \frac{2\pi\Delta Z}{\lambda} \tag{1}$$

where θ is the phase difference of the wave-front before the plate, x and h represents the coordinate along horizontal and vertical directions, both of which are orthogonal to the optical axis. ΔZ is the optical length that induced by the travel of one of the two beams inside the plate, a constant within one experiment set. s is the lateral shearing displacement.

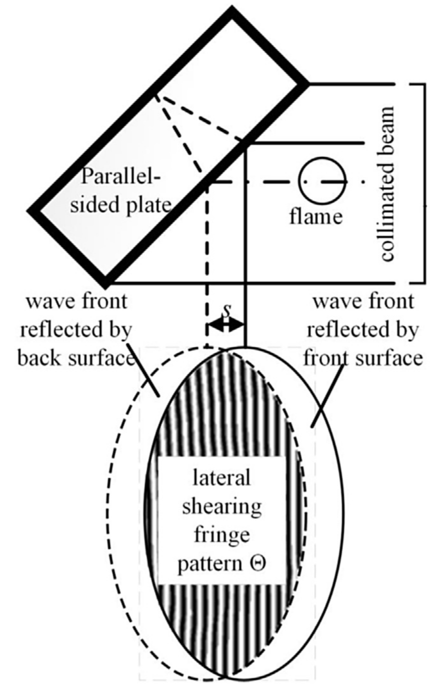

Fig. 1. Principle diagram of the large lateral shearing interferometry.

The parameter θ is the sum of θ_{flame} and θ_{system}, which are the phase differences triggered by the flame itself and the optical system, respectively. In this experiment, two types of fringe patterns are recorded to obtain the distribution of θ_{flame}. Θ_0 is recorded at the extinction state, which means that no fuel is provided, but oxidizer flows at room temperature, while the other fringe pattern Θ_1 is recorded in combustion state.

The expressions of Θ_0 and Θ_1 are as following:

$$\Theta_0(x,h) = \theta_{system}(x,h) - \theta_{system}(x-s,h) + \frac{2\pi\Delta Z}{\lambda} \tag{2}$$

$$\Theta_1(x,h) = \theta_{flame}(x,h) - \theta_{flame}(x-s,h) + \Theta_0(x,h) \tag{3}$$

When the lateral shearing displacement s is more than $2R_0$, twice the maximal radius of the area affected by the flame, at least one of $\theta_{flame}(x, h)$ and $\theta_{flame}(x\text{-}s, h)$ would be equal to 0 at any point within the shearing zone and the value of $\theta_{flame}(x, h)$ can be obtained from:

$$\theta_{flame}(x,h) = \begin{cases} \Theta_1(x,h) - \Theta_0(x,h) & -R_0 < x < R_0 \\ -[\Theta_1(x,h) - \Theta_0(x,h)] & -R_0 - s < x < R_0 - s \\ 0 & \text{remainder} \end{cases} \tag{4}$$

Equation (4) shows that a simple fringe pattern and its mirror image are presented around the locations $x = 0$ and $x = s$. Temperature distributions can then be calculated directly from this fringe without the need for complex iterative deconvolution operations [33].

2.2. Projection transform

The θ_{flame} defined above is a projected phase difference, or, in