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Temperature measurement of wick stabilized micro diffusion flame under the influence of magnetic field using digital holographic interferometry

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ABSTRACT

This paper presents the effect of magnetic field (upward decreasing, uniform and upward increasing) on wick stabilized micro diffusion flame by using digital holographic interferometry (DHI). The investigations reveal that under the influence of upward decreasing and uniform magnetic field temperature inside the micro flame increases in comparison to temperature inside micro flame without magnetic field. This is in contrary to normal diffusion flame, where uniform magnetic field has a little or no effect on the temperature. DHI is inherently more accurate more precise and is having better spatial resolution. DHI is ideally suited to study micro flame.

1. Introduction

Micro diffusion flame is almost spherical in shape and having sizes of several millimeters (~2 mm to 3 mm) [1–2]. The temperature inside the micro diffusion flame is less as compared to normal diffusion flame because the small size and large surface area to volume ratio of micro flame leads to considerable amount of heat loss to environment and combustion system such as burner and candle. There is little or no buoyancy effect on micro diffusion flames because of its small size [3–6]. The micro diffusion flame is controlled by diffusion and convection [1]. The study of micro diffusion flames is useful to understand the structure of diffusion controlled phenomena and diffusion flame itself [2].

Recently, the need of micro scale combustion systems to power the micro devices has increased for space and surveillance applications. The micro diffusion flames are used in microsatellites and unmanned micro aerial vehicle. For developing such combustion systems, an understanding of the characteristic of micro flames is required. Although combustion is well understood and studied for various applications, however, its applications to micro power devices is limited because it is challenging to maintain a sustainable combustion in micro combustion systems. To maintain the sustainable combustion in micro flames is difficult because of higher heat losses due to large surface area to volume ratio of micro flame and negligible buoyancy control flow which leads to quench the chemical reaction. Heat loss from the micro diffusion flame can be minimized by reducing the size of micro flame without reducing generated heat through combustion reaction.

Numbers of contact type [7] and non-contact type methods [8] have been used for the measurement of temperature. Contact type methods using thermocouple are not suitable for temperature measurement inside the micro flame because thermocouple is likely to affect the stability of micro flame and may result in quenching of micro flame. Other limitations of using thermocouple for temperature measurement are that they provide point wise measurements and suffer from conductive and radiative loss from the probe of thermocouple. While optical interferometric methods [8–16] are non-contact, non-invasive, more precise and full field. These methods do not disturb the flow of temperature field inside the micro flames. They are expected to be more suitable to study the micro flames.

Some researchers have studied the effect of magnetic field on the flames using different techniques [17–34]. However most of the studies made on micro flame are theoretical. Recently Digital speckle pattern interferometry (DSPI) has been used to study the effect of magnetic field on the temperature and temperature profile of micro diffusion flame [35].

In this paper, an application of digital holographic interferometry is investigated for the measurement of temperature and temperature profile of a wick stabilized micro diffusion candle flame under the influence of three different configurations of magnetic field i.e. (1) upward decreasing magnetic field (2) uniform magnetic field, and (3) upward increasing magnetic field. DHI is more accurate, precise and provides better spatial resolution than other existing optical interferometric techniques. DHI can also provide temperature fluctuations in the flame as recording process can be made quite fast. The motivation to investigate the effect of magnetic field on micro flame was to study the micro flames and stable and controlled combustion in micro flames.

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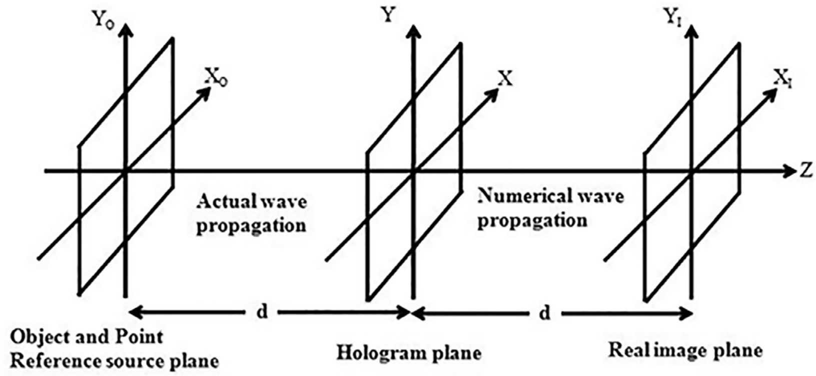

Fig. 1. Schematic of the co-ordinate system of recording and reconstruction planes of digital hologram.

2. Theory

In digital holography, interference pattern between the reference wave and object wave is recorded on an electronic detector such as CCD or CMOS sensor. The recorded interference pattern is sampled and digitized with the help of analog to digital (A/D) converter and stored in computer through image grabber card. The real and virtual image can be reconstructed from the recorded digital hologram if the diffraction of the reference wave is carried out by numerical methods [36]. The diffraction of reference wave at the hologram is described by Fresnel Kirchoff integral [36]. Fig. 1 shows the schematic of the co-ordinate system of recording and reconstruction planes of digital hologram, where (X_O, Y_O), (X, Y), and (X_I, Y_I) are the Cartesian co-ordinates of the object, hologram and image planes respectively. The digitized form of complex amplitude of object wavefront $O(m\Delta X_I, n\Delta Y_I)$ in image plane can be calculated from Fresnel- Kirchoff integral with Fresnel approximation. It can be written as [37]

$$O(m\Delta X_I, n\Delta Y_I) = \frac{i}{\lambda d}\exp\left(-i\frac{2\pi}{\lambda}d\right)\exp\left[-i\pi\lambda d\left(\frac{m^2}{M^2\Delta X^2}+\frac{n^2}{N^2\Delta Y^2}\right)\right] \times FFT\left\{E_R(p,q)H(p,q)\exp\left[-i\frac{\pi}{\lambda d}(p^2\Delta X^2+q^2\Delta Y^2)\right]\right\} \quad (1)$$

where $O(m\Delta X_I, n\Delta Y_I)$ is a matrix of $M\times N$ point, where $M\times N$ is number of pixels on the recording sensor (CCD/CMOS) with $m, p = 0, 1, 2, 3, 4,\ldots\ldots.M-1$, and $n, q = 0, 1,2,3,4\ldots\ldots..N$-1. '$d$ ' is the distance between the hologram and image plane. $E_R(p, q)$ is the digitized reference wave and $H(p, q)$ is the digitized recorded intensity in hologram plane i.e. digital hologram. ΔX and ΔY are the pixel size of the CCD sensor (i.e. hologram plane) and ΔX_I and ΔY_I are the pixel sizes in the reconstructed image, relate as $\Delta X_I = \frac{\lambda d}{M\Delta X}$; $\Delta Y_I = \frac{\lambda d}{N\Delta Y}$;

In this paper, lensless Fourier transform (LLFT) configuration of digital holography is used, in which object (micro flame) and point source of spherical reference wave are kept in the same plane. The advantage of using this configuration is that the spherical phase factor $\exp[-i\frac{\pi}{\lambda d}(p^2\Delta X^2+q^2\Delta Y^2)$ associated with the Fresnel diffraction of the transmitted wave through hologram is eliminated by using of a spherical reference wave $E_R(p, q)$ with the same average curvature that was used during the recording

$$E_R(p,q) = (const.)\exp\left[i\frac{\pi}{\lambda d}\left(p^2\Delta X^2+q^2\Delta Y^2\right)\right] \quad (2)$$

Substituting Eq. (2) into Eq. (1) results in a simpler algorithm for LLFT configuration of DHI [37]

$$O(m\Delta X_I, n\Delta Y_I) = \frac{i}{\lambda d}\exp\left(-i\frac{2\pi}{\lambda}d\right)\exp\left[-i\pi\lambda d\left(\frac{m^2}{M^2\Delta X^2}+\frac{n^2}{N^2\Delta Y^2}\right)\right] \times FFT\{H(p,q)\} \quad (3)$$

Thus, LLFTDH involves only one Fourier transform of recorded digital hologram $H(p, q)$ apart from some multiplicative constant. Hence this method is faster as compared to other reconstruction methods like Fresnel approximation method and convolution method [36] etc., which uses combination of several Fourier transform and complex multiplications. The reconstructed object wave front $O(m\Delta X_I, n\Delta Y_I)$ represented by Eq. (3) is an array of complex function, and hence, both the intensity '$I(m\Delta X_I, n\Delta Y_I)$' as well as the phase distribution '$\phi(m\Delta X_I, n\Delta Y_I)$' of object wavefront can be calculated from Eq. (3)

$$I\left(m\Delta X_I, n\Delta Y_I\right) = \left|O\left(m\Delta X_I, n\Delta Y_I\right)\right|^2 = \mathrm{Re}^2\left|O\left(m\Delta X_I, n\Delta Y_I\right)\right| + \mathrm{Im}^2\left|O\left(m\Delta X_I, n\Delta Y_I\right)\right| \quad (4)$$

and

$$\phi(m\Delta X_I, n\Delta Y_I) = \arctan\frac{\mathrm{Im}[O(m\Delta X_I, n\Delta Y_I)]}{\mathrm{Re}[O(m\Delta X_I, n\Delta Y_I)]} \quad (5)$$

where the operators 'Re' and 'Im' denote real and imaginary part of a complex functions respectively.

To implement DHI, for the measurement of temperature and temperature profile of micro flame, first a digital hologram H_1 *(p, q)* is recorded in the absence of micro flame. It is used as a reference hologram. This hologram corresponds to ambient state of air. Second hologram H_2 *(p, q)* is recorded in the presence of micro flame. When laser light is pass through the micro flame, the phase of the object wave front changes due to the variation in the temperature/refractive index inside the micro flame. The phase distribution of object wavefronts $\phi_1(m\Delta X_I, n\Delta Y_I)$ due to the reference hologram and $\phi_2(m\Delta X_I, n\Delta Y_I)$ in the presence of micro flame, can be numerically reconstructed from digital holograms H_1 *(p, q)* and $H_2(p, q)$ by using Eq. (5). Phase of the reconstructed object wave fronts $\phi(m\Delta X_I, n\Delta Y_I)$ as given by Eq. (5) remains wrapped in the range $(-\pi, +\pi)$ radian corresponding to the principle value of the 'arctan' function. The interference phase, which is the phase difference in the absence and with the presence of micro flame, is calculated directly by modulo 2π subtraction as [36]

$$\Delta\phi\left(m\Delta X_I, n\Delta Y_I\right) = \begin{cases} \phi_1\left(m\Delta X_I, n\Delta Y_I\right) - \phi_2\left(m\Delta X_I, n\Delta Y_I\right) \\ \quad if\ \phi_1\left(m\Delta X_I, n\Delta Y_I\right) \geq \phi_2\left(m\Delta X_I, n\Delta Y_I\right) \\ \phi_1\left(m\Delta X_I, n\Delta Y_I\right) - \phi_2\left(m\Delta X_I, n\Delta Y_I\right) + 2\pi \\ \quad if\ \phi_1\left(m\Delta X_I, n\Delta Y_I\right) < \phi_2\left(m\Delta X_I, n\Delta Y_I\right) \end{cases} \quad (6)$$

This phase difference is continuous between the 0 and 2π, this 2π phase discontinuity is removed by Goldstein phase unwrapping method [38]. This unwrapped phase difference distribution is used to calculate the refractive index distribution inside the micro flame. The phase change $\Delta\phi(X)$ along a line at distance x from axis of symmetry of micro flame is given as

$$\Delta\phi(X) = \phi_2(X) - \phi_1(X) = \frac{2\pi}{\lambda}\int_0^L [n_r(r) - n_0(r)]dZ \quad (7)$$