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Effect of magnetic field on temperature profile and flame flow characteristics of micro flame using Talbot interferometer

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ABSTRACT

In this paper an application of circular grating Talbot interferometer is investigated for measurement of temperature and temperature profile of micro flame under the influence of gradient and uniform magnetic field. Hilbert transform is used for phase extraction from a single Talbot interferometric fringe pattern. In addition to this a numerical study is undertaken to established the effect of magnetic field on flame flow characteristics such as flame length, fuel mass flow rate, magnetic susceptibility and mass fractions of oxygen which is the main oxidizer and products of combustion in candle flame is demonstrated. Experimental investigation reveals that the temperature of the flame is increased under the influence of the upward-decreasing magnetic field and decreased in upward-increasing magnetic field. In a uniform magnetic field the flame temperature is also increased, which is in contrast to the normal diffusion (large size) flame. The system is cost effective, easy to align, less prone to environmental perturbation and capable of measuring temperature of a large size (centimeter) flame to micro size (millimeter) flame.

1. Introduction

An understanding of combustion characteristics of micro flame is required for developing the micro flame based combustion systems. Micro flames are used in micro devices such as microsatellite and micro aerial vehicles etc. These flames are also useful for investigating the structure of diffusion-control combustion phenomena. Physically micro-flame is a flame having the size of several millimeter (approx. 2–3 mm) [1,2]. The small size and large surface area to volume ratio of micro flame results in considerable amount of heat loss to the environmental or to the combustion systems. Combustion is very well understood and developed for numerous applications. But its application to micro scale system is limited as micro scale combustion is difficult to sustain. The unsustainability of micro flame is due to the heat loss caused, because of large surface area to volume ratio and absence of buoyancy controlled flow [3–6]. The loss of heat can be reduced by optimizing the size of micro flame without compromising the heat generated by the combustion process. The electric and magnetic field can be used as an external force to induced buoyancy controlled flow [7]. Thermocouples and interferometric methods have been widely used to measure the temperature in gaseous flame [8–17] but most of the investigations carried out on micro flame are theoretical [18–22]. The measurement of temperature by thermocouple in micro flame is not suitable as it is likely to disturb the flame and quenching of flame. Interferometric methods are not expected to disturb the flow, therefore will not destabilized/disturb the flame.

Many experiments have been conducted for investigating the effect of magnetic field on gaseous flame by using different measurement methods [23–33]. Mainly these research papers are based on the action of magnetic gradient on macro size (centimeter) diffusion flames, premixed flames, catalysis and emission intensity of radicals. S. Swaminathan [34] has studied the effect of gradient

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magnetic field on the temperature of micro flame using thermocouple (flame size ~ 10 mm). However in her thesis no investigation exists for the effect of uniform magnetic field on micro flame. Digital speckle pattern interferometry (DSPI) and digital holographic interferometry (DHI) has been also recently investigated for the measurement of temperature of micro flame under the influence of magnetic field [35,36].

In this paper an application of circular grating Talbot interferometer for the measurement of temperature and temperature profile of a wick stabilized micro flame under the influence of gradient and uniform magnetic field is presented. Circular grating Talbot interferometer is easy to align, robust, non-invasive, common path, temperature measurement technique which is having less sensitivity to vibration and environmental perturbation in comparison to DSPI and DHI [35,36].

2. Theory

Talbot interferometer consists of a pair of identical gratings where, the first grating is illuminated by collimated beam and the second grating is placed at one of the self-image plane of first grating. When an object (micro flame) is placed between these two gratings, the self-image of first grating is distorted and Talbot interferometric fringes are formed [37]. The intensity distribution of Talbot interferometric fringe pattern is given as

$$I\,(x) = A\,(x) + B\cos\left(\frac{2\pi mx}{a} + \varphi\,(x)\right) \tag{1}$$

where $A(x)$ is the background intensity distribution, B is a constant, m is the grating order, a is the period of grating and ϕ is the phase change. Eq. (1) manifest that the interference fringes in Talbot interferometer contain the phase information.

The non-uniform refractive index distribution inside the micro flame due to variation in density, temperature and pressure, results in change in direction of propagation of the light wave and hence, the phase change is observed. The phase from Talbot interferometric fringes is extracted by Hilbert transform.

2.1. Phase extraction by using Hilbert transform

Hilbert transform is easier and simple method for retrieving the phase information from a single interferogram [38,39]. The background intensity or DC term must be eliminated prior to the application of Hilbert transform to make the signal analytic. The Hilbert transform (HT) of the filtered image is performed to get the complex analytical signal associated with the real function of Eq. (1).

The complex analytic signal associated with the real function $u(x) = B\cos\left(\frac{2\pi mx}{a} + \varphi\,(x)\right)$ is given as

$$z(\mathrm{x}) = \frac{1}{2}[u(x) + i\,HT\{u(x)\}] \tag{2}$$

The phase ϕ associated with complex analytic signal $z(x)$ is given as

$$\varphi(x) = \arctan\left\{\frac{\mathrm{Im}\,[z\,(x)]}{\mathrm{Re}\,[z\,(x)]}\right\} = \arctan\left(\frac{HT\,\{u(x)\}}{u(x)}\right) \tag{3}$$

In Eq. (2), $z(x)$ exhibits the rapid phase modulation, thus $\phi(x)$ is strongly wrapped, which is continuous between 0 and 2π. This 2π phase discontinuity is removed by using the Goldstein phase unwrapping algorithm [40].

2.2. Refractive index and temperature measurement

This unwrapped phase is used to calculate the refractive index change. The phase depends upon the refractive index inside the flame and the relation between them is given by [41]

$$\varphi(x) = \frac{2\pi}{\lambda}\int_0^l \Delta n\,(r)\,dz \tag{4}$$

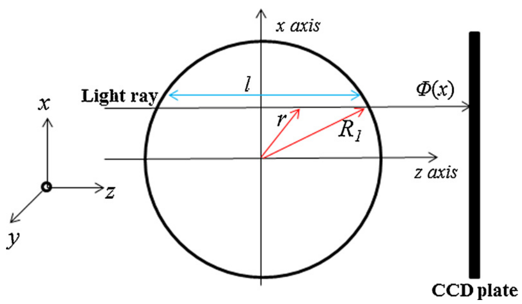

Fig. 1. Cross section of axi-symmetric temperature field.