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APPLICATION OF ARC-LAMP BASED TLAF TECHNIQUE TO TEMPERATURE MESUREMENT IN A LAMINAR CH₄/AIR DIFFUSION FLAME

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ABSTRACT

An arc-lamp based two-line atomic fluorescence (TLAF) temperature measurement system has been designed, built, calibrated and applied to a methane/air co-flow laminar diffusion flame. Instead of the costly dye lasers that are widely used, a Xenon arc-lamp system was introduced to provide excitation illumination for generating the Stokes and anti-Stokes fluorescence signal for Indium atoms. The weak fluorescence signals were successfully quantitatively detected from strong background soot radiation of the flame using a photomultiplier coupled to a lock-in amplifier. The signal was modulated by employing a high-frequency chopper in the arc source excitation beam. A flow-through technique was successfully applied to introduce seeding fluorescence material, TMIn (Trimethylindium), into the fuel flow at a low flow rate, where conventional nebulizers work poorly. It is shown that the system is economical and simple but robust and reliable as a non-intrusive flame temperature measurement apparatus.

INTRODUCTION

Non-intrusive temperature diagnostics of laboratory flames are of great importance to our understanding on the nature of the combustion phenomenon. Various optical techniques, such as Rayleigh and Raman scattering, line-reversal, two-line atomic emission, two-line atomic absorption, two-line atomic fluorescence (TLAF), have been practiced in the last several decades.

TLAF thermometry technique has been widely applied to the temperature measurement in both laboratory flames and industrial combustion systems [1-6]. In this technique, suitable metal atoms [7, 8] are introduced to the combustion region, and bombarded with photons at a wavelength corresponding to the energy difference between one of their accessible excitation states and the next quantum level. Stokes or Anti-Stokes fluorescence will be induced. Fig.1 shows the typical procedures of TLAF for indium atoms. In this figure, λ_{12} and λ_{02} are the central wavelengths of the absorption transitions (as well as the wavelengths of fluorescence), I_{12} and I_{02} the corresponding excitation irradiances at these two wavelengths, and F_{21} and F_{20} the corresponding induced fluorescence intensities. With the assumption of local thermodynamic equilibrium in the flame, the temperature can be determined by comparing the intensity of the two fluorescence intensities [7]:

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$$T_f = \frac{5040V_1}{\log\left(\dfrac{F_{21}}{F_{20}}\right) + \log\left(\dfrac{I_{12}}{I_{02}}\right) + 6\log\left(\dfrac{\lambda_{12}}{\lambda_{02}}\right)} \tag{1}$$

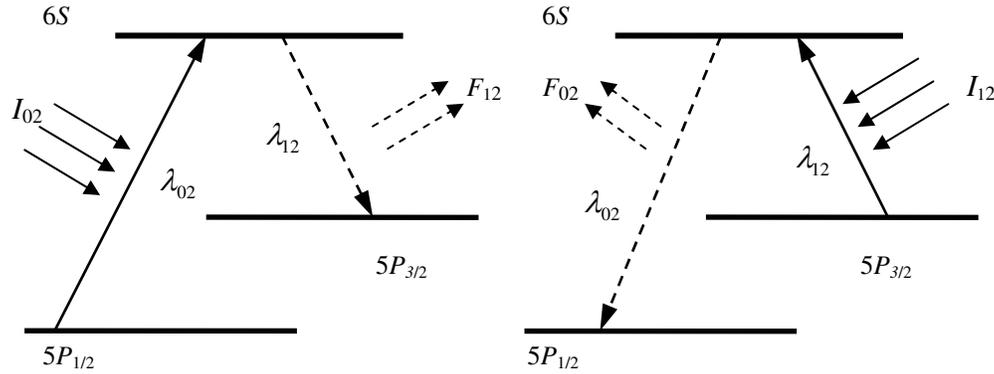where V_1 is the energy difference between the two lower states in eV.

Fig. 1, The absorption and release of photons from an indium atom

Currently, applications of TLAF are primarily made in premixed combustion phenomenon. To our best knowledge, this technique has not been applied to diffusion flames. Generally, premixed flames look transparent hence the fluorescence could be easily identified, while diffusion flames are much more luminous due to the continuous radiation from soot. The main difficulties for the application of this technique to diffusion flame lie in the quantitatively identification and extraction of the weak fluorescence signal from the strong background soot emission.

Indium (In) is one of the most popular metallic seeding atoms in the area of temperature determination in combustion circumstances using TLAF [4-7,9]. Indium was proved to operate well though a temperature range of 700-2600K [7]. Additionally, the fluorescence and absorption wavelengths for indium are within the visible spectrum ($\lambda_{02} = 410$ nm and $\lambda_{12} = 450$ nm), for which most optical equipments are designed. To introduce the metallic additives into the flame, previous experiments [5,7,9,10] utilized an aqueous solution of the metal, such as indium chloride ($InCl_3$), which was introduced into the fuel stream via a pneumatic nebulizer. We have found from experiments that nebulizers operate with the flow rates of between 500-1000 ml/min, which is much higher than the typical fuel flow rate of an ethylene/air or methane/air laminar diffusion flame researched in National Research Council. In-Touch Vaporization (ITV) may be another alternative method for seeding the fuel stream with the fluorescence material. In this method, metal indium is vaporized and introduced to the fuel flow directly. However, it will require a great deal of customization and optimization if employed in our experiment system. Hence, new seeding techniques have to be introduced while TLAF technique being applied to diffusion flames.

On the other hand, recently, LIF (laser induced fluorescence) technique has become very popular in the area of TLAF thermometry technique [4-6,8]. Powerful dye laser has been widely applied as the illumination source due to its high energy density and easy-control on the wavelengths.

However, the accurate calibration for the laser is practically difficult, or has relatively poor repeatability compared to the light source that has a continuous radiation spectrum. The high price of laser equipments is also another disadvantage.

In this paper, an arc-lamp based TLAF technique has been successfully built and applied to local temperature diagnostic within a laminar diffusion flame. Compared to dye lasers, an arc-lamp has relatively stable output, which is much easier for out-put calibration and at lower cost. New flow-through technique has been applied to seed indium compounds into the fuel flow under a low flow rate. With the help of chopper coupled lock-in amplifier, weak fluorescence signals have been detected. Temperatures were determined from the fluorescence signals.

EXPERIMENTAL SETUP

The experiment was carried out in an atmospheric pressure, axis-symmetric co-flow laminar CH_4/air diffusion flame. The burner for generating the flame has been previously described in detail [11, 12]. In brief, the burner consists of a central fuel tube with a 10.9 mm inner diameter surrounded by an annular air nozzle of 100 mm in diameter. The fuel flow rate was 293 cm^3/s, and the air flow rate was 4733 cm^3/s at the standard condition. These conditions resulted in a visible flame height of about 44 mm. The entire burner system was mounted on an adjustable plat-form to allow adjustment of the flames position in 3 dimensions.

The seeding material used in this research is Trimethylindiuim (TMIn, $In(CH_3)_3$), which is a type of metal organic compound generally used for Metal Organic Vapor Phase Epitaxy (MOVPE) processes. It has relatively high vapor pressure and will be sublimated and carried with the fuel gas flowing through it. In this research, the fuel, methane, was flowing through a bubbler that contains TMIn to introduce indium atoms into the flame, as shown in Fig.2.
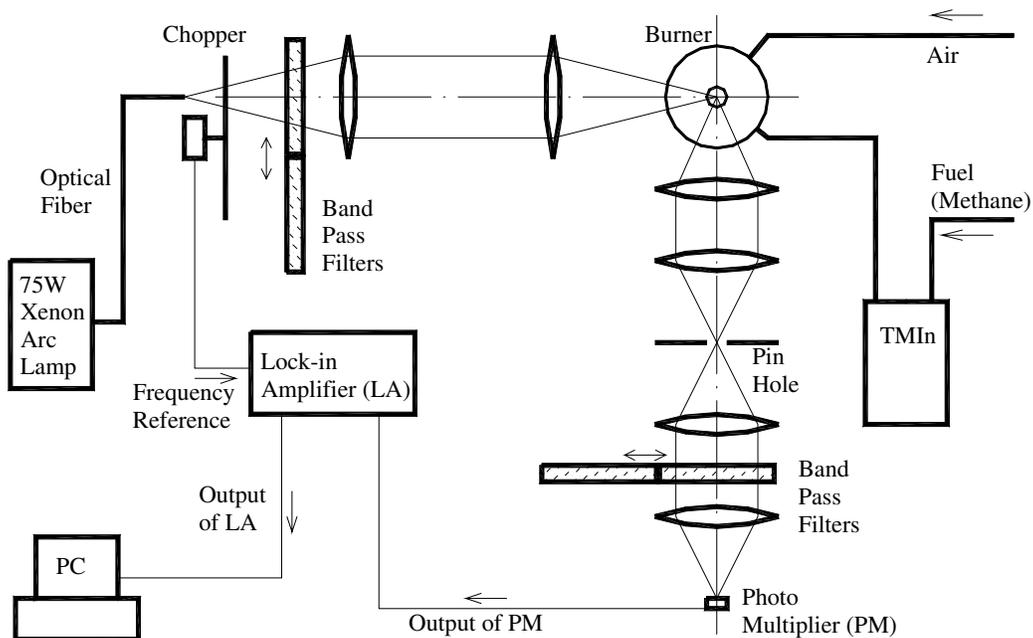

Fig. 2, The Experimental Set-up of the Arc-lamp based TLAF system

The TLAF thermometry system is shown in Fig.2. A 75W Xenon arc lamp (Oriel Inc.) is applied to obtain the excitation light. The excitation wavelengths at 410nm and 451nm were obtained using two band pass interference filters respectively. The filters were held with a laboratory-constructed filter-switch with which appropriate filter could be selected. A similar switch is also applied for the fluorescence receiving optical path. The emitted fluorescence radiation was collected by the photomultiplier and the resulting signal was processed by the lock-in amplifier. The lock-in amplifier and the chopper were working at the frequency of 2370Hz to filter the background soot radiation of the flame. The system was calibrated with a standard tungsten lamp.

RESULTS AND DISCUSSION

The fluorescence signals of the two receiving wavelengths have been successfully quantitatively detected, respectively, at a height of 20 mm above the burner exit. It has been found that the fluorescence signal is in the range of $1/10^4$ of the background soot radiation intensity. A typical amplified fluorescence signal was in the range of 10^{-5} V, while the background soot radiation of the flame in the range of 10^{-1}V. With the help of lock-in amplifier coupled with an optical chopper, the strong background soot radiation was successfully filtered. Fig.3(a) shows the fluorescence signal profiles for the two receiving wavelengths, while Fig.3(b) shows the temperature determined from Eq.(1), where r is the radial position, and r_0 the radius of the inner fuel tube of the burner. Both of the fluorescence intensity profiles follow the same tendency of the theoretical temperature profile for this flame. However, the measured temperatures are substantially higher than those reported in the literature in a similar CH_4/air diffusion flame [13].

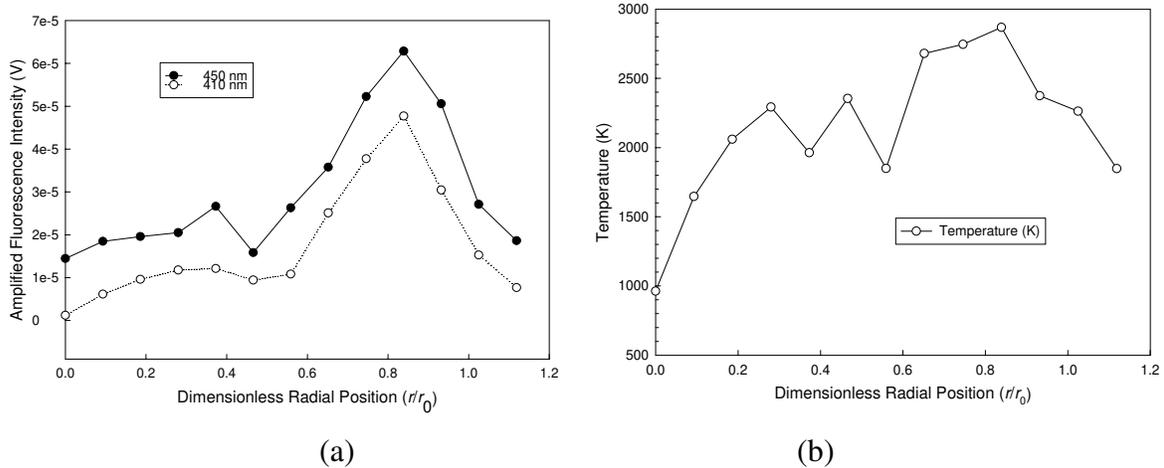(a)   (b)

Fig.3 Fluorescence signal profiles (a) and the calculated temperature profile (b) within the methane/air diffusion flame

Based on Eq.(1), the random error in the calculated temperature strongly depends on the errors in the estimation of fluorescence irradiance ratio:

$$\frac{\delta_{T_f}^2}{T_f^2} = \left(\frac{1}{5040V_1}\right)^2 T_f^2 \left(\frac{\delta F}{F}\right)^2,$$

(2)

where $F = F_{12}/F_{02}$. In this work, the signal/noise (S/N) ratio is relatively low due to the weakness of the fluorescence signal. The random error in fluorescence signals will be dramatically magnified in the calculation of temperature. This could be the main reason for the unexpected high temperatures measured in this study.

This work is the first attempt to apply an arc-lamp based TLAF system to evaluate the temperature profile of a diffusion flame. Although there is still a lot of work to be done to enhance the S/N ratio and reduce the errors in the temperature, the preliminary result is encouraging. Fundamentally, the influence of the introduction of TMIn on flame characteristics needs to be investigated, although the quantity of the indium addictive was believed to be quite small. The fluorescence signal, although quantitatively detectable, is still very weak and with relatively poor S/N ratio, especially at the edge region of the flame. This will lead to tremendous error in the derived temperature in this region.

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