Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 11 (9): 1658-1662, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.1658.1662

Gas Flame Temperature Measurement Using Background Oriented Schlieren

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Abstract: In this study, Background-Oriented Schlieren (BOS) technique is employed to measure the temperature field of a methane flame. High speed camera and a wavelet noise background are used to achieve strong spatial and temporal resolution. The basic optical flow algorithm is modified to account for the intensity variation. This is because the flame flow creates a considerable intensity variation between the pair of images under correlation. Principles of geometric optics are used in order to get the index of refraction. The density information is recovered by slotting the Gladstone-Dale equation in filtered back projection. The computed temperature field measurements are shown as a function of time. Finally, the measured temperature is compared with probe measurements.

Key words: Background oriented schlieren, flame, methane and optical imaging

INTRODUCTION

Background Oriented Schlieren, which was first reported by Dalziel *et al.* (1998), measures the light deflection caused by density gradients of the understudy flow by recording the distortion of a background image. A high frequency two dimensional rigid plane is usually used as a background.

Two pairs of images of the background are recorded, i.e, one image without the flow and the second image of the background with the flow that is under investigation.

Local changes in the refraction index, due to the existence of the under-study flow field, displace the features of the background pattern image. Various types of optical flow algorithms can be employed to measure the light ray deflection based on the deformation of the background. The index of refraction can be computed once the light deflection angles are known. The direct relationship between the refraction index and density of a fluid under investigation can be exploited to measure the temperature and other thermodynamic parameters of the under-study flow.

Preliminary studies on BOS by Raffel *et al.* (2000); Richard and Raffel (2001); Meier (2002) have shown several possible applications of BOS. These include density fields of helicopter-generated vortices and supersonic jets. However, these studies are predominantly qualitative in nature.

Venkatakrishnan and Meier (2004) had made a density measurement for Mach 2 cylindrical cone airflow. Several researchers (Raffel *et al.*, 2000; Richard and Raffel, 2001; Meier, 2002; Venkatakrishnan and Meier, 2004; Elsinga *et al.*, 2004; Vasudeva *et al.*, 2005; Kindler *et al.*, 2007) used cross-correlation algorithm to calculate the displacement vector field which was further employed to generate refractive index field using Poisson equation. Inverse tomographic algorithms had been implemented (Venkatakrishnan and Meier, 2004; Kindler *et al.*, 2007; Goldhahn and Seume, 2007), which can extract two dimensional slices of index of refraction from three dimensional flow.

This study proposes to extract the spatial and temporal variation of temperature field for an open flame. The deflection vectors were computed based on optical flow equation which accommodates scenes where the flow medium absorbs or emits light. In order to find the temperature distribution of the methane flame, the species created due to the combustion reaction were calculated using CANTERA (http://www.cantera.org/). These species concentration information and the calculated index of refraction were used to find out the flame temperature distribution.

BACKGROUND ORIENTED SCHLIEREN (BOS)

The BOS system is used to measure the index of refraction gradients of a medium, resulting from the light ray refraction and deflection due to localized heating

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or composition gradients in a gas. BOS employs computer generated random dot pattern placed behind the flow media. The density field under study is placed in between the camera and the dot pattern. Two different types of the dot pattern images are taken; one with the presence of density field in between the camera and the dot pattern while the other one without density effects. The displacements of the dots are calculated using image correlation algorithms.

The deflection vector can be easily converted into angular deflection in accordance with the relative positions between apparatuses in BOS setup and focal length of the camera lens. By taking paraxial approximation into account, Equation (1) shows the integration of geometrical optics ray equation (Settles, 2001).

$$\begin{aligned} \varepsilon_x(x,y) &= \int_1 \frac{1}{n}\frac{\partial n(x,y)}{\partial x}dz \\ \varepsilon_y(x,y) &= \int_1 \frac{1}{n}\frac{\partial n(x,y)}{\partial y}dz \end{aligned} \tag{1}$$

where, ε is the light deflection angles in X,Y directions and n index of refraction.

Based on Gladstone dale equation, there is a linear relationship between the field density and index of refraction, given as:

$$n-1=G(\lambda)\rho \tag{2}$$

where, G (λ) Gladstone-Dale constant and ρ density of the test field

EXPERIMENTAL SETUP

The experimental setup comprises of the LABOGAZ 206 gas flame delivery system and the Background Oriented Schlieren setups.

For optical measurements, the BOS setup consists of a wavelet noise generated background pattern, optical lenses, Xenon stroboscope light, Photron Fastcam-x 1280 PCL high speed camera with Nikkor optical lens of 60 mm focal length and Fastcam Control software. A wavelet noise developed by Cook and DeRose (2005) is generated and printed on transparency using laser jet printer.

Table 1: Optical measurements setup

BOS setup distances (mm)	Camera setup	
Focal length (60)	Max. frame rate	16000 frame/sec
Distance between (1300) background and center of the nozzle	Min. shutter speed	1/1000 sec
Distance between (70) nozzle center and camera lens	Max. spatial resolution	1280×1024

BOS IMAGE PROCESSING

The displacement vectors of the background pattern can be computed using PIV like window based interrogation technique or other optical flow algorithms. The former practice is the most widely used technique in BOS experiments. The optical flow algorithms use local derivatives to approximate the image motion of optical interest. In our case, it is the displacement of the background feature. Optical flow assumes that all the temporal intensity change between two images is due to the flow motion only. Recent studies have shown arguing that the gradient based optical flow algorithms suit BOS technique best (Atcheson *et al*., 2008). Both of the above techniques don't consider change in intensity due to the flow field. Since an image intensity is the convolution of the object function (O) and transfer function (T):

$$I=O*T$$

It is obvious that the change in transfer medium affects the background image intensity. The flow media which is being investigated in this study is a flame, which has a distinctive behavior of emitting light, makes the fundamental assumption of intensity constancy principle inapplicable. To alleviate this problem, an intensity variation constant term was added to the original optical flow equation. Filtered back projection tomography was used to reconstruct two dimensional index of refraction information. Once the index of refraction is obtained, the density field can be computed by Gladstone-Dale equation of gas mixtures.

Light beam deflection measurement: The original optical flow estimation can be stated as (Barron *et al*., 1994):

$$I_t(x,y,t)=I_{t+1}(x+\Delta x,y+\Delta y,t+\Delta t) \tag{3}$$

Δt is taken to be unity for ease of calculation, Eq. 3 is the optical flow differential equation which assumes object tends to maintain their intensity values.

BOS literatures show most of the deflection vector computing techniques are either a region based (PIV like) optical flow algorithms or techniques which use first order differential techniques. Both techniques assume pixel intensity constancy. But this assumption only works when there is no change in illumination, camera lens distortion and many other factors that affect the assumed image intensity invariance.

To account for the intensity variation, the back ground intensity of I (x, y, z) was multiplied by a certain constant K and compared with the image intensity taken through the flow, which is I ($x+\delta x$, $y+\delta y$, $t+\delta t$) (Iffa *et al*., 2010).

The 3 unknowns, namely δx, δy and K, were solved using Lucas-Kande first order differential estimation. (Lucas and Kanade, 1981).

The displacement vectors were converted into angle of deflections based on the relative position of background pattern, camera lens and concentration field location within the BOS Set-up.

Once the angles of deflections are obtained, the index of refraction can be obtained by inverting the geometric ray equation (Eq. 1). The density data can be computed using Gladstone dale equation (Eq. 2).

Data extraction: The temperature measurements of the flow field can be obtained by utilizing ideal gas equation and Gladstone-Dale equation for gas mixtures (Settles, 2001) as:

$$n-1=\sum_i G(\lambda)_i \rho_i \tag{4}$$

where, i is the species type generated during flame combustion. The temperature and new species created by the chemical reaction of the fuel and the oxidant was calculated using CANTERA [http://www.cantera.org/]. The Gladstone-Dale constant (G (λ_i), real gas constant (R) and species molecular weight M_i can be found from data books. Based on these given information the index of refraction was calculated using Eq . 5. The calculated index of refraction values were compared with the index of refraction (n) which was computed using Eq. 1. Once the index of refraction values matching by the two methods are done, the respective temperature values are obtained.

$$n-1=\frac{P}{RT}\sum_i G(\lambda)_i X_i M_i \tag{5}$$

where, X_i is species mole fraction M_i is species molecular weight.

RESULTS AND DISCUSSION

The flame imaging was conducted using three techniques namely: direct visualization, schlieren imaging and BOS. An image taken by direct imaging in Fig. 1 helps for qualitative visualization and for measuring macro spray/flame parameters like flame area and flame cone angle.

On the other hand, a conventional schlieren image in Fig. 2 tells the density gradients of the gas flow before and after it is ignited.

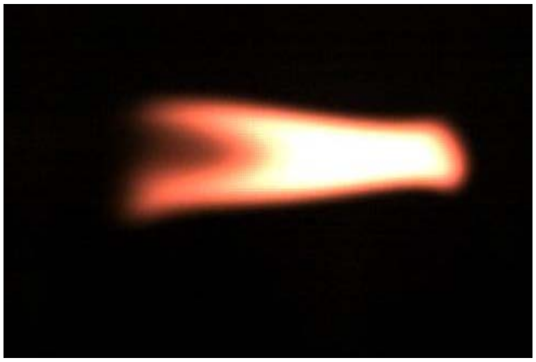

Fig. 1: Direct flame visualization

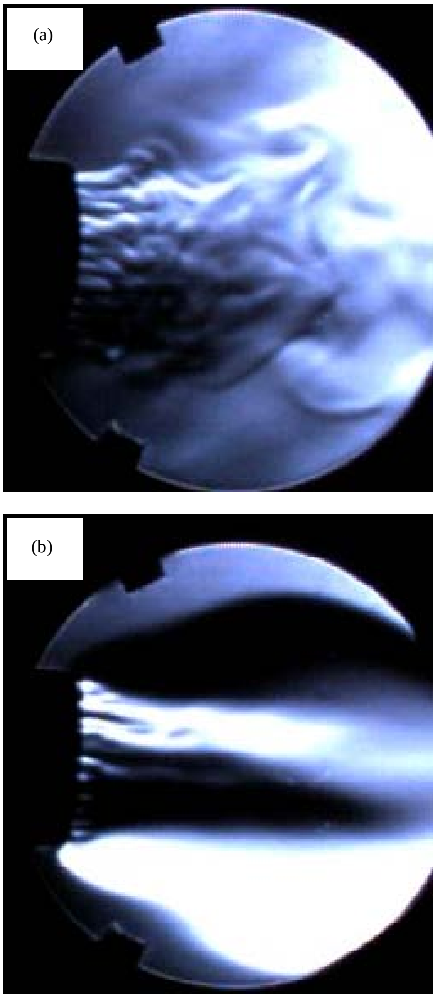

Fig. 2: (a)-The gas flow schlieren image before ignition (b)-the flame schlieren image after ignition

In order to measure temperature of the flame, we used BOS technique to measure the deflection vector of the wavelet background. Figure 3 shows the background

Fig. 3: The BOS image taken through gas flame media

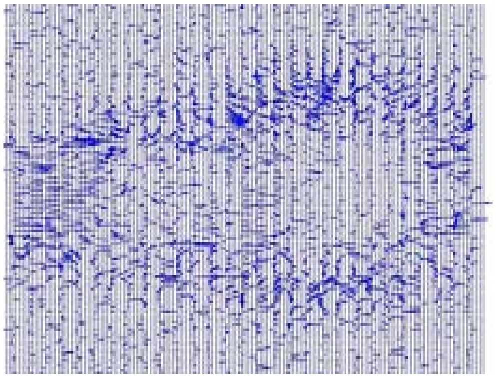

Fig. 4: Displacement vector field

image taken through the gas flame. The background image taken with and without the flame media in between the camera and background are used as image frames to measure the background features displacement. The computed displacement vector field is shown in Fig. 4.

For fast reacting flames, Bilger (1976) noted that some scalars, for example mixture fractions, are uniquely related to major species concentrations in the flame. Based on Bilger's assumption, Agrawal *et al.* (2002) has inferred temperature and species mole from rainbow schlieren measurements of the refractive index difference of pure hydrogen.

The fuel species data generated using CANTERA showed 50 different species due to chemical reaction between the fuel and air, assuming chemical equilibrium. Species with the maximum mole fractions less than 10-5 were removed to adapt a procedure proposed by (Agrawal *et al.*, 2002). This assumption effectively reduces the number of species under consideration to 12. A table that relates the varying specific mole fractions, temperature and the change in index of refraction with 8 digit precision was made based on Eq. 5. Figure 5b and how the temperature distribution along the axi-symmetric axis of the flame.

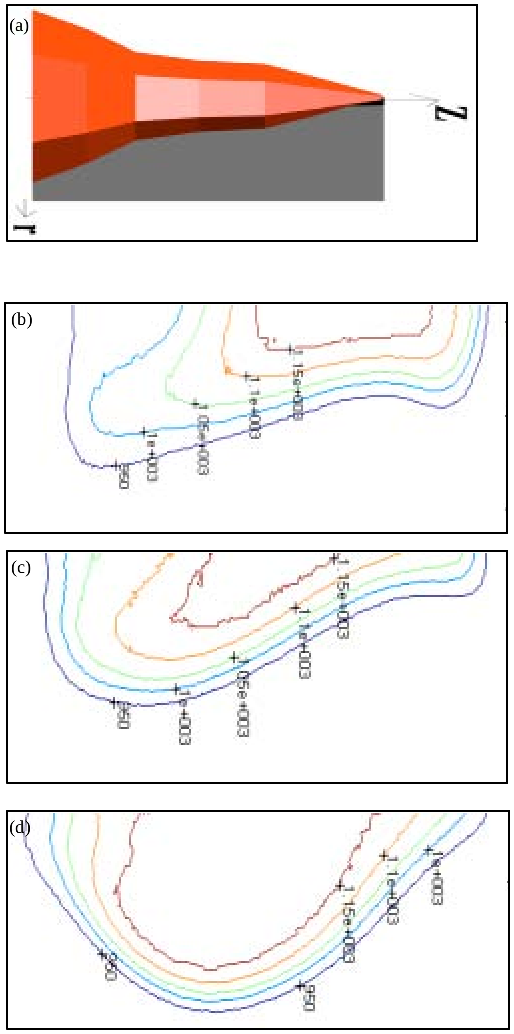

Fig. 5: (a)-Plane used to show temperature distribution. (b-d) Temperature distribution contour plot in steps of 50^0 K in every 30 ms interval

The obtained flame temperature values are compared to Thermocouple measurements that are made in a radial plane at 50 mm from the nozzle at different points. A good agreement is found with BOS measurements. The graph that compares thermocouple with BOS measurements is shown in Fig. 6.

The RMS percentage error between the two measurements is less than one percent (0.78 %).

CONCLUSION

BOS technique is employed to measure the temperature of a natural gas flame. An optical flow model that embraces the intensity variation is developed. The measured temperature values are compared with thermocouple measurements and a high degree of

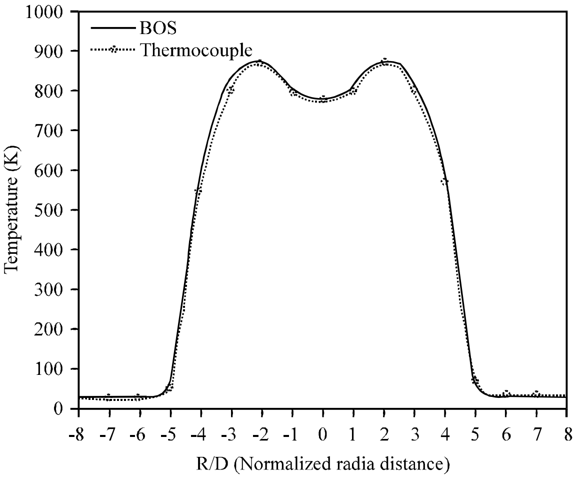

Fig. 6: Mean temperature values on radial plane

correlation is achieved. This result shows the modified optical flow algorithm has helped the BOS to be a high-quality optical technique to measure thermodynamic parameters like temperature.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Department of Mechanical Engineering, Universiti Teknologi Petronas, for providing Laboratory facilities.

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