Quantitative Measurement of Heat Flow in Natural Heat Convection Using Color-Stripe Background Oriented Schlieren (CSBOS) Method

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Abstract

Quantitative image measurement of the flow fields in convective heat transfer is of great importance for the optimum energy consumption problems. In the natural and forced convection phenomena in fluids, the complexity of the flow field prevents us from detailed three-dimensional (3D) experimental analysis in steady/unsteady dynamics of the fluids, which have locally different density values. This paper deals with application of color-stripe background oriented schlieren (CSBOS) and Computed Tomography (CT) method to the quantitative measurement of natural heat convection.

Key words
Background Oriented Schlieren (BOS), Colored-stripe, Natural Convection, Density Gradient, Temperature Gradient

1. Background

The recent development of the Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) technique leads us to the quantitative investigation of flow fields depending on vector velocity field in experimental research. On the other hand the density and temperature distributions have been grasped in only two-dimensions and qualitative image of the flow field was obtained by some classical flow visualization technique such as shadowgraph and color schlieren method. This paper deals with the application of our originally investigated and developed color-stripe background oriented schlieren (CSBOS) technique and Computed Tomography (CT) method, for the 3D quantitative measurement of natural heat convection parameters. By using a lighter flame of natural convection, the deviations of color stripes are measured, integrated density gradient and temperature gradient are estimated quantitatively. This experimental data is applied to reconstruct 3D distribution and natural heat convection parameters.

2. Introduction of BOS Technique

The principal of BOS is similar to the conventional schlieren idea. It utilizes the deviation of light path caused by variation in the refractive index distribution corresponding to the density change in the medium. Both techniques are sensible to density gradient distribution. Historically, for BOS measurement the random dot pattern has been utilized as background image. The pattern change is calculated by image analysis of the cross correlations and comparison of the designated areas between two images, without flow and with flow images [1, 2]. In short, the refractive index or density information is obtained by the image processing technique that has been commonly used in PIV. In our BOS method, color stripes or grids are employed as background. As compared to the PIV-related BOS, the CSBOS needs only one image which includes main flow field. The pattern stripes begin to deviate with the density variation caused by convective flow field. We can give numbering to the stripes and tracing of the stripe deviation due to the density change that can be processed using computer.

Optical setup for BOS technique is shown in Fig.1 The BOS experiment requires only a background image and a digital still camera, which can easily recognize the quantitative measurement of refractive index (density or temperature gradient). If there is a distribution change in refractive index between the background and camera, then stripe pattern will cause to be deviated. These background stripe deviations are captured by a charge-coupled device (CCD) image sensor with displacement Δh, because of the refraction of the light passing through density change, as shown using solid line. A symbol ε indicates deflection angle of light.
The relation between $\Delta h$ and refractive index $n$ is expressed as an Eq.(1) [10], where $L_b$ denotes the distance from background to phase object, $L_c$ the distance from phase object to camera, $f$ the focal length of camera and $n$ is the refractive index. $I$, denotes the integrated value of refractive index gradient. From Eq.(2) [10] density ($\rho$) information can be determined by the relation of $n$ and $G$ (Gladstone-Dale constant). In our study for natural convection phenomena however, the temperature gradient and temperature distribution in the convective flow are important parameters. According to the linear relation of density and temperature in convective phenomena, we have obtained the BOS relation between the deviation of image (background stripes) and temperature gradient as Eq.(3). This relation can be reduced to the simple relation of Eq.(4). Here the single coefficient is expressed in Eq.(5) was named as Zeb’s coefficients, one of the author’s name. These equations have special convenience in the quantitative analysis of convection experimental and 3D CT analyses and have made calculations very simple for the diagnoses of heat convection phenomena. From Eq.(4) local temperature gradient is obtained quantitatively by CT reconstruction and image analysis using ART, where $T$ is absolute temperature. $T_0$ in Eq.(3) and Eq.(5) is the temperature of surrounding air (sink). By using a lighter flame of natural convection, the deviations of color stripes are measured, from which the integrated temperature gradient are estimated quantitatively. This experimental data is applied to CT reconstruction for to obtain 3D temperature distributions.

3. General Introduction of Experiment

In this paper we have applied the CSBOS method to the convectional flow field. As candle and lighter flames are ideal for BOS experiments due to its high amount of heat dissipation and we can get large displacement on CCD camera. In this experiment we took a lighter flame with natural convection in atmospheric air and the obtained deviation of stripes was analyzed by our finite-stripe analysis program using a personal computer (PC). We have
used three sets of digital camera, color stripe background image and flashlight. These sets were arranged 60° apart from each other as in Fig. 2. All three flashlights were connected with one master camera and were controlled instantaneously. The basic aim for this setup is to obtain the images on the same instance simultaneously. As there is a continuous heat flow from the Heat Generating Source (HGS) and it is very important to capture instantaneous images during flow. In our experiment we have succeeded and the BOS image results are satisfactory. Fig.3, Fig.4, and Fig.5 are the observed images by digital camera1, camera2, and camera3 and are respectively indicated. While in Fig.6, Fig.7, and Fig.8 are the numbered stripes. During BOS process first the deviation of stripes is calculated and then interpolated for the remaining number of stripes. These stripes are then numbered. These numbered stripes are interpolated using CSBOS images of camera1, camera2, and camera3, are indicated respectively in Fig.6, Fig.7, and Fig.8. In Fig.9, Fig.10, and Fig.11, the CSBOS processed results, of digital camera1, camera2, and camera3 respectively indicated. Here it is mentioned again that the BOS data in each figure has been obtained from only one image of color stripe background pattern, and reference image is not necessary. Image analysis can be done using only one background image captured during the convective flow. Reconstruction and CT for 3D density-related information in convective flow field just above the heated body from multi directional CSBOS images were also examined and are discussed in detail in the following section.

4. Algebraic Reconstruction Technique (ART)
Our research group has developed our own 3D Laser interferometric computed tomography (LICT) technique and succeeded to elucidate the complex 3D flow field induced by discharging shock wave from several kinds of nozzles [3], [4]. In these studies, a pulsed nitrogen laser and a Mach-Zehnder interferometer were employed for quantitative measurement of density field. 3D density distribution can be reconstructed from projection data with Filtered Backed Projection (FBP), Algebraic Reconstruction Technique (ART) and Maximum Likelihood Expectation Maximization (MLEM). In LICT, projection data for reconstruction have been obtained as the integrated amount of density change with an analysis of finite-fringe interferogram. In schlieren method the integrated value of the density gradient corresponds to the deviation of light path and displacement of the images. Several researches about the significance and importance of ART are available and prove the necessity and accuracy of this technique. A combination of algebraic reconstruction and digital ray tracing appears ideal for imaging lightly refracting objects [5], [6]. A survey of digital ray tracing and ray linking for this purpose is also available [7]. If a refracting object has special symmetries, then it may be possible to reconstruct the object without ray tracing [8]. Combination of algebraic reconstruction with digital ray tracing for the cross-sectional imaging of lightly refracting objects has been determined in 1983 [9].
5. Experimental Results and Discussion
For natural convectional heat flow experiments using CSBOS measurements we have used Eq.(4) to obtain the temperature gradient. In Eq.(5) all values for this experiment are constant and are combined under one simple constant $K_{Zeb}$. This constant is named on one of the author’s names of this paper. Figure 12 shows the sectioned lines at three different sections. This image is processed image of camera3 using BOS image analysis. Similarly we can obtain the results for the remaining two cameras too. In Fig.13, 14, and 15, are the quantitative graphs for vertical displacement of stripes $\Delta h$ (and can be assumed as average displacement of horizontal and vertical directions) at sections $A-A'$, $B-B'$ and $C-C'$ using Eq. (3). Figures 16, 17, and 18, represent the reconstructed ART and 3D CT quantitative images by using ART. Figure 16 is the image of $x-z$ plane and looking into $y$ direction. Figure 17 is the image of $y-z$ plane and looking into $x$ direction. Similarly Fig.18 is image of $x-y$ plane and looking into $z$ direction. Through the number of experimental camera sets are not sufficient, but still we can obtain the 3D reconstructed flow field of convection phenomena. Thus in this way we can obtain different images at different location on the desired axis from the 3D reconstructed data. In this paper, here for discussion we will take only one image on $x-y$ plane. This plane consist the actual heat flow, flowing upward from the HGS. The section of this image, Fig.19, is located at 1140 pixels in $z$ direction. To determine the temperature gradient we have drawn three section lines into three different sections in this image, i.e. $D-D'$, $E-E'$ and $F-F'$ as shown in Fig.19. Similarly various images, in all three axes and at any point located on them, can be obtained and temperature distribution can be discussed using our BOS-CT technique.

In ART 3D reconstructed results as indicated by the color bar, the intensity of temperature gradient is in between 0.031 and -0.046 values. In these results the areas which are red colored consists of the highest amount of heat while yellow colored areas indicate less than red colored areas. The green color areas have amount of heat less than yellow colored areas. While the areas represented by blue colored have the smallest amount of heat. The temperature gradients obtained from these figures are shown quantitatively in graphs. As these images have strong artifacts and the surrounding green parts are presenting the same artifacts but still we believe that we have been able to get real 3D results and are encouraging for future studies.

In Fig.20, 21, and 22, there are the graphs at these sectioned lines $D-D'$, $E-E'$ and $F-F'$ respectively for temperature gradients. Vertical axis indicates temperature gradients in absolute degrees per millimeter while the horizontal axis shows the number of pixels. These graphs are indicating real experimental temperature gradients, which are obtained from 3D calculated data using ART and 3D CT techniques.

6. Conclusions
For natural convectional heat flow experiments, CSBOS (Color Stripes Background Oriented Schlieren) measurement has been employed. Three sets of background color stripe image and camera were employed to clarify the validation of CSBOS technique for the
convection heat flow phenomena. Although only three sets of camera, background image and flash light are not in satisfactory, for real experimental CT and reconstruction techniques, but we have employed this setup just to investigate the result whether this technique is applicable for the heat conduction phenomenon or not. After obtaining the results we conclude:

1. In our BOS measurements the background of horizontal color stripes and finite-fringe analysis technique has been used and from this setup, real 3D temperature gradient information was obtained and presented in quantitative graphs.

2. As only three images at angles 60° apart from each other are used, and the reconstructed 3D field has strong artifact, but we still have been able to measure satisfactory real 3D CT flow field.

3. The quality of resultant reconstructed image can be improved by arranging more sets of background image and camera around the HGS using the BOS and finite-fringe image analysis technique.

4. Images of heat flow in natural convection are possible to be analyzed by using our CSBOS technique.

Nomenclature

- $L_c$: distance between phase object and camera, [m]
- $L_b$: distance between phase object and background, [m]
- $f$: focal length of camera, [m]
- $\rho$: density, kg/m$^3$
- $G$: Glade-stone Dale constant,
- $n$: refractive index
- $T_0$: Temperature of surrounding, [K]
- $K_{Zeb}$: Zeb’s constant, [m/K]
- $\Delta h$: displacement [m]
- $\theta$: deflection angle of light

Subscripts

- $0$: surrounding fluid

References


