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A comparison of three quantitative schlieren techniques

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ABSTRACT

We compare the results of three quantitative schlieren techniques applied to the measurement and visualization of a two-dimensional laminar free-convection boundary layer. The techniques applied are Schardin's "calibrated" schlieren technique, in which a weak lens in the field-of-view provides a calibration of light deflection angle to facilitate quantitative measurements, "rainbow schlieren", in which the magnitude of schlieren deflection is coded by hue in the image, and "background-oriented schlieren" (BOS), in which quantitative schlieren-like results are had from measuring the distortion of a background pattern using digital-image-correlation software. In each case computers and software are applied to process the data, thus streamlining and modernizing the quantitative application of schlieren optics. (BOS, in particular, is only possible with digital-image-correlation software.) Very good results are had with the lens-calibrated standard schlieren method in the flow tested here. BOS likewise produces good results and requires less expensive apparatus than the other methods, but lacks the simplification of parallel light that they feature. Rainbow schlieren suffers some unique drawbacks, including the production of the required rainbow cutoff filter, and provides little significant benefit over the calibrated schlieren technique.

1. Introduction

Quantitative schlieren techniques are those intended to measure refractive-index-distributions and related quantities in transparent media [1]. Since the schlieren effect is due to refraction, it was suggested in the 1930s by Schmidt [2] and Schardin [3,4] that it be used to measure refraction, from which density and temperature are readily extracted in simple fluid flows. Since that time many different quantitative schlieren methods have been published.

Quantitative schlieren was, however, somewhat ahead of its time in that pre-computer era. Since schlieren results required densitometry and integration by hand, the more-direct interferometry approach was preferred. Computers can now, however, conveniently manage all data handling and processing chores for quantitative schlieren (and interferometry). The overall result is that journal publications on quantitative schlieren rose steadily from a handful in the 1940s to more than 70 during 2000–2010: not a widely used scientific tool, but also not a negligible one.

Given the many quantitative schlieren methods proposed in the literature, potential users need to know relative performance metrics in order to choose which method to use. Studies that apply several such methods to the same flow are very useful for this purpose, but are rare. There has been one such study published in the past decade: Elsinga et al. [5]. These authors did an elaborate comparison of a quantitative color schlieren method with background-oriented schlieren (BOS) for the investigation of density fields in a supersonic wind tunnel. Both methods produced results within about 2% of the known theoretical curves, but BOS suffered in this comparison due to limited spatial resolution because the wind-tunnel test section was not sharply focused. We believe further comparison is warranted, especially between traditional schlieren methods and the new non-traditional BOS technique.

The BOS technique was introduced almost simultaneously by Meier [6] and by Dalziel et al. who called it "synthetic schlieren" [7]. A better name for it would be "synthetic background-distortion schlieren," but the BOS acronym has now firmly taken hold. In its simplest form it consists merely of a randomly speckled background and a camera. High-resolution images are made of the background by the camera with and without refractive disturbances between the two. Post-processing of image pairs using software then reveals small distortions of the background due to refraction, from which schlieren-like images can be derived.

These authors, however, were not the first to discover the background-distortion effect of transparent refractive media, which was published by Hooke [8] and more recently by Schardin [4], who established this as a rudimentary schlieren technique. Neither the camera nor the background is essentially new in BOS, but the addition of digital cameras and image processing makes this a new and valuable flow visualization technique [9–18].

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The prolific Schardin [4] also first described the quantitative use of color in schlieren imaging, including the use of a prism near the light source to produce spectrum colors and later the replacement of the knife-edge by a lattice filter (*Gitterblende*) composed of transparent color bands and opaque bars. The quantitative use of these techniques provided schlieren images in color, where the various colors identified the magnitudes of the light refraction. However, many applications of these techniques remained qualitative due to the workload involved in handling and integrating the experimental data.

Howes [19,20] introduced the term "rainbow schlieren" to describe color schlieren images created by replacing the knife-edge with a color transparency having a continuous spectrum rather than discrete bands as used by Schardin. Greenburg et al. [21] built upon this to pioneer the digitization of the rainbow-schlieren image and the use of digital colorimetry to automatically extract quantitative refraction data from it. This trend toward computer-automated data acquisition and reduction was later taken up by Agrawal et al. who published prolifically on quantitative rainbow-schlieren imaging in planar and axisymmetric flows, unsteady flows, and combustion experiments, e.g. [15,22–29]. Rainbow schlieren has become the leader of quantitative schlieren methods in the literature today because it is simple, robust, useful, well-developed, and highly automated.

The third method of interest is photometric quantification of the gray scale in an ordinary schlieren image. This has also been done before on a number of occasions [1], but we revisit it here for its simplicity and ease of use. This technique is quantified here using a weak positive lens in the schlieren image as a "calibration Schliere," as suggested by Schardin [3,4]. Though it has seen limited use, this approach to quantitative schlieren measurements has some important advantages including simplicity: typically no modifications are required to an existing schlieren optical system.

In order to compare these three quantitative optical approaches the simple refractive two-dimensional steady flowfield of the free-convection laminar boundary layer on a heated vertical flat plate is used, as was done in [30], where a grid-cutoff schlieren method (focal filament) has been employed. This classical heat transfer test case avoids problems of glass windows and wind-tunnel vibration that have clouded other quantitative schlieren studies. Further, the theoretical temperature profile of the boundary layer is well-known [31].

2. Background

2.1. Laminar free-convection flat plate boundary layer

The laminar free-convection flat plate boundary layer was solved theoretically by Ostrach using a similarity solution to relate the non-dimensional temperature and velocity profiles to a length parameter η [31]. The similarity parameter η combines the distance from the plate leading edge, x, and the perpendicular distance from the plate surface, y:

$$\eta = \left(\frac{Gr_x}{4}\right)^{1/4} \frac{y}{x} \tag{1}$$

Where the Grashof number, Gr, at a distance x from the leading edge of a flat plate is defined as

$$Gr = \frac{g\beta(T_p - T_\infty)x^3}{\nu^2} \tag{2}$$

In which g is the gravitational acceleration, T_p is the plate surface temperature, T_∞ is the free-stream air temperature, ν is the free-stream air kinematic viscosity, and β is the coefficient of thermal expansion.

The boundary layer temperature distribution, T, is given by the function H:

$$H(\eta) = \frac{T - T_\infty}{T_p - T_\infty} \tag{3}$$

This similarity solution is solved numerically and tabulated by Ostrach for varying Prandtl number, Pr [31], which is used here with $Pr=0.72$ to define a theoretical temperature distribution around the flat plate in air. The flat plate used here has dimensions of $0.152 \times 0.013 \times 0.152$ m, measured in the x (length along plate in gravity direction), y (width across schlieren light beam), and z (length along optical axis) directions, respectively. The plate was heated electrically by a resistive heater on the side opposite the measurement face. The plate was heated until it reached steady state, determined when its surface temperature did not change for 10 min. The surface temperature at multiple locations on the plate was measured using a thermocouple, and was found to vary a maximum of ± 1 K. The steady-state plate surface temperature was $T_p=333.0$ K with $T_\infty = 293.7$ K.

2.2. Light refraction principles

Light rays passing through a transparent medium of varying refractive index are bent based on the spatial refractive-index gradients [1]. Fig. 1 schematically shows a light ray being refracted due to the hot thermal boundary layer surrounding a flat plate of length Z. A light ray, traveling in the z-direction, is refracted through an angle ε_y due to the refractive-index gradient in the y-direction. For a two-dimensional schliere of extent Z this is

$$\varepsilon_y = \frac{1}{n}\int \frac{\partial n}{\partial y}\partial z = \frac{Z}{n_\infty}\frac{\partial n}{\partial y} \tag{4}$$

The refractive index, n, of a gas is related to the density of the gas, ρ, through the Gladstone–Dale relation [1], which is used here with the Gladstone–Dale constant for air, $\kappa = 2.23 \times 10^{-4}$ m^3/kg:

$$n = \kappa\rho + 1 \tag{5}$$

The density-gradient field within a gas can thus be directly quantified by measuring the refractive-index gradient field, which is obtained through each of the three experimental techniques presented here. The refractive-index gradients are "calibrated" here through the use of a weak simple positive lens as shown by Schardin [4] (other calibration objects are also presented by Schardin).

2.3. Calibration lens

A simple positive lens, with incoming parallel light, will focus all of the light rays to a point, as shown schematically in Fig. 2. Each light ray that passes through the lens at a different radial location r will be refracted through a different angle, from zero at the center of the lens to a maximum refraction angle ε_R at the radius of the lens, R.

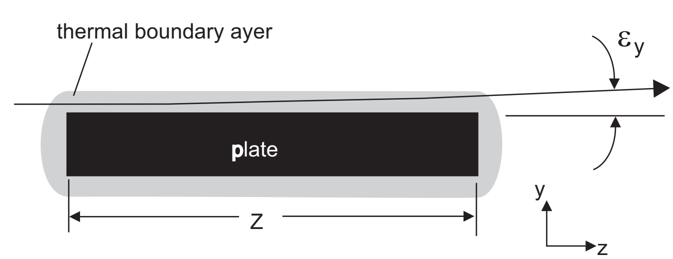

Fig. 1. The thermal boundary layer on a heated plate of length Z refracts a light ray through an angle ε_y. For purposes of quantitative analysis, the entire ray deflection ε_y is assumed to occur at once in the center of the present two-dimensional flow, i.e. at the center of the plate.