11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

VISUALIZATION OF THE THREE-DIMENSIONAL TIME-EVOLVING CONCENTRATION FIELD IN A TURBULENT BOUNDARY LAYER : PRELIMINARY RESULTS

Carl DELO and Alexander J. SMITS

Department of Mechanical and Aerospace Engineering
Princeton University, Princeton NJ 08544, USA

ABSTRACT

Preliminary results are reported on the visualization of the time-evolving, three-dimensional, passive scalar concentration field in a turbulent boundary layer at a Reynolds number based on momentum thickness of 525.

INTRODUCTION

We are currently performing an extensive investigation of low Reynolds number boundary layer structure. The primary objectives of this work are to study the origin of coherent turbulent motions at the wall, to observe their growth and interaction with other turbulent motions; to determine the role of the forcing produced by the outer layer structure on the stability and coherence of the inner layer structure; and to improve our understanding of the mixing and dispersion of passive scalars, especially with a view to unraveling the relationship between structures within the concentration field and those in the velocity field. Here, we report preliminary results based on the visualization of the three-dimensional passive scalar field as a function of time.

The visualization was accomplished using a scanning laser sheet technique (see Figure 1). By scanning the sheet at high repetition rates, and by using a high speed video camera to record the images, the time-evolving three-dimensional concentration field could be reconstructed using volumetric visualization software. The technique was first developed by Nosenchuck and Lynch (1986) who studied the structure of a turbulent spot in water, where the spot was marked using a fluorescent dye in water. The two-dimensional data (that is, the two-dimensional images of fluorescence intensity) were assembled into three-dimensional volumes using a fast ray tracing algorithm developed by Russell and Miles (1988). The volumes could be viewed from any angle and could be rotated to make a movie. The three-dimensionality of the image was enhanced considerably by the use of transparency, whereby hidden features were visible at all angles of view.

More recently, Goldstein and Smits (1990) presented some results from a low Reynolds number turbulent boundary layer using a similar technique. The study was performed in a smoke tunnel where the freestream velocity was 0.79 m/s, the Reynolds number based on momentum thickness was about 705, and the boundary layer thickness was 123 mm (310 wall units). The laser used for the illumination was first directed onto a scanning mirror which oscillated rapidly about an axis aligned with the freestream direction. The oscillating beam was used to form a sheet using a cylindrical lens. The imaged volume had dimensions $x^+ = 146$, $y^+ = 94$, $z^+ = 207$. The laser sheets were oriented in the x-y plane, and one pixel corresponded to 0.29 mm in x, and 0.22 mm in y (0.73 and 0.55 wall units, respectively), compared to a Kolmogorov length of 1.4 mm and a Batchelor scale of about 0.04 mm. There were 20 sheets in the z direction per time step, and therefore they were spaced a distance of approximately 10 wall units apart. The oscillating laser sheet completed a spanwise traverse of the boundary layer every 0.02 s ($t^+ = 1.9$). The digitized images were then assembled into volumes using VoxelView, a variable opacity, volume-rendering software package created by Vital Images.

A three-dimensional image obtained by Smits and Goldstein, representing a single time step, is shown in Figure 2. There is clear evidence of large outer scale motions, and in this time step, a bursting event of considerable strength is in progress. Images such as these, as a function of time, can be used to obtain, for example, convection velocities of structures, time scales of features such as the low speed streaks, space correlations, and correlations between inner and outer layer events. Note that it is also possible to extract velocity information by determining the distance features move between successive time steps. This procedure was called Scalar Image Velocimetry by Dahm et al. (1992). Some interesting results were obtained from this preliminary work (see Goldstein [1991] for a full discussion), but the results were not conclusive on any point, mainly because the size of the imaged volume was simply too small, and insufficient data were taken to resolve the large events occurring at low frequencies with any statistical significance.

In addition, several problems inherent to the approach used by Goldstein were identified. First, the location of the sheet was determined entirely by the synchronization pulse of the camera. Consequently, there was considerable uncertainty with regard to the location of any given image from one sweep (that is, one time step) to the next. Second, the oscillating mirror displayed severe vibrations near the points of maximum acceleration, and this effect reduced the useful number of image planes. Third, the back and forward sweeping of the image volume yields an interleaved data set which is not trivial to analyze. In fact, Goldstein only used the forward sweep, thereby increasing the time step to 0.04 s ($t^+ = 3.8$). Fourth, the use of a cylindrical lens introduces non-uniformities in the intensity of the laser sheets due to beam spreading, as well as imperfections in the lens itself. Fifth, there was some ambiguity regarding what was being marked by the smoke. Now, this ambiguity is always present in the interpretation of flow visualization results, but it was aggravated to some extent by the need to distinguish between inner layer and outer layer structures. Goldstein used a smoke slot placed 21 boundary layer thicknesses upstream of the imaging volume to mark the outer flow, and another placed 2 boundary layer thicknesses upstream to mark the inner layer motions. There was a strong disparity between the intensity of the light scattered from the inner and outer regions, which sometimes made the interpretation of the pictures difficult.

In an effort to correct some of the shortcomings of this earlier work, we carried out the experiments reported here.

EXPERIMENTAL METHOD

In the work reported here, the size of the imaged volume was increased by about a factor of four in each direction, the number of time steps were increased by an order of magnitude, and the experiment was moved from the smoke tunnel to a water tunnel (allowing the use of fluorescing dyes of different color, where the color can help to mark particular parts of the flow). As shown in Figure 3, the sheets were oriented in the x-z plane rather than the x-y plane to extract correlations between different heights in the boundary layer more simply, and to reduce diffuse reflections from the floor of the channel. In addition, an innovative scanning device was used to avoid the mechanical jitter experienced with the scanning mirror arrangement used by Goldstein and Smits, to improve the intensity of the images and to fix each laser sheet position.

This scanning device is shown in Figure 4. A helical array of 45^o mirrors was fixed to the twenty faceted faces of a rotating drum. When used with a continuous light source such as the Spectra-Physics 5W argon ion laser used here, the focused laser beam is directed along the axis of the drum, and reflects off each mirror as the drum rotates. The motion of the flat mirror face causes the beam to sweep through an angle of 18^o, creating a laser sheet of uniform intensity. The image is recorded by keeping the shutter of the video camera open during the sweep. As the drum continues to turn, the beam reflects off the next mirror forming another sheet at a different height. Because the location of each sheet is determined by the height of the corresponding mirror, the sheet locations are exactly repeatable and they can be accurately determined by a single calibration.

This apparatus was then used to study a flat plate turbulent boundary layer in the water channel facility at the Princeton University Gasdynamics and Fluid Dynamics Laboratory. The facility has a width of 457 mm, and a water depth of about 150 mm. The freestream velocity was fixed at 150 mm/s, and at the location of the imaging volume (1.10 m from the leading edge of the plate), the Reynolds number based on momentum thickness was about 525, and the boundary layer thickness was 28 mm. Two dye slots were located at x = 203 mm and 875 mm downstream of the leading edge, corresponding to 32 and 8 boundary layer thicknesses upstream of the measuring volume, respectively.

The imaged volume was 80 mm by 40 mm by 100 mm in the x (streamwise), y (normal) and z (spanwise) directions, corresponding to $x^+ = 640$, $y^+ = 320$, $z^+ = 800$. There were 10 sheets in the y-direction, spaced 4 mm apart. The sheets were imaged using a 200 mm f4 lens on a Panasonic wv-BD400 camera, framing at 30 Hz, with exposure times of 1 millisecond. There were therefore three time steps per second, corresponding to $t^+ = 22$. Compared to Goldstein's work, the time step was larger by a factor of about 6. The spatial resolution of the two experiments are not directly comparable since the sheets were oriented in different directions. The worst case is represented by the distance between successive sheets, which was a distance of 10 wall units in the spanwise direction for the experiment of Goldstein and a distance of 32 wall units in the normal direction in the present experiment.

The two-dimensional images were recorded on to video tape, transferred to a Personal Iris workstation using a Panasonic AG-6500 editing VCR and an Imaging Technology Series 151 frame grabber. Whyndham Hannaway image processing software was used to control the frame grabber, and to enhance the images.

RESULTS

Examples of the raw images are shown in Figure 5. The quality of the images are much better than the earlier images obtained in the smoke tunnel by Goldstein and Smits, mainly because of the improved scanning apparatus used here. The primary output from this investigation is the video showing the time-evolving three-dimensional dye concentration field. To this end, 19 time steps, comprising 190 individual images were collected on videotape and digitized. The two-dimensional images are currently being assembled into volumes, but no three-dimensional images can be shown at this time because of the following difficulties we have encountered: (1) To create smooth volume-filling data it is necessary to interpolate between data planes. Voxelview is the only software package that provides an interpolation option, albeit only a linear interpolation. Unfortunately, Voxelview is no longer available to us because of its extravagant cost. Introducing interpolation schemes in alternative software packages has delayed our analysis considerably. (2) The data planes need to be shifted to allow for the time delay between images: at this framing rate, there is considerable streamwise motion during a time step (a maximum shift of about 1.7 boundary layer thicknesses between the first and the last data plane during a full timestep), and corrections for that motion must be made. At present, the local mean velocity is being used to align the sheets properly. This is clearly unsatisfactory, and the next data set will be taken using a high speed video camera to obtain the same time resolution achieved by Goldstein and Smits (see below). (3) We are still evaluating software for the three-dimensional reconstruction. Since Voxelview is not available, we are comparing Fieldview by Intelligent Light for the Iris, and Image by the National Institute of Health for the Macintosh (the latter is freeware). (4) We are also studying the best means for image enhancement, which is a step performed prior to reconstruction. The greylevels of all images are always offset and stretched to provide the maximum range of grey scales. This process preserves the relative intensity levels. However, further enhancements may be used to isolate the edges of the passive scalar structures. For example, the individual images may be convolved with a two-dimensional Marr operator (the Laplacian of a 2-D Gaussian, also known as a Mexican Hat). Since the greylevels no longer represent a physically meaningful property, the convolved images are then again stretched to fill the range of grey values. The results of this convolution and stretching on the raw data given in Figure 5 are shown in Figure 6.

Now, to obtain higher framing rates, which will allow better time and space resolution, we need to use a high speed video camera. We found that the argon ion laser gave more than sufficient light to provide high quality images using a standard 30 Hz video camera, even with exposure times less than 1 millisecond and with low levels of seeding using disodium fluorescein dyes. However, the particular high speed camera available to us, a Spin Physics Ektapro High Speed Motion Analyzer, has very low light sensitivity at the required framing rate of 500 frames per second. Hence we will need to use the Plasma Kinetics Series 1051 copper vapor laser used by Goldstein to obtain sufficient illumination. This is a pulsed laser, and therefore the sheets cannot be formed by sweeping the laser beam, as described above. The beam must first be directed on to a cylindrical lens before being directed by the 45^o mirrors, and we loose some of the advantages of the rotating drum apparatus. On the positive side, the distance between sheets is reduced by a factor of 2, and the time step is reduced by a factor of 8. And since the repetition rate of the laser is slaved to the video camera so that the exposure of each frame is less than 20 ns.

In the presentation at the meeting we will show the entire three-dimensional time-evolving high-speed scanning sequence obtained using the slower framing rate. In addition, we hope to have extracted some quantitative data from the images, such as convection velocity and space correlations. We also hope to be able to answer some of initial questions regarding scale interactions in a boundary layer more definitively than the tentative answers given by Goldstein (1991). Finally, we will present some preliminary efforts to relate the scalar field, as given by the dye intensity levels, and the velocity field, obtained by scalar image velocimetry. It seems unlikely at this stage that the scanning sequence using the higher framing rate will be available by the time of the meeting.

ACKNOWLEDGEMENT

This work was performed under AFOSR URI Grant 90-0217, monitored by Dr. J.M. McMichael.

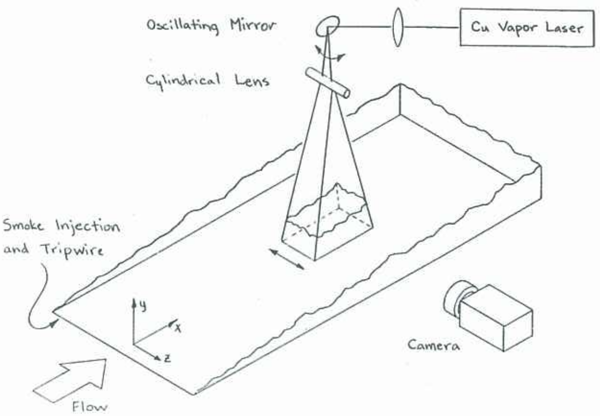

Figure 1. Experimental arrangement used by Goldstein and Smits (1990).

REFERENCES

Brasseur, J. and Lin, W.-Q. (1991) "Characteristics of Intermittent Regions in Homogeneous Turbulent Shear Flow," AIAA Paper 91-0232.

Dahm, W.J.A., Su, L.K and Southerland, K.B. (1991) "Scalar Imaging Velocimetry studies of turbulent floe field structure and dynamics," APS 44th Annual Meeting of the Division of Fluid Dynamics, Tucson, AZ.

Goldstein, J.E. (1991) "Volumetric Visualization of a Low Reynolds Number Turbulent Boundary Layer," MSE Thesis, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton N.J., U.S.A.

Goldstein, J.E. and Smits, A.J. (1990) "Volumetric Visualization of a Low Reynolds Number Turbulent Boundary Layer," Paper #GA6, 43rd Annual Meeting, Division of Fluid Dynamics, American Physical Society.

Nosenchuck, D. M. and Lynch, M. K. (1986), "Three-Dimensional Flow Visualizations Using Laser-Sheet Scanning," In Proc. AGARD Conf. on Aerodynamics and Related Hydrodynamics Studies Using Water Facilities, pg. 18.1.

Russell, G. and Miles, R. B. (1987), "Display and Perception of Three-Dimensional Space Filling Data", Applied Optics 26: 973.

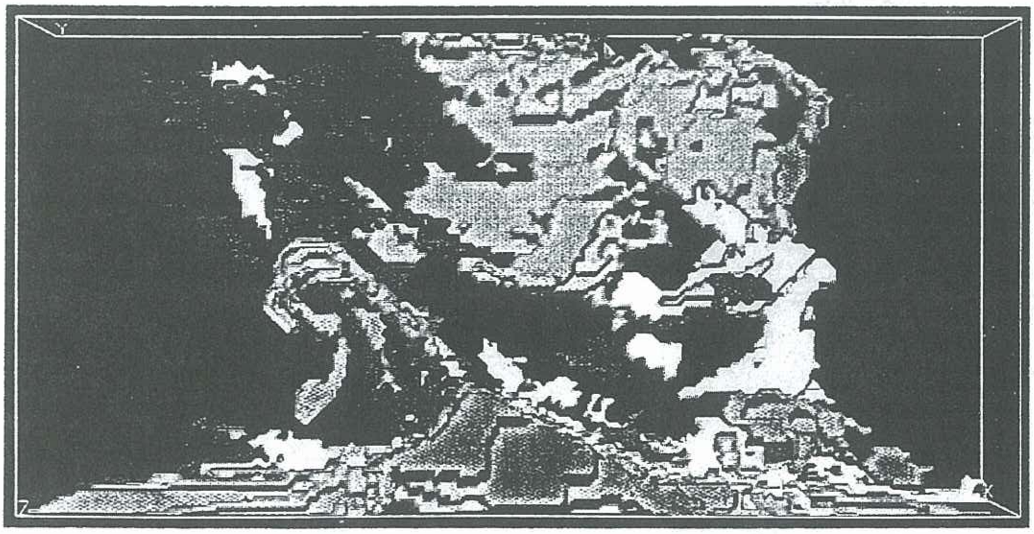

Figure 2. Three-dimensional image of the smoke concentration field at a Reynolds number of 705, obtained by Goldstein and Smits (1990). The concentration level has been analyzed using the method described by Brasseur and Lin (1991) and shaded to show "connected" regions. Flow is from right to left.

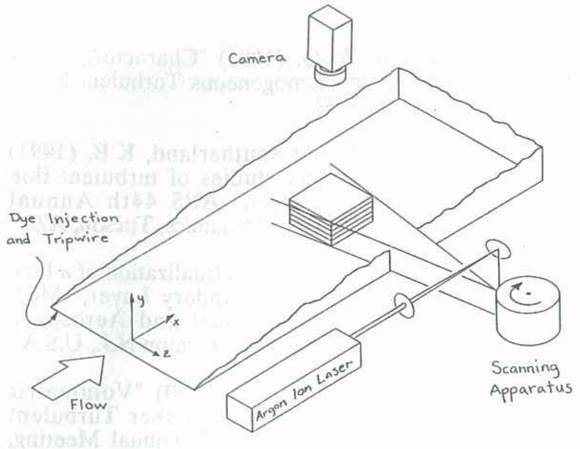

Figure 3. Experimental arrangement used in the current work.

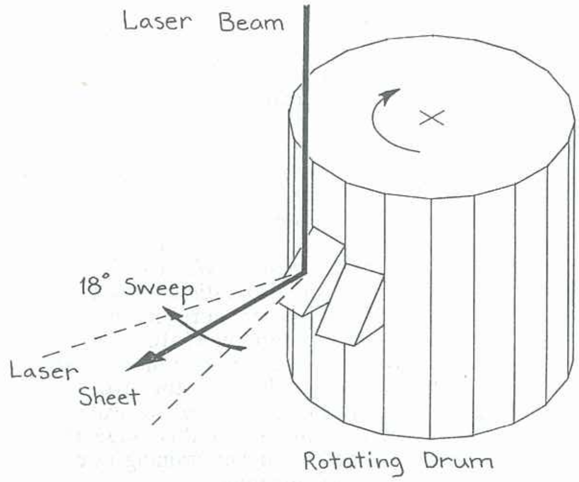

Figure 4. Improved laser sheet scanning apparatus.

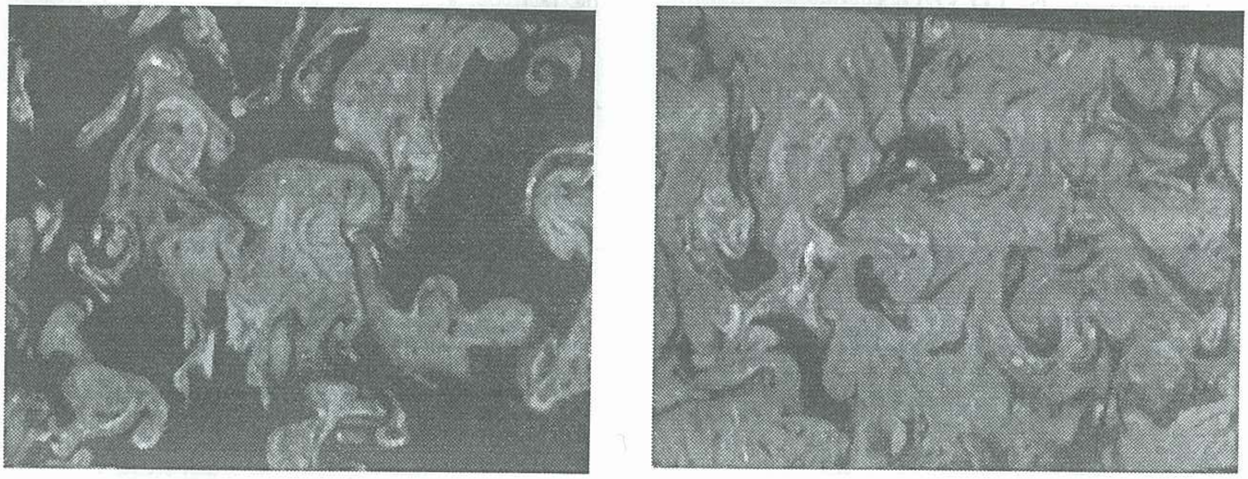

Figure 5. Two-dimensional images obtained in the water channel at a Reynolds number of 525. The flow is from top to bottom, and the field of view is about 2.9 x 3.6 boundary layer thicknesses. (a) Raw image data at $y^+ = 192$, $y/\delta = 0.85$; (b) Image (enhanced to use all grey values) at $y^+ = 96$, $y/\delta = 0.42$.

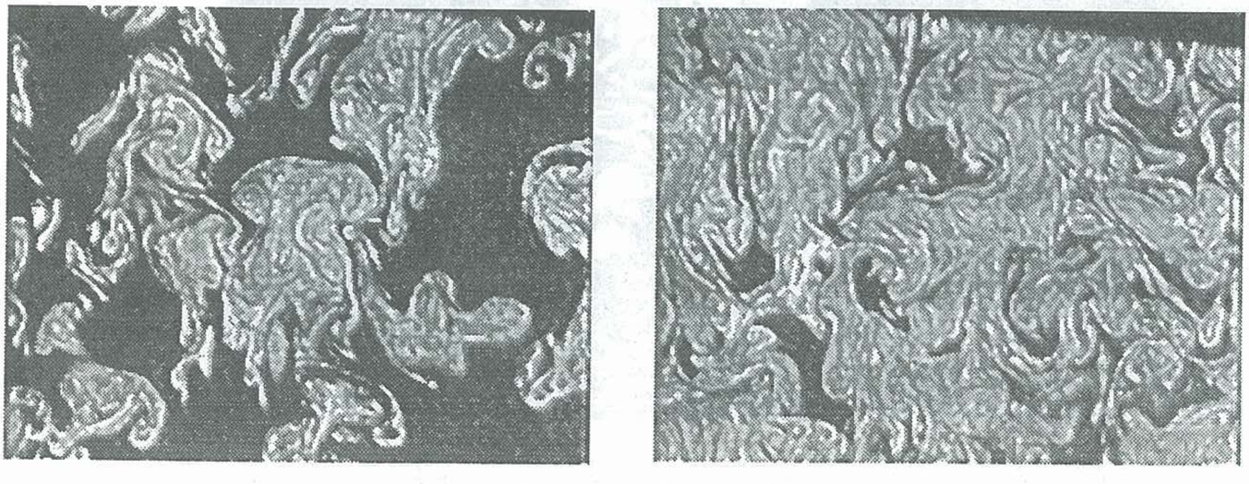

Figure 6. The data of Figure 5, after convolution with the Marr operator. The operator had a "diameter" of 6 pixels or 8 wall units.