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STEREOSCOPIC PHOTOGRAPHY OF SHEAR FLOW TURBULENCE

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ABSTRACT

The last several years have seen numerous advances in the understanding of the coherent motions that exist in turbulent shear flows. These studies have provided the underlying basis of most of the experimental investigations of coherent motions using conditional sampling, quadrant splitting, pattern recognition, etc. Lacking, however, in the visual work is a true three-dimensional view of the processes, which are known to be three-dimensional in nature. Possible means of providing information about the third dimension are reviewed. Details of an evaluation of a stereoscopic-photographic, high-speed motion picture system are given. The system utilizes the boundary layer flow channel previously developed in our work by Nychas, Hershey and Brodkey (J. Fluid Mech. (1973) 61, 513).

INTRODUCTION

The visual studies of the last ten years have revealed the existence of coherent structures in turbulent shear flows and formed a basis for anemometry studies using new techniques like conditional sampling, quadrant splitting, pattern recognition, etc. The many investigations of turbulence structure clearly underscore the necessity of visual studies in formulating realistic physical models.

All the visual studies so far have been essentially two-dimensional. The different interpretations given to the observations in the wall and outer regions can be attributed to the fact that turbulent structures are three-dimensional in nature but have been described from different two-dimensional views.

Three-dimensional visual examination of flows seem to be a logical course for further studies. The present effort was undertaken to develop a three-dimensional photographic technique that was compatible with our existing flow facility and to obtain qualitative information about the nature of the coherent structures in turbulent shear flow. The three-dimensional technique provides a convected view (moving with the flow) so that the evolution of structured regions can be studied in detail as they develop. It is impractical to try to piece together a number of stationary films to give what can be seen from one film convected with the flow.

This paper describes the successful experimental technique we used (stereoscopic photography) and in addition reviews most three-dimensional photographic methods, namely holography, a multicolor-filter technique, and stereography. Their significant applications in fluid mechanics and their suitability for use with a typical boundary layer flow system such as ours are discussed.

THREE-DIMENSIONAL PHOTOGRAPHIC TECHNIQUES

Holography

Holography involves recording the fringe patterns produced by the interaction between a wave front reflected by an object illuminated with coherent light and a coherent reference beam. Three-dimensional photographic applications of holography have been limited to particle size analysis, velocimetry and non-destructive testing. To date, only stationary laser-optical systems have been used for flow visualization studies. However, to use the techniques with the existing boundary layer flow unit, a key part of the laser-optical system would have to be transported on the hydraulically moved lathe carriage in the direction of flow. The dynamical forces involved would pose serious stability problems; for if the system is not stable to distances of the order of the wave length of the light, the fringe patterns recorded will be affected by the disturbances. This is the main reason laser-optical systems are normally designed for stationary operation. The use of holography for a three-dimensional convected view would necessitate the design of a moving flow system, which for our flow system would be impossible. Moreover, holography is limited to relatively small volume objects due to the energy output and coherence length limitations of currently available lasers. At this time, it would seem that further developments are necessary to make holography a more useful three-dimensional visualization technique for this specific application.

Multicolor-Filter Technique

Van Meel and Vermij (1961) developed a multicolor-filter technique which allowed the three velocity components to be measured simultaneously on a single color picture. The color of the tracer particle was the indicator for the third dimension. The technique involved using tracer particles suspended in the flow, a parallel light beam, a multicolor-filter and a highly sensitive color film. The light beam was made to pass through the multicolor-filter thus giving parallel light beams of different colors. When this light passed through the volume of the fluid under investigation, tracer particles at different levels acquired different colors. Thus, the colors of the particles seen in the photographs indicated their location in the third dimension.

Praturi (1972) made an evaluation of this technique for use with our visual study of turbulent shear flows. To obtain accurate results, a perfectly parallel light beam, clear field illumination and tracer particles at least as big as the width of the individual color filters are essential. The last criterion restricts this technique for our flow visualization because individual color filters of about 50 - 100 microns width are not available and particles of bigger size will not follow the fluid motions. For the 1/8-inch color filters available and for the small particles that would follow the flow, the particles often remained the same color or just changed color once during the entire time they were visible in the flow. Clearly, the resolution of this technique was not adequate for the problem at hand.

At best this is an indirect three-dimensional visualization method. A composite three-dimensional picture of the fluid motions has to be reconstructed from the observation of the motions of individual tracer particles. These motions themselves have to be reconstructed from the color changes. These reasons seriously limit the use of this technique for three-dimensional visualization of flow phenomena.

Stereography

Stereoscopic photography had been successfully used in a variety of flow situations. The principal difference between stereography and other techniques is that two pictures --one for each eye-- are presented to the viewer, who then receives the same view the photographer saw with his own two eyes, by means of binocular vision. The basic principle in stereoscopy involves taking two slightly dissimilar photographs, called a stereo pair, stereograph or stereogram of the same object. A stereo camera, ordinary cameras with stereo adapters or stereo lenses, or a pair of cameras can be used to obtain stereo pairs.

Nedderman (1961) used stereoscopic photography for the measurement of velocity components in liquids. Two Contax-II cameras, fitted with f:3.5, 50 mm Tessar lenses and 12 cm extension tubes were mounted in a vertical plane with their axes converging at 40°. Flash illumination was used to make multiple exposures on the two single frames of film. This enabled the path of the tracer bubbles to be recorded as a continuous row of dots. In all of his experiments, the photographic system was stationary.

Boge (1963) determined upper atmosphere wind movements from stereo photography of rocket vapor trails. He took time sequenced stereo photographs with Photo-Theodilites of vapor trails exhausted by high altitude rockets. By knowing the position and orientation of each terrestial camera, the displacemnt vectors of various points on a vapor trail appearing on consecutive sets of stereo photographs were determined.

Charles and Lilleleht (1965) used two small, field cameras to obtain stereo pairs of interfacial waves in stratified flow. They used a metric Zeiss stereoscope to measure the amplitude and wavelength of the interfacial waves to a high degree of accuracy.

Sorensen (1968) made a stereo-photogrammetric analysis of form and variation of surface waves generated by a ship model. Two wide angle Rolliflex cameras with 55 mm Carl Zeiss Distagon objective lenses were used to obtain the stereo pairs. The cameras were mounted on an aluminum channel beam so that dual coverage of an area of approximately 16 sq. ft. was obtained. A stereo plotter was used to analyze the stereograms.

Tatterson (1974) made 16 mm high-speed, stereo motion pictures of the fluid and particle motions in a stirred vessel. He used a stereo adapter, with built in capabilities for close-up focusing.

The works cited above are only a few examples of the applications of stereoscopy in fluid mechanics research. Stereography is useful in many other fields (especially in photogrammetry) under widely different situations.

Stereography was chosen for the present study due to its ease of adaptability to our flow system and to the simplicity of operation.

DESCRIPTION OF THE FACILITY

The flow loop previously developed by Nychas et al. (1973) was used; a detailed description of this can be found in reference (9) Nychas (1974). However, a brief summary is provided here to orient the reader. The photo-optical system is a new development and is presented in detail.

Flow Loop

A schematic diagram of the flow loop is given in Figure 1. It consisted of a 200 gallon, rubber coated storage tank (A) from which the fluid was pumped by one of the two centrifugal pumps (B) and (C) to the entrance section (D) of the channel (E). The flat plate (F) was positioned securely in the channel. A glass window (G) was provided on one side of the channel for illumination and photographic purposes. The fluid flowed past the flat plate, through the perforated plate (H) and finally to the dump tank (I). A 50 gpm capacity filter (J) was installed in a bypass line, after the pumps, to clear the fluid of any particles larger than 5 microns, before the tracer particles were dispersed in the fluid. A porcelain bactereological filter (P), installed in parallel with the main filter unit, removed ultra fine dust particles, when necessary. Two expansion joints (K) and (L) were installed in the flow loop to minimize the transmission of pump vibrations to the channel. The flow rate in the channel was controlled by a globe valve in the variable flow resistance (Q) and the fluid level in the channel by the perforated plate (H). The photo-optical system was mounted on the lathe carriage (N), which was transported on the lathe bed (M) by means of a hydraulic drive.

The major modifications of this study to the flow loop of Nychas (9) were the installation of heat exchangers and a variable flow resistance. The heat exchangers consisted of a steam coil in the storage tank to degas the water and a cooler in the dump tank to maintain a steady temperature in the fluid circulating in the channel flow loop. The exchangers performed well and the circulating water in the channel reached a steady-state temperature in 30 minutes and remained at that temperature throughout the run.

The toughest problem encountered in making the flow loop operational was the appearance of bubbles in the flow. Degasing and cooling the water removed some of the bubbles. The system was thoroughly checked for any air leakage and none was found. After instrumenting the system with pressure gauges and a thorough investigation of each section of the loop, the origin of the remaining bubbles was traced to cavitation in the pumps. This problem was solved by providing a variable flow resistance before the entrance section of the channel. This enableed the collapse of the water vapor bubbles before entering the channel. The details are shown in Figure (2). The variable resistance consisted of 20 x 20 mesh, stainless steel screen and a globe valve. The screen was installed between a flange coupling with rubber packing for easy replacement.

The entrance section consisted of a deflection baffle which eliminated the jetting effect created by the incoming water from a 2-inch pipe. The tube bank following the baffle consisted of 420 polyethylene tubes of 1/2-inch O.D., 1/16-inch wall thickness and 4 inches length. These served as straightening vanes. The tube bank was preceded by a 20 x 20 mesh copper screen and followed by a cascade of 7 stainless steel screens. The first six were 30 x 30 mesh size and the last one was 32 x 32 mesh size.

The variable flow resistance not only eliminated the bubbles problem but also reduced the time consuming periodic cleaning (a two day shutdown period) of the entrance section to a simple task of replacing the 20 x 20 mesh screen in the flange coupling.

Water as working fluid and Pliolite* particles as tracers, selected by Nychas (1974) were used in this study. The size range of the particles used was 62-74 microns. Nychas (1974) demonstrated the ability of these particles to follow fluid motions. The optimum concentration of the tracer particles was reached by trial and error. Too many particles might give rise to particle-particle interactions and did deteriorate the image quality. With too few particles one would not be able to define the flow structures. A concentration of 0.75 gms of the 62-74 microns size particles dispersed in the total volume of 150 gallons of water satisfied all the requirements.

Photo-Optical System

Stereo adapters can be classified as before-the-lens systems and independent lens systems. In either case the ability to take close-up stereo pairs involves additional complexity. The two stereo systems utilized in this study are sketched in Figure 3. For before-the lens systems, the outer set of mirrors must be towed in to allow viewing close-up objects. For the independent lens system, a set of prisms must be used to view close-up objects. The preliminary work on obtaining stereo pairs was done with a radically modified Honeywell Pentax stereo adapter (2). Although the modified adapter confirmed the feasibility of close up stereoscopy, the quality of the image left much to be desired. A stereo adapter, similar to the Pentax but with built in

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* Pliolite is the commercial name of polyvinyl toluene butadiene, manufactured by Goodyear Chemicals.

features for close up photography (Stitz stereo system) was then used to make a series of stereo movies of the boundary layer flow. It was used for both photographic and projection purposes. A special 16 mm Kodak cine camera fitted with a 1/15 H.P. model NSH 34 Bodine shunt wound motor and a model SH-33 Minarik speed controller allowed a filming speed range of 10-300 frames per second. The lens used with the camera was an elgeet, model MF-143, wide angle lens with a focal length of 13 mm and largest aperture of f:1.5.

An examination of the stereo movies revealed the following deficiencies of the system: 1) The amount of light loss through the stereo adapter was excessive; the maximum filming speed attainable was 100 frames per second despite the high intensity quartz halogen lamp (1100 watts); 2) the registration of the stereo pair was not precise; 3) the resolution of the images was poor; and 4) the projection of the stereo movies using the adapter and cross polarized filters was unsatisfactory.

The inadequacies of the before-the lens stereo adapter necessitated a search for better and more precise stereo photographic equipment. A used Bolex stereo system with a close up turret (not in production since the early 1950's) was acquired which fulfilled all the needs.

The Bolex stereo lens consisted of a pair of rhombic prisms in front of the prime optics. The prime optics were actually two identical lenses located side by side in the same mount. The focal length of the stereo lens is 12.5 mm with a maximum aperture of f:2.8. The advantage of a pair of lenses over a before-the lens adapter is that the optical center of each lens is close to the optical center of each frame of the stereo pair which resulted in greater spatial resolution across the stereo field. With a before-the lens adapter the central portion of the taking lens, where spatial resolution is greatest, is wasted by the area between the stereo pair. The close up turret which formed an integral part of the stereo lens permitted accurate focusing at 2 feet and 3-1/2 feet by means of two pairs of wedge prisms. The third position of the turret was simply a pair of openings for the unaltered standard lenses to be used for distances of 5 feet to infinity.

The short focal length of the stereo lens precluded the use of movie cameras with rotating prisms before the film plane. A high diopter correction lens would be necessary in this case and would result in image distortions and lens aberations. A rotating disc shutter (model HS-16C) Benson-Lehner 16mm camera was obtained so that the distance between the lens seat and the film plane was exactly 0.67 inch. The camera has film speed settings of 100, 200, 300 and 400 frames per second. The 100 frames per second setting was used for the present study. Timing lights, which imprinted timing marks on the edges of the film at a rate 120 per second, allowed accurate determination of the actual filming speed. The 100 frames per second setting gave an actual filming speed of 66 frames per second. The lens mount was slightly modified to align the lens axis with the center of film plane.

A special multiple bulb, high-intensity lamp was designed to meet the light requirements. The large volume of field and high intensity necessary made the use of air cooled quartz-halogen lamps imperative. The construction details of the lamp are depicted in Figure 4.

A LW Photo-Optical Data Analyzer (model 224-A) with a Bolex stereo projection lens was used to project the stereo movies. The lens has built-in polarizers which allows, when viewed with cross polarized glasses, the left half of the stereo pair to be presented to the left eye and the right half to the right eye.

Procedure

The water was degassed by heating it in the storage tank to a temperature of about 70° for approximately two hours by means of the steam coil. It was then pumped into the circulation loop and run through the filter unit for about two hours to eliminate particle contamination. At the same time it was cooled by the heat exchanger. The clean and cool water was returned to the storage tank and the required quantity of Pliolite particles was added. The particles were thoroughly dispersed by circulating the water through a bypass valve within the storage line for a half hour. The water with the tracer particles was pumped back into the channel, and the globe valve in the variable flow resistance was adjusted until the water vapor bubbles disappeared. The water was allowed to circulate further for about an hour until steady state conditions were reached. The level in the channel was finally adjusted by means of the perforated plate at the end of the channel. Clear and dry plexiglass sheets were placed on top of the flat plate to eliminate surface waves and the miniscus effect at the interface of the water and the flat plate. The lathe carriage velocity was matched with the mean velocity of the flow by following selected particles. Kodak Tri-X reversal film was used.

DISCUSSION OF THE FACILITY

The use and validity of small suspended particles of tracers for flow visualization had been extensively treated by Brodkey et al. (1971) and by Nychas et al. (1973). The reasons for the preference of small particles suspended in the entire flow to injection techniques (dye or bubble) was discussed in the first article in some detail and will not be repeated here. The points involved are mainly 1) flow disturbances and 2) injected flow markers form a streak line or streak sheet in an unsteady flow field and then spread to assume various configurations (i.e., all structures are equally marked at the injection line and can be followed for about a boundary layer distance downstream). Questions that arise involve interpretation of a developing marker field in an unsteady velocity field, an uneven marked field in time where high concentrations remain in low velocity areas and high velocity areas and high velocity regions are no longer marked, adjacent regions that were never marked, and the difficulty of interpretation of a streak line as compared to a pathline. However, as pointed out in that article, this is not to say that useful information cannot be obtained by these alternate methods.

Flow Loop

The modifed flow loop performed extremely well. The degassing procedure prevented the release of dissolved gases from the water. The variable flow resistance was a major improvement which eliminated the troublesome water vapor bubbles generated by cavitation in the pumps.

Photo-Optical System

The arrangement of the camera, lamp and variac on the lathe carriage and their location with respect to the channel are shown in Figure 5. The camera and the lamp were aligned (X-Y plane) so that the illuminated region was within the photographed region. The glass window of the channel was masked with friction tape to provide a 2.5 cm wide horizontal opening along the length of the window. The vertical position of the lamp was adjusted to position the 2.5 cm slit on the lamp exactly opposite the opening on the glass window. The camera was mounted on the lathe carriage, with the film plane horizontal. A line connecting the optical centers of the two lenses was parallel to the flat plate so that the Y coordinates of any particles appearing in both frames of the stereo pair were the same.

The Benson-Lehner camera was precision engineered and the film transport was smooth and accurate. The only drawback of the camera was the absence of a viewfinder. This problem was overcome by keeping the film plane of the camera at exactly 2 feet from the center of the region photographed. The precision optics of the stereo lens provided excellent registration of the two frames of the stereo pair. The choice of focusing distance was limited to 2 or 3-1/2 feet due to the design of the close up turret. The setting of 2 feet was used in all the movies. The special multiple bulb lamp provided more than the minimum light requirements for this distance. This helped by allowing the use of a smaller aperture opening with a corresponding increase in the depth of focus. In spite of the parabolic mirror and slits, the light beam emerging from the lamp was not collimated. The divergence of the light beam, however, did not affect the quality of the stereo movies as the depth of field attainable with the stereo lens was greater than the depth of the flow region illuminated.

Field of View and Image Quality

Three test targets were photographed to determine the image quality and field of view attainable at the focusing distance of 2 feet. An ordinary centimeter graph paper, attached to a firm stand was photographed to determine the two-dimensional field of view. The plane of the graph paper was exactly parallel to the film plane. The field obtainable* was about 14 cm (X) by 20 cm (Y).

The second target was a three-dimensional scale. It consisted of a plastic sheet (13.4 x 26.6 cm) fixed to a steel plate. A diagrammatic sketch of the scale and its positioning for the test are shown in Figure 6. The geometrical center of the scale was 2 feet away from the film plane and the scale was inclined at an angle of 25° with the lens axis. With this arrangement the scale defined a volume element of 20 cm (X) by 13.7 cm (Y) by 24 cm (Z). The width of the black and white strips denotes the dimensions in Y or Z directions. X-directions dimensions were marked with black ink in the middle area of the scale. The width of the strips for the Y-direction had values of 2, 4 and 8 mm, while for the Z direction the values were 1, 2, 3, 4 and 5 mm. The width of the strips on the scale correspond to the real dimensions by the sine of the angle.

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* The X direction corresponds to direction of flow; the Y axis is perpendicular to the flat plate.

Two aperture openings (f:4 or f:5.6) were used in the test. The stereoscopic field of view measured 14 cm (X) by 13.7 cm(Y) by 24 cm (Z). The focus was excellent for all parts of the scale. The 2 mm strips in the Y-direction and 1 mm strips in the Z-direction were clearly recorded.

The third target was a precision optical resolution chart, mounted on a stand. It was used the same way as the three-dimensional scale except that the inclination angle was 30°. This gave a linear resolution of 35 line pairs per mm in all parts of the stereo field defined by the resolution chart (14 by 14 by 24 cm).

The three tests described demonstrated the capa bility of the Bolex stereo lens to photograph a field of 14 by 14 by 24 cm volume with a linear resolution of 35 line pairs per mm. The volume of the flow region illuminated by the light beam is shown in Figure 7 which was less than the stereo field obtainable. For the flow conditions used, 1-inch is approximately 100 wall units (e.g., the Y distance corresponds to a Y^+ of about 800). The image quality was consistent over the entire stereo field except near the region adjacent to the flat plate. In spite of the black paint on the flat plate, specular reflections of the light beam caused the image to be slightly more bright and less sharp in a narrow region next to the flat plate. These reflections from the flat plate, however, were kept to an absolute minimum by positioning the camera in such a way so that the plane of the flat plate surface bisected the film plant. The region of concern extended out to a Y^+ of about 25. Although motions could be seen in this region, they were not as clear as further out into the flow.

Stereo Effect

The focus and illumination of the movies were of good quality; but the stereo effect observed in the movies (i.e. the three-dimensional perception of the image) was found to depend on several factors, i.e. sharpness, brightness, equal quality in both frames of the stereo pair, presence of clear three-dimensional motions, stereo perception ability of the individual and projection technique. The sharpness of the image in the entire region photographed is of critical importance for a good stereo effect. The depth of field of the stereo lens system used here was greater than the depth of the fluid region photographed which gave excellent sharpness over the entire volume field. The brightness of the images should be and was distinguished clearly from the dark background. To obtain equality of both the frames of the stereo pair, the stereo lens and the projection lens had to be maintained in a very clean condition.

The presence of clear three-dimensional motions in the movies facilitates stereo viewing. Vortices and other large scale motions in the flow were easily observed in three-dimensions. It was more difficult to perceive the stereo effect when there were no large scale motions present.

The projection technique is of vital importance to the stereo effect. Ordinary screens destroy polarization of the images and hence the stereo effect. Silver screens or rear projection screens are necessary. In the present study a frosted glass was used as a rear projection screen. Perfect superposition of the two images of the stereo pair (Y coordinate of conjugate points in the stereo pair should be same) greatly accentuated the stereo effect. The excellent quality of the Bolex stereo projection lens to polarize the images and its ability to superimpose the two images was of great help. The viewer has to be positioned as close as possible to the screen so that he can see the entire stereo field; otherwise the stereo effect is lost and it is like looking at the stars in the sky on a clear night.

Last, but not least, is the ability of the individual to perceive the stereo effect. There are many factors which can aid stereo viewing like the presence of large three-dimensional objects in the background, different sizes of the objects, tranquil state of mind of the observer, etc. Masking of the observer, etc. Masking of the non-stereo portion of the images (the portions of the images in the stereo pair which are not common to both) helped. The reader is refered to the article by Julesz (1974) which discusses these points.

Analysis of the Stereo Movies

For the most part the stereo movies were analyzed visually by projecting the movies on the frosted glass stand and using cross-polarized spectacles. While the large scale structures of the flow could be seen clearly in three dimensions, the small scale features were more difficult to observe.

For quantitative data acquisition a semi-automatic X-Y scanner, interfaced with a PDP-15 computer was used. Two-dimensional data could be easily obtained by locating and following certain particles in one frame of the stereo pair. Three-dimensional data, however, are very difficult and laborious to obtain due to the difficulty in discriminating between various particles so as to locate exact conjugate points in the stereo pair.

A lower concentration of particles would have facilitated pair matching somewhat. In these experiments the concentration of particles was chosen for easy visualization of the flow.

PRESENTATION OF RESULTS

Figure 8 presents two enlargments of stereo pairs as taken from our stereo movie camera. The first is a view of the facility whereas the second is a frame from our films on turbulent flow. The stereo effect is not present under normal viewing conditions. Hence it is not possible to show meaningful still pictures. A summary of our results so far follows.

Visual examination of the turbulent region of the boundary layer flow has revealed the existence of a distinct wall region ($0 \leq Y^+ \leq 100$). The events observed in the wall region included decelerated flow, high speed fluid, ejections and vortices. In most of the stereoscopic movies the chain of events in the wall region started with the observation of decelerated flow followed by high speed fluid. Immediately following the appearance of high speed fluid, ejections of particles were observed which initiated the formation of vortex motions. These vortex motions are not the transverse vortices described by Nychas et al. (1973), which were for most part in the outer region ($100 \leq Y^+ \leq 450$) of the flow. Ejections were rapid outward motions of particles which lasted up to a Y^+ of 100. The path of the ejected particles, in the convected view of the camera, appeared to be a straight line motion in the Y direction. The ejections were seen to start and become a part of the vortex motions in the inner region. The majority of the vortex motions were tilted streamwise vortices, which changed their axis of rotation while being convected in the flow. The rest of the vortex motions in this region are transverse helical vortices which did not change their axis of rotation. In some extreme cases the streamwise vortices changed their axis of rotation by 180° in the plane. The streamwise vortices were seen in both helical and cylindrical configuration. The vortex motions traveled with a slightly higher convection velocity than the mean flow. The diameter of the vortices ranged from 20 to 50 Y^+ units. The vortex motions were intense and appeared for a short time. They rarely made more than three complete rotations about their axes. During the time that none of these events were present the flow was laminar like.

These are only preliminary results of the analysis of the stereoscopic movies. A complete analysis and comparison to the work of others of the entire boundary layer and nonturbulent regions is currently being carried out and will be published at a later date.

Concluding Remarks

Stereoscopic photography is a viable technique for the study of the three-dimensional nature of the structure of turbulent shear flows. The structural features of the flow can be clearly visualized in three-dimensions. Three-dimensional data may be obtained from the stereo movies if one can provide reference planes and automate the process of locating conjugate points. A three-dimensional view of the flow field can shed new light on the interactions and structure of the individual flow events that have been previously described by ourselves and by others.

ACKNOWLEDGEMENTS

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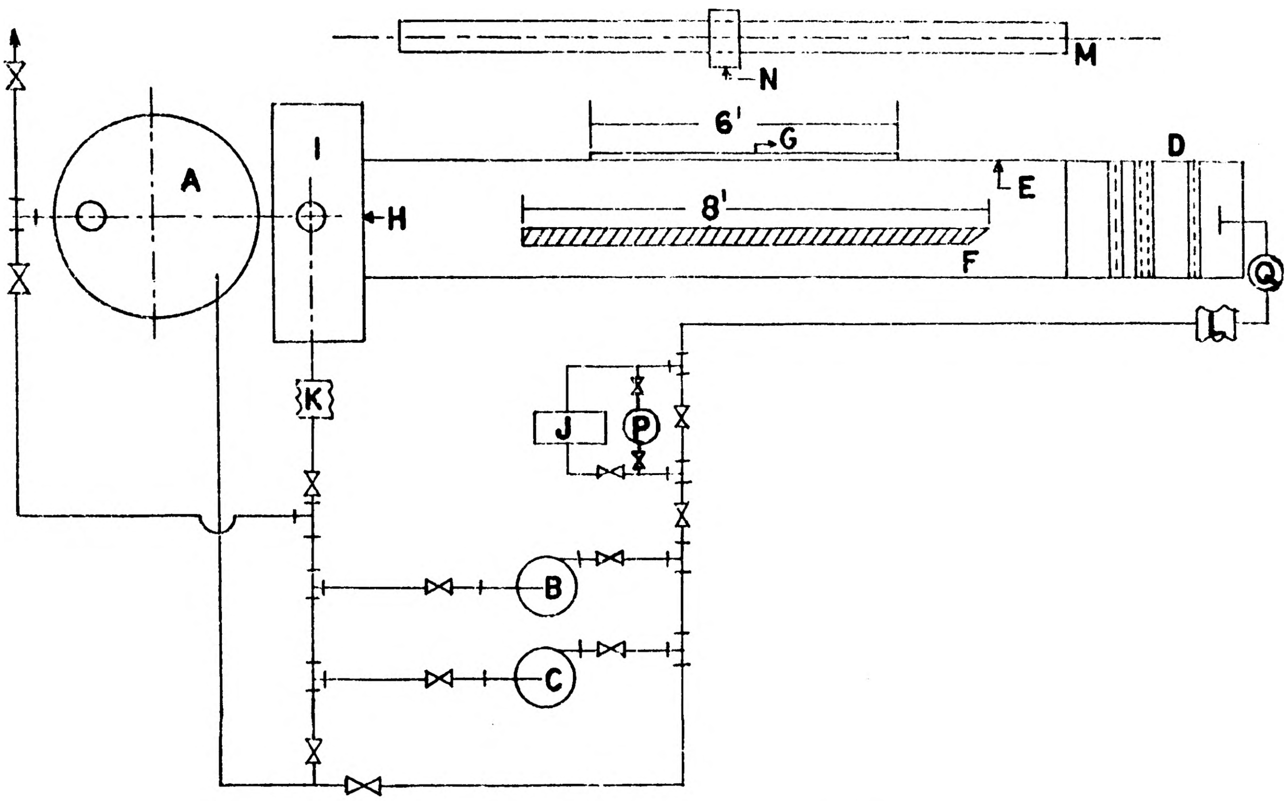


FIGURE 1. DIAGRAMATIC SKETCH OF FLOW LOOP

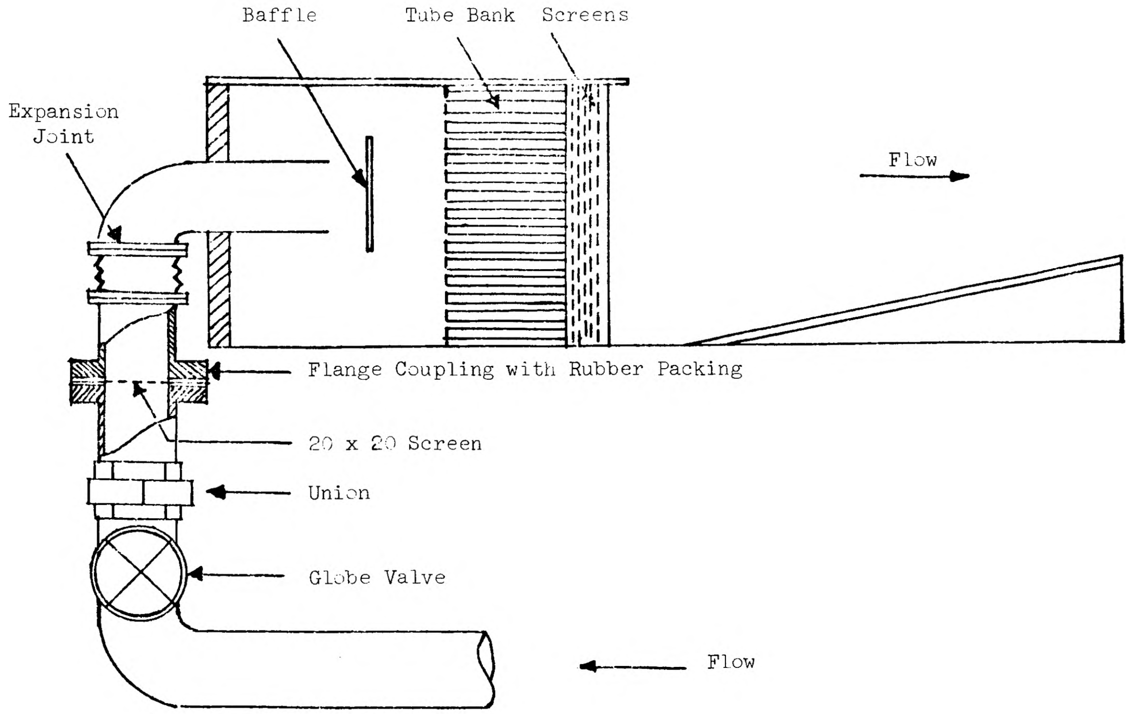
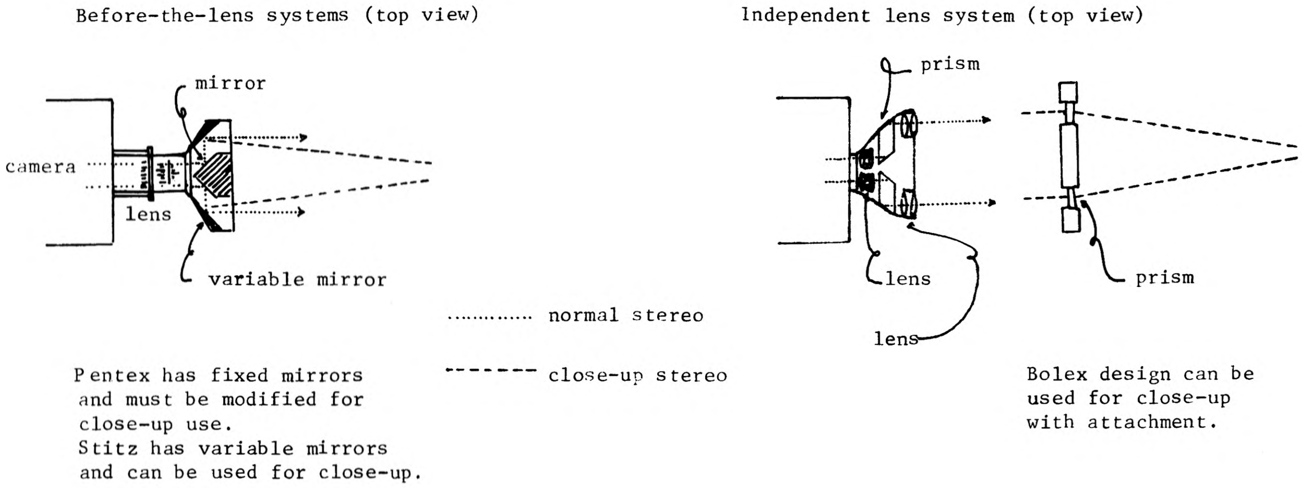


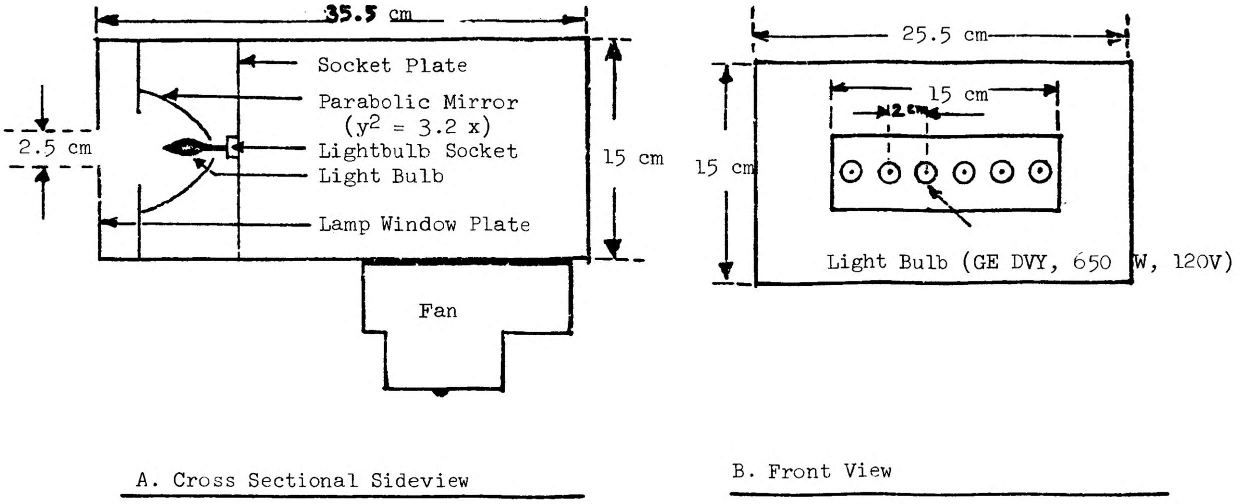
FIGURE 2. ENTRANCE SECTION



Pentex has fixed mirrors and must be modified for close-up use.
Stitz has variable mirrors and can be used for close-up.

Bolex design can be used for close-up with attachment.

FIGURE 3. STEREO ADAPTER SYSTEM



A. Cross Sectional Sideview

B. Front View

FIGURE 4. CONSTRUCTION DETAILS OF LAMP

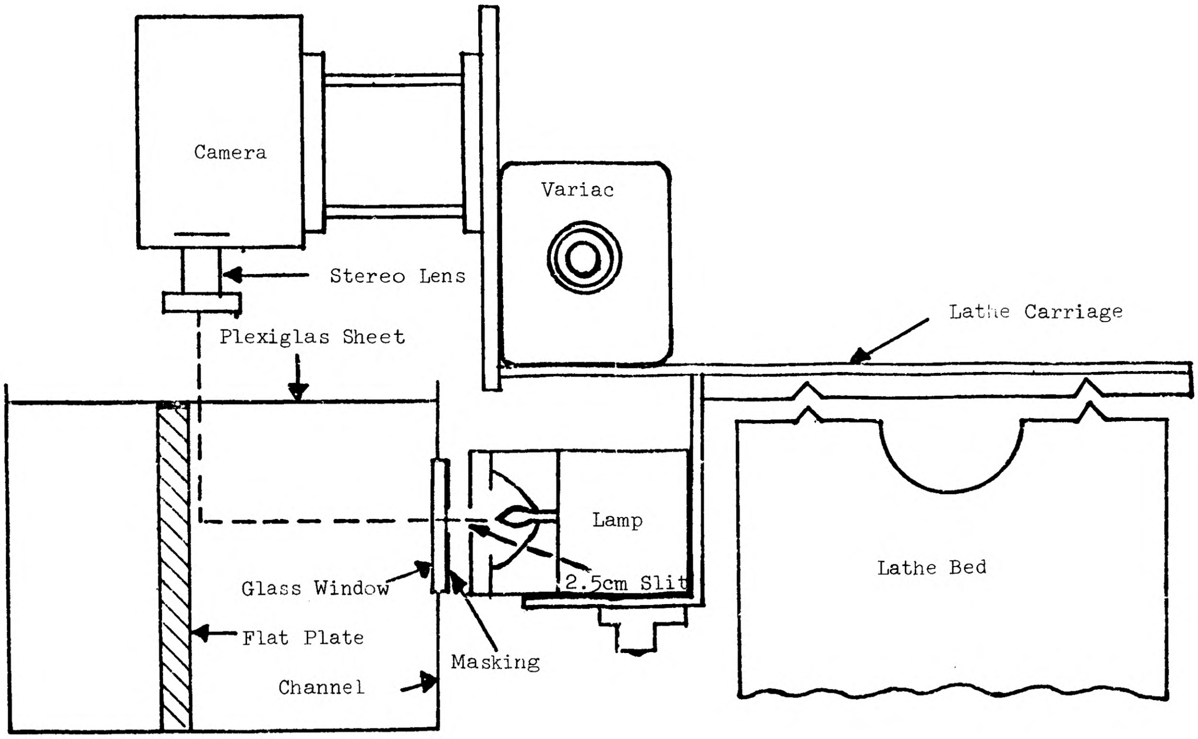


FIGURE 5. PHOTO OPTICAL SYSTEM

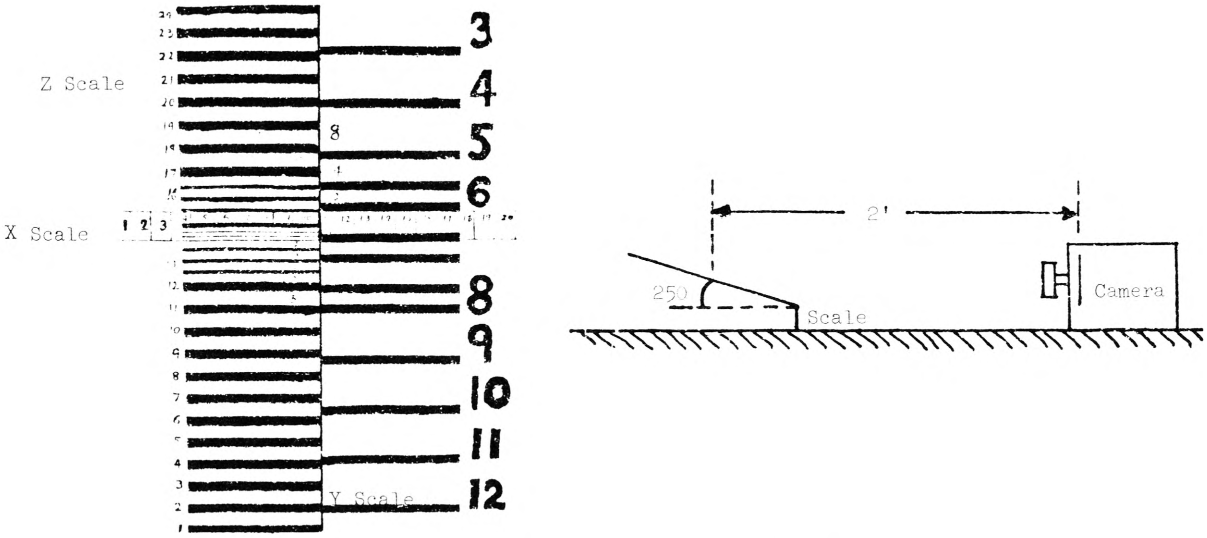


FIGURE 6. THREE-DIMENSIONAL SCALE AND TEST SET UP

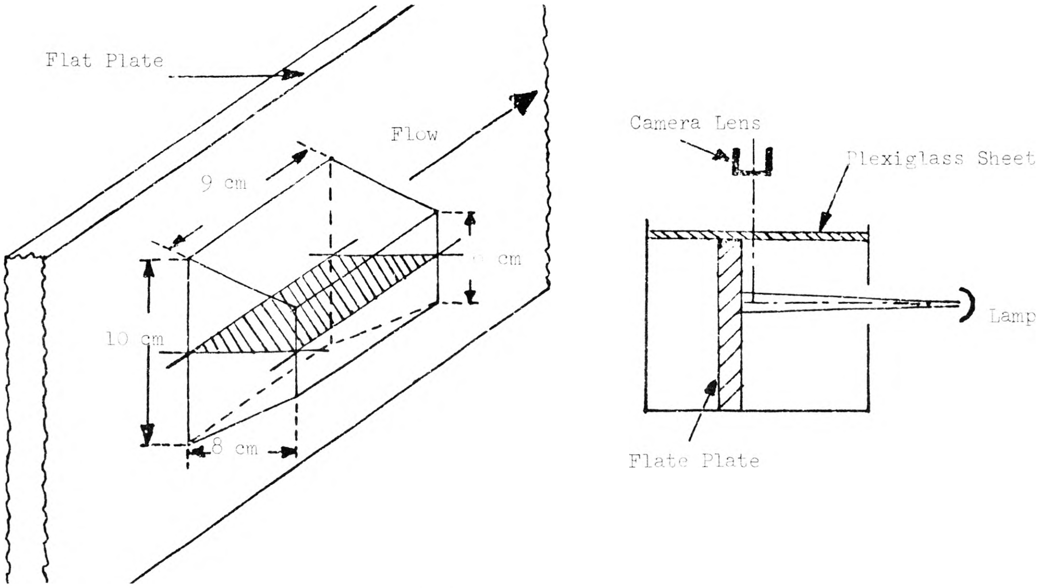
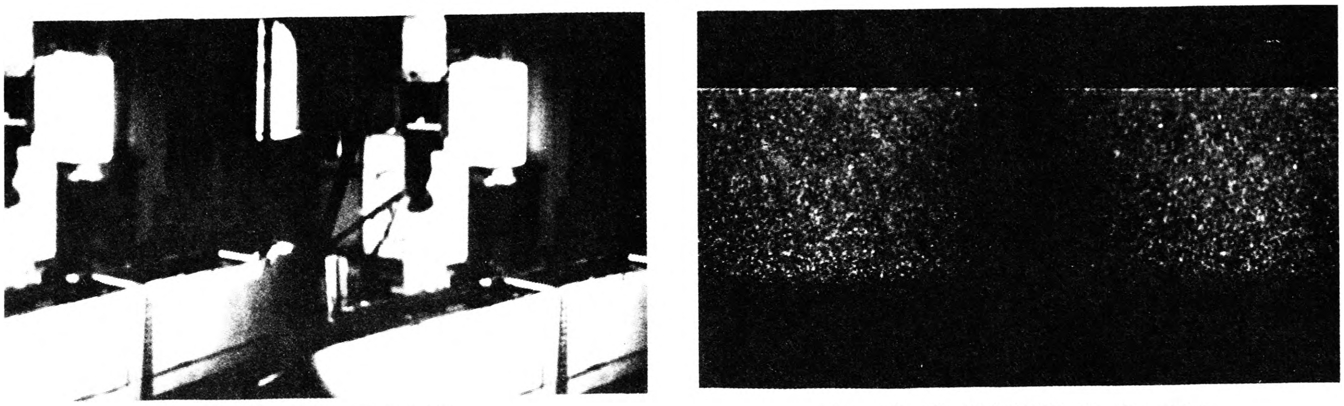


FIGURE 7. FIELD OF VIEW AND CAMERA VIEWPOINT



A. EXPERIMENTAL FACILITY

B. FLUID PARTICLES IN THE FLOW

FIG. 8. STEREO PAIRS