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An Experimental Facility for the Visual Study of Turbulent Flows

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AN EXPERIMENTAL FACILITY FOR THE VISUAL STUDY

OF TURBULENT FLOWS*

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ABSTRACT

An experimental technique which allows visual observations of the wall area in turbulent pipe flow is described in detail. It requires neither the introduction of any injection or measuring device into the flow nor the presence of a two-phase flow or of a non-Newtonian fluid. The technique involves suspending solid MgO particles of colloidal size in trichloroethylene and photographing their motions near the wall with a high speed movie camera moving with the flow. Trichloroethylene was chosen in order to eliminate the index of refraction problem in a curved wall.

Evaluation of the technique including a discussion of limitations is included. Also the technique is compared with previous methods of visual observations of turbulent flow.

INTRODUCTION

During the past several years an experimental technique has been developed for detailed visual observations of the region near the pipe wall, including the viscous sublayer. This technique is unique in that it requires neither the introduction of any injection or measuring device into the flow, nor the presence of a two-phase flow or of a non-Newtonian fluid to complicate and perhaps invalidate the interpretation of results. Basically, the technique involves suspending solid particles of colloidal size in a liquid and photographing their motions near the wall with a high speed motion picture camera moving with the flow.

The many preceding studies of turbulent motions attest to the importance of visual observations in helping to establish the mechanism for turbulent flow, and more particularly, the nature of that flow in the wall region. It has been well-established that the wall region is of extreme importance in the control of transport phenomena and the generation and maintenance of turbulence. It is this latter aspect that makes more extensive knowledge of this region of importance for drag-reducing fluids.

The present facility has been modified to allow measurements on drag reduction fluids. Simultaneously with the visual observations, the pressure drop in the system can be monitored. It is hoped that future visual studies will shed light on the mechanism and reason for drag reduction.

Since only a brief account of the original facility has been presented previously[1], this paper will discuss in detail the system including the recent changes that have been made to add versatility. Evaluation of the entire technique including a discussion of limitations is also included.

GENERAL DESCRIPTION OF THE FACILITY

The flow system, shown in Figure 1, consisted of a 150 gallon carbon steel tank (A)* from which the test fluid was pumped by a centrifugal pump (B) through a control valve (C) to the test section. Two versions of the test section were constructed. The first was a ten foot length of 2-inch ID Pyrex glass pipe (D) preceded by two 10 foot lengths of 2-inch ID glass pipe (adjacent to test section) and one four foot length of 2-inch schedule 40 galvanized pipe (F). The second was a ten foot length of 1-inch ID Pyrex glass pipe preceded by a 20 foot length of 1-inch ID smooth (± 0.0025-inch tolerance on ID) carbon steel tubing (adjacent to the test section 1F) and a 39-inch length of 1-inch ID schedule 40 galvanized pipe of the same nominal pipe diameter as the ID of the test section and a 5-micron filter unit[14].

The flow rate was determined from an orifice (G) in the return line (high flows) or from a rotameter (L) of range 0 to 3 gpm. The orifice meter and rotameter had been previously calibrated by weighing the efflux collected for a timed interval. However, for drag-reduction studies this was not adequate, and an efflux weighing system was developed which is also shown in Figure 1. This consisted of quick turn valves (J), a weigh tank and scale (K). The temperature was monitered continuously by either a thermometer or a thermocouple and when necessary the temperature could be controlled to within 0.1°C by means of heat exchangers (M) located in the return line and a Thermocap relay (I) located at the beginning of the calming section.

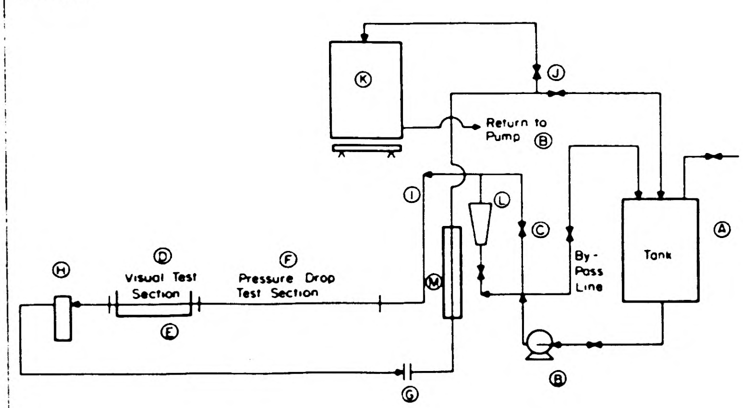

Figure 1 Schematic Diagram of Flow System

The photo-optical system which consists of all the lighting, photographic, and optical equipment needed to record the particle motions on film is shown in Figure 2. The high-speed motion camera (A) was a 16 mm Fastax WF3. The light source (B) consisted of a very high intensity DC mercury arc lamp, Osram HBO-1099, mounted in a metal housing. Behind the lamp was a spherical

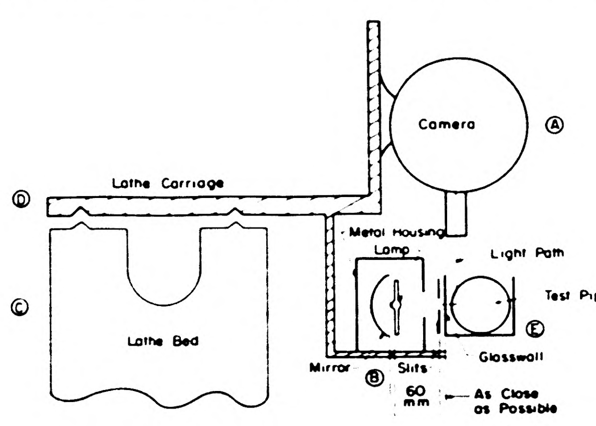

Figure 2 Photo-Optical System

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* Letters refer to marked parts in the figures.

mirror while in front were adjustable slits to provide dark field illumination. The quartz body lamp emitted an intrinsic brightness of 140,000 candles per sq. in. at 100 watts DC. The power supply for the light and low ripple electric filter were standard units from the Gates Co. The test section (2-inch or 1-inch glass pipe) was totally immersed in a rectangular cell (E) filled with trichloroethylene. Trichloroethylene was also selected as the test vehicle primarily because its refractive index (1.474) closely approximated that of Pyrex glass (1.473-1.477). Thus the refraction problem caused by the curved pipe wall was eliminated by the matching refractive indices of Pyrex glass and trichloroethylene.

Both the camera and the light source were securely mounted on a lathe carriage so that the entire photo-optical system could be transported with the flow. The carriage was driven by a Circuit Pak hydraulic power unit coupled to a Sheffer hydraulic cylinder so that any constant speed between 0 and 1 ft/sec was available. Thus any local mean axial velocity in the wall region could be matched by the carriage velocity, and therefore, a particular segment of fluid could be kept in view as the fluid motions developed. A calibrated nichrome resistance ribbon was mounted on the lathe bed and used to monitor the carriage velocity with the aid of a sliding contact mounted on the carriage.

PROCEDURE

The experimental runs were conducted in the following manner: The flow conditions or Reynolds number desired was established by adjusting the control valves in the flow system. The area of view and axial position within the test section was selected, and the photo-optical system aligned and focused accordingly. The filming speed desired was set on the proper controls. The carriage speed was selected, and the controls for the hydraulic drive mechanism adjusted. If the carriage was to remain stationary during the run, the photography was begun at this point. If, however, the carriage were to move, it was first moved upstream beyond the point where photography was to be initiated, and then started downstream. When it reached the initiation point, the camera was turned on. In this fashion, any possible acceleration effects associated with the carriage motion were eliminated before photography was begun.

The filmsresulting from these runs were analyzed in detail to provide the desired information concerning the nature of the fluid motions in the wall region. A short movie* has been made which illustrates the experimental facility and its manner of operation. In addition, the movie gives a very brief summary of the experimental results of the wall region study (1,2,3). Our interest here is not so much in these specific results but rather in the nature and quality of the films shown.

DISCUSSION OF THE FACILITY

The foregoing material provides a general idea of the facility. A somewhat more detailed description is available[3]. Many important details which bear on the validity of the experimental technique and on possible alternate interpretations of the results will be dealt with at length in the following paragraphs.

Fluid

The same fluid and solid marker system was used in all of our studies; however, there were some differences in the manner of dispersion of the solid into the fluid. As mentioned previously, trichloroethylene was selected as the test fluid primarily because its refractive index (1.474) closely approximated that of glass (1.473-1.477). The viewing cell was also filled with trichloroethylene for the same reason. With the glass pipe completely covered with liquid of the same refractive index as the glass, the problems of refraction were eliminated, and the wall region could be examined. Since the light source used was not monochromatic, no attempt was made to achieve agreement in the third decimal place of the refractive indices of the pipe and fluid.

The experimental technique required that the fluid elements be marked for visualization by small particles inhomogeneous with the trichlorethylene. Ideally, the particles should be small in size and of the same density as the fluid. The possibility of using a mixture of liquids which would be inhomogeneous with the main fluid and yet have the same density was considered, but the difficulty of dispersing the material in sufficiently fine form, and maintaining this at high concentrations without coalesence was too great to warrant extensive study. Solid particles of very small size were available, but they have densities greater than the fluid. Fortunately a compromise could be reached. If the particles of solid material were sufficiently small. the fact that their density is greater than that of the fluid would be compensated by the small size. "Seemag" grade magnesium oxide was selected, since its particle size range is excellent, and its shape and density were acceptable. It also did not react with the trichloroethylene, and being inorganic and highly dispersed, showed no tendency to agglomerate. A particle shape that was nearly equal in the three dimensions was considered better than plates or flakes. The general crystal structure of magnesium oxide and statements from the manufacturer indicated that this would be so. This was supported by examination with an electron microscope. The most important feature, however, was the particle size. Seemag as analyzed by the manufacturer with a Fisher Sub-Sieve Sizer was described as having an average diameter of 0.5-0.6 microns, with approximately 0.6% retained on a 325 mesh screen. The approximate particle density was 3.59 as compared to 1.46 for trichloroethylene.

The particle concentration was dense enough so that a large number of particles appeared with the field of view simultaneously, but sufficiently dilute so that particle-particle interaction almost never occured. The test fluid appeared perfectly clear and colorless in normal light and only under dark field illumination were the particles visible. Then they appeared as bright points of light against a dark background. This is a result of the well-known Tyndall or light-scattering effect. It should be emphasized that these particles were suspended in the fluid at all times, and no injection was required during a run.

Several methods of dispersing the particles in the fluid were tried. The most tedious and most successful was to add about 500 cc (by volume) of magnesium oxide powder to approximately 5 gallons of trichloroethylene which was being mixed with a laboratory-type mixer equipped with a turbine impeller. The solution was mixed overnight and then allowed to settle. When the liquid was clear, it was decanted off. This operation was repeated until the particle concentration in the 5 gallon batch reached the optimum for the photography experiments. By this technique it took about four months to make up 55 gallons.

Other techniques were tried and found to be less successful. Concentration by evaporation proved to be a slower operation from the one already described. An Eppenbach colloid mill, model QV6-3, was used to disperse magnesium oxide in the trichloroethylene. The colloid mill, which was powered by a 3 hp 10,000 rpm motor and had a 3 gallon batch capacity and an adjustable shearing blade clearance, could allow the preparation of a 55 gallon test solution in

*Request "The Wall Region in Turbulent Flow" from Motion Picture Division, Department of Photography, 156 W. 19th Ave., The Ohio State University, Columbus, Ohio 43210. A service charge of five dollars is made to cover costs.

one day by first making three gallons of a suspension of concentration of 100 ppm, letting it settle for 10 to 20 hours, and then diluting the decanted layer to 55 gallons.

Unfortunately fluids made with the colloid mill technique seemed to have a general background haze which caused a loss of contrast on the film. Even when the number of particles per unit volume appeared to be the same, the solution from the colloid mill was much more hazy in the photographs. A possible explanation may be in the fact that the extremely high shear rates in the colloid mill result in the particle being thoroughly "wetted" by the solvent whereas in the tedious technique there is only enough wetting to obtain a suspension. Thus in the latter there is an air-trichloroethylene interface and an air-magnesium oxide interface which may contribute significantly to the scattering and make the particles much more visible in the photographs. The disparity between the two methods of preparation is currently under investigation.

After the particles were dispersed in trichloroethylene, the mixture was filtered through a 50 micron and finally a 5 micron filter. The most desirable concentration was determined by trial and error from photographs made under conditions similar to those used in an actual run. These photographs were examined for particle content and degree of particle-particle interaction. The objective was to arrive at a concentration where a sufficiently large number of particles appeared in each frame of the film and yet were dispersed enough so that contact between particles was not a problem. The first is necessary if one hopes to define the fine scale turbulent motions, since if a dilute concentration is present, the separation distance between particles will possibly be greater than the scale of the turbulent motion, and therefore no measurement of it would be possible. This emphasizes another reason why extremely small particle diameters are necessary in a study of this type, for only if the particles are very small compared to the scale of the turbulence can one hope to achieve a large enough concentration to delineate this motion and yet not have particle-particle interaction. The concentration finally accepted fulfilled both objectives. The resulting fluid used in all runs exhibited a particle count in any given frame of the order of 50 to 100 or more, and particle-particle collisions were observed only very rarely. A frame usually had dimensions of 0.069x0.095 inches (4X magnification) and might be thought of involving a volume of fluid of the order of 1.8×10^{-4} cubic inches. A rough calculation of concentration gives a value of 5.6×10^{5} particles/cubic inch, but the volume occupied by all particles, assuming a cubic shape 0.6 microns on an edge, is less than 1×10^{-6}% of the total volume. These particles were uniformly distributed throughout the fluid. Even after standing undisturbed for months in a sealed large diameter vessel the particles did not settle out of suspension. Under proper lighting conditions Brownian motion was visible. This motion was, however, of such relatively small magnitude compared to the fluctuating motions of the fluid that it was never apparent when the fluid was flowing. Even motion pictures taken at high speed of laminar flows failed to reveal any evidence of Brownian fluid. Since this treatment ignores the effects of turbulence and Brownian motion it represents an extreme case. The particle diameter is known to be around 0.6 microns; however, since a 5 micron filter element was used in the line, this latter value was selected for calculation and thus represents the worst possible case. The terminal velocity is

$$U_t = \frac{d^2}{18\mu}(\rho_f - \rho_p)g \quad 1.79 \times 10^{-3} \text{ ft/sec}$$

The important time for consideration is the period during which the particle is viewed. A reasonable value for this time is 3×10^{-3} seconds so the particle can drop 6.4×10^{-5} inches while in view. Comparing this to the viscous sublayer thickness of approximately 4×10^{-3} inches at $N_{Re} = 50{,}000$ in a 2-inch tube shows that the worst possible case gives a movement of approximately 1.6% of the sublayer thickness. For a smaller particle diameter and lower N_{Re} the effect is much less.

At the other extreme would be the initial impulsive starting of a particle from rest. As a model, assume that a particle is surrounded by a fluid element initially at rest which suddenly undergoes an acceleration a_f. Because of the impulsive start of the motion, this is an extreme case. The particle within this element will be accelerated according to the forces exerted upon it, and conceivably could have an acceleration a_p quite different from that of the fluid. For simplicity the only force assumed to act is that described by Stoke's law. $F_p = 3\, d\mu(u_f - u_p)$. Other forces are acting, some in a negative direction to the above force, but they will be small for small velocity differences and are neglected for this simple case. From this model and the assumption that the particle accelerates from zero velocity to u_f in time t, the relation

$$u_f = u_p\,[(d^2\rho_p/18\mu t) + 1]$$

is obtained. Clearly, if $(d^2\rho_p/18\mu t \lll 1$, then $u_f = u_p$. For an extreme case take $u_f = 0.5$ ft/sec, d = 5 microns instead of 0.6 microns, and t equal to the time of a single motion picture frame, i.e., 1.25×10^{-3} sec, the relation be-motion, and it was concluded that these motions would not be a factor when the analysis for turbulent motion was undertaken.

The addition of solids to a liquid could conceivably affect the viscosity, especially its Newtonian character. While magnesium oxide does not show this characteristic, and therefore was very unlikely at the existing dilute concentrations to affect the fluid, there are colloidal materials which in very small quantities drastically change liquid viscosities. Therefore a check of the fluid viscosity both before and after particle addition was made. A long capillary tube viscosimeter was used, and the variation in shear rate necessary for determination of departures from Newtonian viscosity was obtained by varying the height of the constant head tank above the capillary inlet. The measurements for pure and particle-containing trichloroethylene gave congruent straight lines through the origin when shear rate was plotted against shear stress, which showed that the two fluids had identical, constant viscosities. The viscosity was found to be 3.61×10^{-4} lb/ft-sec at 27.5°C. This compares with the published value of 3.64×10^{-4}.

The question as to how well the suspended particles follow the turbulent motions warrants discussion. There are a number of realistic treatments of this problem in the literature but as a prelude to these a simple calculation of extreme conditions can be made to determine if it is reasonable to expect the particle to follow the fluctuations.

Although the particles did not settle out of the suspension upon standing, they are still subject to the force of gravity. At the extreme being considered here, this would cause a downward movement as the fluid flowed through the test section. An estimate of the extent of this movement may be made by considering the terminal velocity of a spherical solid particle suspended in a non-turbulent becomes

$$u_f = u_p\,(.0076 + 1)$$

For this simple analysis of an extreme case the difference in fluid and particle velocity is negligible.

In both of these cases, the particle size enters as the square of the diameter; the conservative estimate of 5 microns versus the average of 0.6 microns actually is more like a factor of 70 or so in the final answer. In the first case one can conclude that the particles will not settle away from the fluid elements, and in the second case one can conclude that the particles will accurately follow the fluid motions.

There are a number of more realistic treatments of the particle-fluid interaction problem. Hinze[4] presents a modification of Tchen's[5] theoretical treatment of the motion of a small particle suspended in a turbulent fluid. Friedlander[6] used an alternate approach to essentially the same problem. In both of these cases the effect of the small particle size is overwhelming so that the particle motions follow the fluid motions in spite of the density differences. These theoretical relations have not included the effect of the presence of a solid boundary on the particle fluid motions. Soo and Tien[7] treated this problem theoretically for a simplified flow system. They considered the effect of an infinite wall on a single, spherical particle suspended in a semi-infinite turbulent fluid. The particle diameter was assumed to be smaller than the microscale of the turbulence. Local isotropy and fully developed flow were also assumed to exist. Once again the particle size outweighs all other considerations and the theory suggests that the particles will truly follow the fluid motions.

Experimental studies of this problem have utilized particles of much greater dimensions than those used in the present study. The smallest particles used in reported experiments [8,9] were of the order of 50 times the diameter of the present particles, and in most studies the size was much greater than this.

Flow System

Great care was taken to minimize disturbances from vibration or from joints. The glass to steel joints were flanges with standard teflon gaskets and were very carefully aligned. All glass to glass joints were the standard supplied by the manufacturer.

It would have been more desirable to use a continuous thirty-foot length of plastic pipe and eliminate the joints entirely. Unfortunately, the requirements that the pipe be transparent, and that the fluid flowing within it be clear, colorless, Newtonian, of low viscosity, and, most important, have an index of refraction equal to that of the pipe, eliminated all potential fluids except hydrocarbons. Of these, the ones of proper index of refraction also attacked the plastic. Thus, glass pipe was the only alternative, and the ten-foot length the only practical length available. The question of the effect of the joints on the flow was examined experimentally. It was observed that the disturbance created by a trip wire (0.0032-inch diameter) propagated only a very short distance as expected. Since the wire extended into the flow further than the joint, it was concluded that in the present study the joints had no effect on the motions observed within the fluid in the test section. To be as conservative as possible in eliminating all possible end effects, only the central part of the 10 foot visual test section was used in the photographs.

The 20 ft. length of drawn pipe which preceded the visual test section was designed to assure that fully developed turbulent flow existed within the test section. Hinze[4] in reviewing the various estimates states that 40 diameters can be used as a minimum value. In the present case, the entry was disturbed, and the entry lengths of more than 40 diameters satisfy even the most extreme requirement. Thus, it may be safely assumed that fully developed turbulent flow existed within the test section. This assumption was checked by hot-film anemometer measurements for the 2-inch line that had an entry length of 145 diameters and was found to be valid. Also the number of diameters of straight pipe downstream from the test section exceeded the literature estimates of the minimum required for an undisturbed test section. In the section of pipe downstream of the test section there was a Selas Flotronic filter (H) with a series F Micro-Filter element which could remove all solids larger than 5 microns. The filter porosity of 5 microns was much greater than the average particle diameter of the solids used, but it was designed primarily to remove any extraneous dirt or agglomerations from the system. An element of 0.5 micron porosity would have required impractically high pressure drops for high flow rates, and so was not used. Periodic examination of the filter element showed that agglomeration of the magnesium oxide was not occurring, indicating that the majority of particles were still of the order of 0.6 microns.

The pressure drop measuring system (F) in Figure 1 is shown separately in Figure 3. Section F was included with the 1-inch test section only. The pressure taps (1/32-inch holes) were valved to one of three manometers whose ranges were 0-40 psi, 0-6 psi, and 0-0.4 psi. Before the equipment was assembled, the interiors were thoroughly scrubbed with trichloroethylene to remove dirt and grease. After assembly, the entire system was flushed with pure trichloroethylene which was then drained.

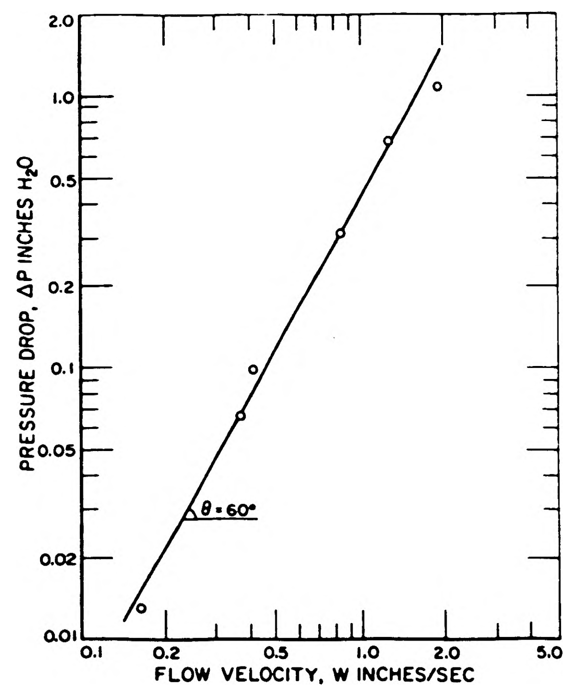

FIG. 3. PRESSURE DROP ACROSS ONE-INCH OF POROUS MATERIAL VERSUS FLOW VELOCITY.

Photo-Optical System

Kodak No. 2475 recording film (black and white negative) was the best all-around film for these studies. It was processed and developed by the laboratory of WBNS-TV, Columbus, Ohio, in a D 19 solution at a rate of 20 ft per min, giving an ASA rating of about 2000. Filming speeds of 650 to 1000 frames per second were used in the 2-inch test section. These correspond to shutter speeds of 0.00051 to 0.00033 seconds, respectively. Best results in the 1-inch tube were obtained at a filming speed of 3500 frames per second.

The 16 mm Fastax camera holds 100 feet of film all of which is exposed at one time. When the camera is turned on, the film accelerates rapidly until the variable speed motors driving the film reach a relatively constant speed. For the very high speeds, a constant filming speed is usually not reached before the end of the roll. An AC timing light makes timing marks in the film margin corresponding to the 60 Hz line current (as discussed in detail later) so that the frames per second and the shutter speed at any place in the roll can be accurately calculated.

The camera was always operated at the lowest possible speed in the range between 650 and 3500 frames/sec for two reasons. First the amount of light available to expose the film was limited even though an extremely powerful source was used. This is because much of the light input passes directly through the fluid and was not transmitted to the camera by the particles (recall that the direction of view is at right angles to the direction of light input). It was possible to obtain exposures as high as 4000 frames/sec, but only at the cost of a considerable reduction in quality of the images and content. The second reason for the limitation is that at higher speeds the real time recorded is reduced so that there is a greater chance of a developing or sequential type occurrence being missed.

The pictures at lower framing speeds were always more satisfactory; thus, since the 2-in. system allowed a lower framing speed, it was always easier to obtain these pictures than in the 1-in. system.

Some magnification of the field of view was necessary for detailed investigation of the fluid motions because the wall region is of such small dimensions. The lens system of the camera was adapted by means of extension tubes and by mounting lenses in reverse to produce magnifications of 4.3X and 2X. These magnified images greatly enhanced the ability of the system to define the fluid motions within the very narrow wall region.

The amount of light from the particles which reaches a unit area of film for exposure is inversely proportional to the extension tube length between the lens and the film plane which produces the magnified image. Since the amount of available light from the particles was limited, any increase in magnification required a proportionate decrease in framing speed for photographs of comparable quality. Thus one must pay for increased information from magnification by reduced information from slower framing speeds or poorer quality images. Another consideration is that as the magnification increases, the field of view decreases. At higher magnifications the field of view becomes too small, and certain aspects of the fluid motion which were larger in scale than the field would not be defined. The 4.3X magnification was found to be most satisfactory as it provided sufficient enlargement of the wall region to permit detailed investigations, but still provided a large field of view.

The actual field of view available at 4.3X was 0.095 inches measured parallel to the pipe wall, and 0.069 inches measured along a radius perpendicular to the direction of view. For 2X the respective dimensions were 0.205 inches and 0.147 inches. The dimensions were measured by photographing a ruled scale with the appropriate lenses, and measuring the image obtained.

Each magnification also had a depth of field associated with it. The depth of field is defined as the thickness of a plane perpendicular to the direction of view in which all objects are in focus. The actual depth of view was determined by the optical system's depth of focus and not by the light beam, since the latter was thicker than the depth of field of the optical system. The depth of the field was determined by photographing with the appropriate lenses for each magnification a hairline mounted on the inclined face of a 45° right angle prism. The resulting photographs showed a line which was sharply in focus over a given distance, less well focused over another distance, and so on until it was completely out of focus. By measuring the length of the line to the degree of focus desired, and knowing the magnification the depth of field can be calculated. This was done for each magnification at the f stops used in the experimental runs. The gradual deterioration of the line focus in the photographs introduced some arbitrariness into the selection of a working depth of focus. The depth of 0.027 inches was selected for 4.3X and 0.041 inches for 2X. The degree of choice was not great. For example, from the photograph at 4.3X magnification the working depth must lie between 0.022 and 0.027 inches.

The field of view is a volume of fluid which for 4.3X is .095 x .069 x .027 inches in axial, radial and line of sight, respectively. Since the field of view is a dimension at a particular magnification, the dimensionless or y^+ distance of the wall region encompassed by a single frame will vary with the Reynolds number. Thus at N_{Re} = 20,000 in the 2-in. pipe the full frame width will include a y^+ of approximately 45 while at N_{Re} = 50,000 this same width will include a y^+ of approximately 90. The corresponding values for the 1-in. pipe are: at N_{Re} = 20,000 $y^+ \approx 90$ and N_{Re} = 50,000, $y^+ \approx 180$.

The light source could be adjusted in all directions. Also within the light source the distance between the lamp and mirror was adjustable. The quality of picture was very sensitive to this distance.

Several types of slits were tried. The object of the slit was to ensure a dark background, and the resultant improvement in contrast more than offset the diminished amount of light. Because of the spherical mirror, a circular slit proved to be better than a horizontal slit. The slit size was determined by trial and error.

The view cell served a second purpose in addition to eliminating the index of refraction problem. An intense light beam focused on the exposed pipe wall could rapidly heat the glass in the area of focus and cause convection currents which at low flow rates might introduce extraneous motions into the pictures. The plate glass and cell fluid effectively absorbed this heat so that the problem was eliminated. In addition, the movement of the light source with the flow during the runs prevented local regions of the cell or pipe wall from becoming heated, although this was not likely under most circumstances of operation anyway. The question of local heating was examined experimentally by photographing laminar flows with the light stationary at a particular axial position. Not only are these conditions most conducive to producing heat effects, but the laminar flow would most readily show these effects if they existed. No such effects were observed.

Cameral Transport Unit

There were two important reasons for moving the camera with the flow. The difficulties with lighting, magnification, and framing speed have already been discussed. If the camera is held stationary at a particular axial position, the framing speed must be increased to slow down sufficiently the mean axial velocities so that the fluid will remain in view for long enough period of time to permit analysis of its motions. This increase in framing speeds results in a decrease in image quality if the magnification is held constant, or necessitates a decrease in magnification to maintain image quality. In either case a decrease in information results. Also, the problem of the real time available for examination in a single roll of film is present. If the real time is reduced to too small a value, the number of reels exposed must increase greatly if a reasonable sampling of the random events of turbulent motion is to be obtained. The second reason for the movement was the discovery that with the camera following the selected fluid elements, the development of certain motions could be readily observed, and the various measurements could be made more easily.

Although the lathe bed was aligned to within 0.03 inches with the pipe over the entire test section, over shorter sections used for most of the studies the alignment was much better. No further improvement of the alignment was possible because of the flexibility of the glass pipe and the necessity of not having any solid support on the top or front face of the pipe. The test section alignment was carried out by using the camera view finder with 4.3X magnification.

Fortunately, this degree of alignment was perfectly satisfactory. The position of the wall was visible in the field of view, and prior to each run it was aligned so that it would appear in all frames. This necessitated sacrificing part of a frame by having the wall position within the frame at some axial positions so that the wall would just be aligned with the edge of the frame. Over the short sections used for most studies the alignment was quite good and the wall could be maintained at the edge of the frame. Vertical alignment was established by mounting a feeler gauge on the carriage and keeping it in contact with the pipe surface while adjustments were made.

To check the nichrome ribbon recording device and to check the constancy of the carriage movement, a steel tape was mounted on the pipe surface, and high speed motion pictures taken of it while the carriage was moved downstream. The carriage velocity was recorded and calculated. Two different but representative velocities were checked in this fashion. The timing marks on the film and the scale image in the frames permitted an accurate calculation of the absolute carriage velocity for each inch or fraction of an inch of carriage movement. In actuality, 3-inch segments were examined. It was found that there was no variation in carriage velocity from segment to segment, i.e., it was constant. The velocity determined in this fashion agreed with the values given by the recording device. The photographically determined velocities were 0.680 and 0.208 ft/sec, and the recorder values were 0.679 and 0.209 ft/sec, respectively, for the 2-inch tube whereas for the 1-inch tube 0.86 and 0.43 ft/sec were compared with 0.83 and 0.40 ft sec. The films also showed that there was no vibration of the system which affected the photographs.

Camera Viewpoints

Although the camera line of sight must be at right angles to the light beam, there is some choice as to the position of focus.

Wall View. In Figure 4, as part (a) shows, the light beam enters the field

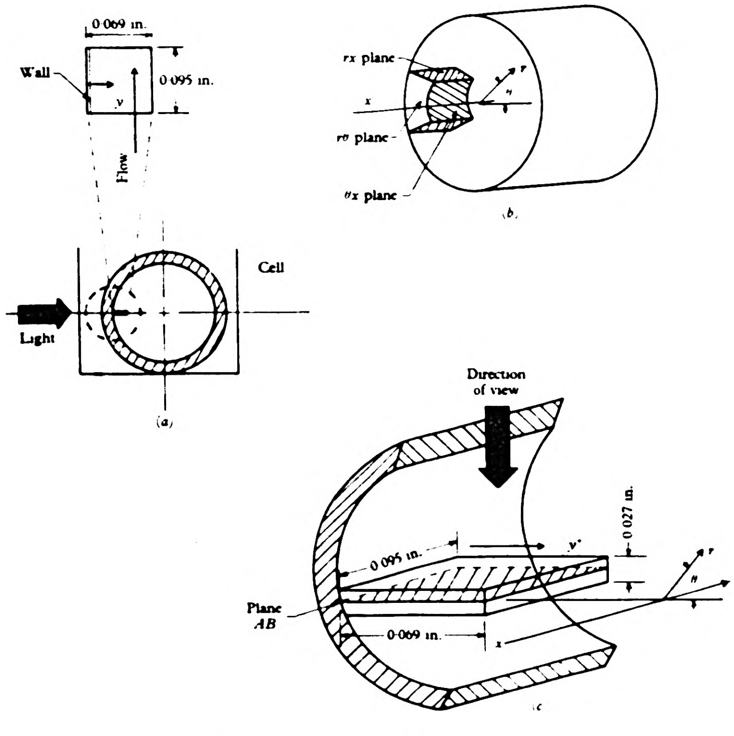

Figure 4 Wall View (From Ref 1)

at right angles to the line of sight of the camera. The camera is focused on a horizontal plane AB (part c) with the interior pipe wall aligned with the edge of the frame. Part (b) of this figure shows the orientation in polar coordinates. If the camera were focused only at the geometric plane AB, the view would coincide exactly with the rx-plane of the polar coordinates. However, as part (c) shows, the camera acutally "sees" a certain distance on either side of this plane along the line of sight due to the depth of field of the lens system. Since the lenses present flat surfaces parallel to AB for the camera to view, these planes separated from AB by one-half the depth of field will not coincide with the rx-planes at that position. However, because of the extremely small dimensions of the field of view, the actual differences are insignificant and no differentiation need be made. Because of the depth of field, the camera actually "sees" a volume of fluid and not a plane, although the thickness of this plane is quite thin. Since the optical system cannot show three dimensional effects in the motion pictures, the particles within this volume all appear to be on a single rx-plane, and in this view there is no accurate means of determining at which rx-plane within the volume they are located.

The refraction of the light beam from within the pipe at the wall was calculated. At a distance of 0.002 in. from the wall (about a y^+ 2 at N_{Re} 50,000 in the 2-inch tube and less for lower N_{Re} values) the incident beam had an angle of 86° 23', and the refracted beam an angle of 87° 19'; thus very little distortion occurs. A similar calculation was made to determine the distance from the wall at which the light beam would have to originate in order to be totally reflected internally at the pipe wall. This distance was 0.0009 inches, which for the present experiments is always less than a y^+ of one. This is only an approximation because monochromatic light was not used, but it is a good estimate. This distance can be considered the distance which the wall refraction effect intrudes into the sublayer. Because not all the light is refracted and some is transmitted, and because a monochromatic light source was not used and it is probable that at some range of wave lengths the index of refraction of the glass did equal exactly that of the fluid, one can expect that a dark region slightly larger than 0.0009 inches will exist in the sublayer, but because some light is transmitted, motions within the region should still be visible.

Top View. As part (a) Figure 5 shows, the light enters at right angles to the camera line of sight, but in this case the light is directed to the interior wall region at the top center. This view is essentially rotated 90° from the wall view. The line of sight is now along the r coordinate, and the planes

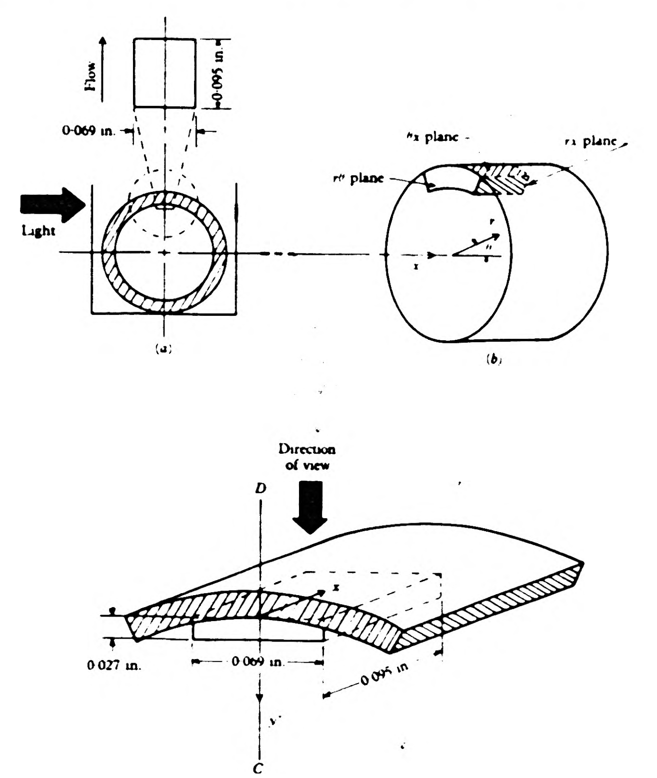

Figure 5 Top View (From Ref 1)

perpendicular to the direction of view are θx-planes because of the small depth of field, and there would be motions parallel to the line of sight in the wall view, just as the motions of the wall view in the rx-plane are parallel to the line of sight in this view. Although these viewpoints were used separately, careful analysis of each series of films permitted a three dimensional picture of the fluid motions to be constructed.

Since the wall of the pipe did not appear in this view, the camera alignment procedure was more elaborate. A positioning scale was inserted into the pipe from the downstream end by a long steel rod. The brass collar supporting the scale was designed to push the edge of the scale against the inside pipe wall surface. The scale was first aligned with the AB plane of Figure 4. The viewfinder of the camera was sighted in on the appropriate scale reading which corresponded to the pipe radius and the lateral movement mechanism locked in place. The other adjustment concerned the focusing of the camera on the θx-plane at the inside pipe wall. This was accomplished by rotating the brass collar so that the scale was aligned with the CD plane of Figure 5. The camera was then focused on the brass collar surface such that the upper limit of the depth of field coincided with the surface. Since the collar was in contact with the pipe wall, this adjustment meant that the entire depth of field was available for viewing from the inside pipe wall radially inward. After this adjustment, the scale was removed.

Away from the wall. The limited dimensions of the field of view permitted observations to only small y^+ positions when the camera was focused at the wall. In order to examine the fluid motions at greater y^+ values, it was necessary to focus the camera at greater distances from the wall as measured along the AB plane of Figure 4. The resulting views were essentially the same as the wall view, but displaced varying distances from the wall. In order to position the camera, the scale device described in the top view section was used. In this case, of course, the focus was at the plane AB.

ANALYSIS OF PHOTOGRAPHIC FILMS

All analyses of the fluid motions were made from projections of the motion picture films. Furthermore, only films of good, comparable quality were used in the detailed analyses. The films were projected by a motion analyzer onto a screen ruled with a rectangular grid. The speed and direction of projection could be controlled. The projected image magnified the film image by 93X so that the films taken at 4.3X showed the wall region magnified 400X on the screen. The increase in magnification by the projector made the observations and measurements easier by revealing all that was on the film on an expanded scale. It could not, of course, do more than this, so in a real sense the important magnification was the one at which the films were taken. The rulings on the screen were drawn to the scale of the magnified image so that each line of the grid corresponded to a given dimension of the wall region. To be certain that the proper magnification and alignment were used for all analyses, the grid was marked with reference lines which correspond to marks on a calibration film. This film contained an image of a grid where the spacing between lines was accurately measured with a microscope equipped with a micrometer eyepiece. By aligning the screen calibration marks with the corresponding marks on the projected image of the calibration film, proper magnification of the projected image was attained.

The projector was adapted to count the number of frames of film projected by installing a minature microswitch under the film advance sprocket wheel and connecting it through a switch to an electric impulse counter. As the sprocket wheel turned, it opened and closed the microswitch one time for each frame. This ability to count frames was necessary for the determination of real time as opposed to projection time. The counter was periodically calibrated by using a strobotac to measure the sprocket wheel revolutions. Timing marks, which appeared as distinct dark streaks, were automatically imprinted on the film margin at 120 marks/second. By measuring the number of frames of film covered by the timing mark the filming speed in frames/second could be calculated. Then by counting a number of frames during which a particular event occurred, the real time of occurrence could be determined. This proved to be an excellent means of timing events of very short duration because the high-speed photography caused even these events to appear over a large number of frames, very seldom less than 29, usually more, and the low-speed projection permitted the event to be seen and the frames accurately counted.

Among the most important measurements that can be made are those of particle velocities and trajectories. In each of the camera views, but in particular the wall view, the motions of particles or fluid elements across the projection grid were quite readily determined. In many cases the particles exhibited a straight or only slightly curved trajectory, so that by recording the grid coordinates at the beginning and end of a particular movement, and counting the frames elapsed, the velocity of the particle as well as the trajectory could be calculated. This procedure neglects the three-dimensional movement of the particle, i.e., movement along the line of sight, and so underestimates the velocity in most cases. Since some estimate of the extent of this three-dimensional movement is available from the two views, the potential error can be estimated. For low N_{Re}, which should be the worst case[3], the error was less than 4 per cent.

The study of the u_r or u_θ fluctuations is greatly enhanced by the fact that the carriage moves with the flow. This movement reduces the relative motion between the camera and the local mean axial velocity, and the apparent axial velocity is often of the same magnitude as the u_r or u_θ velocity. On the films these motions appear as deviations from axial flow. Since the camera moves with the flow, these deviating particles remain in view for a longer period of time, and therefore travel a greater observable distance. The motion of the camera is matched to the local mean axial velocities at selected y^+ positions. At these positions the particle motions have approximately zero relative velocities, and a reversal of apparent direction u_x velocity occurs as one moves from the wall toward this y^+ position and then beyond it. During any run, the carriage velocity is constant, so if the position of zero relative velocity changes, it must mean that the u_x velocity has changed. This permits some observation of large fluctuations in the x-component, but generally these fluctuations are not as readily observed or measured as u_r or u_θ.

In addition to the various measurements, the different films were carefully and systematically analyzed for qualitative information concerning the fluid motions. The position of occurrence and dimensions of various occurrences could be readily noted because of the scaled grid on which they were projected. From the observations of the movement of particles separated by various distances, some estimate as to the size of the disturbances could be obtained. If a group of particles covering a given region of the grid moved together as a deviating element, it could safely be assumed that they were all part of a single disturbed eddy. Since the scale of these disturbances in the wall region was less than the field of view, this method was quite effective. Often more than one group of particles could be observed within the field, each group moving differently from the other, but at the same time.

In order to determine the position of occurrence of any event from the projected image, it was necessary to align the wall of the pipe as it appeared in the image with the line corresponding to the wall on the grid. Once this was done all positions relative to the wall were fixed. Due to the imperfect matching of the index of refraction, a thin dark line appears in the motion pictures at the wall position. Careful examination of the motion pictures showed that particle motions were visible within the darkened region. This region was always very small compared to the frame width, and was very dark only within an extremely narrow line at the wall-side of the region. During the analysis, this dark line was aligned with the line on the grid corresponding to the wall. The lack of absolute precision in locating the wall causes some uncertainty in the location, with respect to the wall, of particular events, but this uncertainty was definitely less than 0.002 inches, as discussed earlier.

The effect of refraction was not present in the top view, and it afforded an excellent opportunity to examine the sublayer region. The observations from this view generally confirmed those made in the wall view.

COMPARISON WITH OTHER TECHNIQUES

The experimental method used in this study has some distinct advantages over other type visualization methods which inject (or displace) a dye or use a birefringent fluid. Even if the latter could show sufficient detail to reveal the fine structure of fluid motion (this ability has yet to be demonstrated), the fact that the fluids are highly non-Newtonian in character introduces a number of uncertainties into an already complex problem. For one thing, the mean velocity profile cannot be accurately predicted for such fluids. Dye or particle injection techniques require a mechanism to inject the material into the flow, and in the wall regions the effect of such a mechanism can be a source of concern. The present method, of course, requires no injection since the particles marking the flow are uniformly distributed throughout the fluid. This distribution provides another distinct advantage over dye injection methods. In these the tracer fluid is injected at a point or line, and the fluid motions cause the tracer to spread and assume various configurations. From these configurations, information concerning the fluid motion is deduced. The diffusion and spread of the dye is an unsteady state process. While it might satisfactorily delineate the fluid motions in a steady-state flow, for turbulent flow it is less satisfactory. This is especially true in the wall region where the fluid motions exhibit locally a distinct unsteady state nature beyond that of the quasi-steady turbulent flow. In this region, the combination of a developing dye field with a developing velocity field compounds the difficulty of interpretation. Another factor is the uneven distribution of dye after development has proceeded for a time. This leaves high dye concentrations in areas of low velocity and depletes the dye in the area of high velocity. Thus the motions of the fluid in the high velocity regions are not marked. With the uniformly distributed particles of the present study both of these disadvantages are removed. In addition the particles permit a more detailed study of the fine structure because they mark very small elements of fluid and not large regions as dye does. Finally, because the particles are not segregated or dissipated with time, they permit the study of a developing motion over a longer period of time than do injection methods.

For unsteady state flow, tracers injected at a point produce streak lines which define neither streamlines nor the paths of individual fluid elements. The particles, being distributed and marking local fluid elements, define these paths and thus are pathlines. This is a fundamental difference, and although for simple unsteady flows streaklines, streamlines, and pathlines may be calculated from one another and a knowledge of the velocity field, for unsteady turbulent motion this is impossible.

Although these alternate methods of flow visualization are more difficult to interpret, they can be modified so as to allow interpretation. As a prime example of this, the reader is referred to the hydrogen-bubble technique which has been brought to a high degree of perfection by Kline and his co-workers[10]. The accord between the results obtained by the present technique and those of Kline et al. are excellent and are detailed in references 1 and 2.

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SYMBOLS

d	particle diameter
F	force
g	gravity
N_{Re}	Reynolds number for pipe based on center-line velocity
t	time
u	velocity
U_t	terminal velocity
X	times
y^+	dimensionless distance from wall = U^*y/ν
ρ	density
μ	viscosity
ν	kinematic viscosity
Subscripts	
f	fluid
p	particle
x, r, θ	pipe directions

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