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SUBJECT: Instantaneous Velocity Profile Measurement
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(Report prepared by H. W. Hoffman)

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APPENDIX II

Description of Apparatus

A schematic drawing of the experimental apparatus is shown in Fig. 20. The phosphor-containing fluid was pumped from a storage tank, through a surge volume, and thence to the test section. The direction of flow in the test section was controllable through a series of valves; the flow rate was determined either by an orifice plate and a mercury manometer or by a set of Fischer-Porter Rotometers. The geometries studied were as follows:

- 1) 3-in.-ID pipe having an entrance region of 34 tube diameters followed by a Pyrex glass test section of 22 diameters.
- 2) 1-in.-ID glass pipe with $L/d = 60$.
- 3) 2.5-in.-ID transparent Plexiglas section of $L/d = 20$ with a hydrodynamic entrance of $L/d = 50$.
- 4) $1/4$ -in. x 6-in. Plexiglas wedge of 8-deg half angle (Fig. 21).
- 5) 1-in.-ID glass tube arranged in a single loop of 12-in. diameter (Fig. 23).

For the quantitative studies, a grid, constructed from $1/16$ -in.-thick Plexiglas sheet on which was scribed rectilinear co-ordinate lines, was inserted in the test piece. When this plastic sheet was edge illuminated (in a darkened room), sufficient light was scattered from the interior by the grid lines to enable photographic recording of the grid. If the system was then filled with water (the phosphor suspension medium), the optical distortion could be evaluated. The grid and profile photographs, taken from a fixed camera position, were then superimposed. A typical result is shown in Fig. 15.

The light source was a General Electric FT-503 xenon-filled electronic flashtube. Power was supplied to this flashtube by four condensers capable of charging to 3200 watt-seconds. The condensers and the associated Sunlight Master Power Supply (converting 115-volt 60-cycle AC to high-voltage DC) were manufactured by the American Speedlight Corporation. The flash duration was $1/1250$ sec, and the light spectrum was approximately daylight (6500°K). The strength of the source, using a 16-in. parabolic reflector, was 100,000 beam candle power seconds (BCPS). Only a small portion of the total energy was used since a light collimator (consisting of a pair of holes of either 0.182-in. or 0.250-in. diameter) was located between the source and the test section. While smaller diameter collimators were tried with the 1-in.-dia tubes, it was observed that the phosphor activation was too weak for photographic purposes.

Two cameras were used in the course of these experiments: (1) a 4-in. x 5-in. Grover Monorail equipped with a Ernemann Ernostar coated $f/1.8$ lens with a focal length of 125 mm and (2) a Leica 111-f with a 50-mm Summarit $f/1.5$ lens. The Ernostar lens was mounted in a Wollensak No. 5 Alphax shutter having speeds ranging from $1/2$ to $1/50$ sec. For faster speeds, the Leica was used. The camera was placed at approximately a 90-deg angle to the light beam. This is illustrated in Fig. 23 for the helix geometry, the camera of course being located such that it viewed the tube. The camera shutter was manually controlled. The zero-time position was obtained by flashing the light source with the shutter open; the shutter was then closed and reopened some time later to record the velocity profile.

The time lapse between the initial flash and the recording of the profile was measured with a conventional Hewlett-Packard Electronic Counter actuated by a start-stop pulse originating in a manual trigger unit. This trigger consisted of a DPST push-button switch which simultaneously flashed the light

source and activated a circuit sending a pulse to the start side of the counter. When the camera shutter was opened to record the profile, internal contacts on the shutter completed a second circuit sending a pulse to the stop side of the counter.

A number of phosphors were studied to establish optimum matching of the emission spectra of the phosphors with the spectral sensitivities of the films available. Thus, equal quantities of five phosphors were placed in water-filled tubes. These were mounted, along with a water-only control, so that they received constant agitation and uniform light. Figure 24 shows a photograph taken approximately 0.2 sec after excitation of the phosphors. The outline of the control results from reflection of the light originating in the phosphor-filled tubes. Two Eastman films (Royal Pan and Royal-X Pan) and duPont's SX Pan were studied; the photograph of Fig. 24 was obtained with Royal-X Pan. This film is a new product developed by Eastman for night sport or indoor with existing illumination photography where exposure times must be short to freeze the action. The exposure index (ASA 200) is 2 to 4 times that of the more standard Royal Pan, varying of course with the development history. The color sensitivity of the negative film is panchromatic Type B (high green, low red). Qualitative examination of the exposed negatives indicated that the two yellow phosphors (Zn-Cd sulfides), duPont 1302 and duPont Q11-2403, gave maximum visual density. Finally, these two phosphors, along with the duPont 1300, were tested with the Eastman Royal-X Pan and the duPont SX Pan. Both films were exposed to the three phosphors for 1 sec at $f/4.7$ approximately 1 sec after excitation of the phosphors by an ultraviolet source. The films were developed for 8 min in duPont X-ray developer. Resulting transmission densities are given in Table 1 along with

several pertinent physical characteristics of the phosphors. On this basis the combination of duPont 1302 phosphor and Eastman Royal-X Pan was selected.

Table 1. Film and Phosphor Data

duPont Phosphor	Net visual Diffuse Transmission Density ¹		Phosphor Properties ²		
	Eastman's Royal-X Pan	duPont's SX Pan	Avg. Size Microns	Density (gm/cc)	Settling Velocities (cm/sec)
1302	1.87	1.46	18.1	4.59	0.941
Q11-2403	1.71	1.22	11.8	4.60	0.613
1300	1.71	1.26	26.5	4.40	1.010

¹Data obtained by H. W. Knop, Jr., and Emery Meschter at duPont's Parlin Research Laboratory, Parlin, New Jersey.

²Density and settling velocity measurements made by C. M. Boyd of the ORNL Analytical Chemistry Division.

APPENDIX III

Errors in Analysis

To obtain accurate quantitative velocity data, a number of factors must be considered in the analysis of the photographs. Thus, corrections should be applied for (1) the finite shutter speed, (2) turbulent mixing, (3) particle settling, and (4) residual errors associated with the timing circuits and interpretation of the profile photographs (particularly with respect to its edges).

Shutter Speed Corrections

At high values of the Reynolds modulus, it was observed that the profiles were "smeared out". A major cause of this was the motion of the phosphorescent band during the finite time the shutter was open. To illustrate this consider the 4-in. x 5-in. camera at an aperture of $f/1.8$ and a nominal shutter speed of $1/50$ sec. Measuring from the instant of shutter release ($t = 0$), 19.5 milliseconds elapse before the shutter is completely open. The timer contacts within the shutter are activated at $t = 23.5$ milliseconds, sending a stop signal to the counter. The shutter remains open until $t = 37$ milliseconds and is fully closed at $t = 51.5$ milliseconds. Then, if it is initially assumed that sufficient film density results only when the shutter is fully open, the leading edge of the profile will move approximately 0.84 in. (using an average velocity based on $N_{Re} = 80,000$ in the 2.5-in. pipe and a nominal shutter speed of $1/50$ sec). About 0.58 in. of the travel will occur in the 13.5 milliseconds following the stopping of the counter. This correction can then be applied at the radius at which the fluid is moving at the average velocity. The radial location of this average velocity is

established by plotting y/y_0 (the ratio of the axial distance traveled by the leading edge at any radial position, r , to the maximum as measured at the tube centerline) as a function of the radius ratio, r/r_0 . By graphical means, this plot is used to evaluate the integral defining the average, i.e.,

$$\overline{(y/y_0)} = \frac{\int_0^1 (y/y_0) d(r/r_0)}{\int_0^1 d(r/r_0)} .$$

Then, the r/r_0 at which the average velocity exists can be read from the original plot; and the corrected leading edge profile can be drawn. In similar fashion, the adjusted profile for the trailing edge (correcting for motion during the 4 milliseconds between full shutter and stopping of the counter) can be determined. The extent of these corrections can be reduced by going to faster shutter speeds. Thus at 1/500-sec exposure, the motion is cut to 1/10 of the above values; i.e., the leading edge profile will travel only 0.084 in. This is illustrated by the series of photographs in Fig. 8 taken at various shutter speeds.

Settling Velocity Corrections

Since the density of the phosphor particles is somewhat greater than that of water, it is to be expected that there will be some settling of the particles. This effect will probably be significant only in the laminar flow regime; in turbulent flow the gross eddy motions of the fluid will counteract the settling phenomena. The motion of the particles can be estimated from the settling of particles under no flow conditions; the settling velocities are listed in Table 1. Then, the product of the settling velocity

and the time the shutter is open yields the distance the particles fall. By way of example, for a time lapse of 1 sec (as existed between excitation and recording of the profile in a typical run at $N_{Re} = 640$ in the 1-in. pipe), the duPont 1302 phosphor particles would have settled 0.37 in. Recent work by Happel and Brenner (AICHE Journal, 3, 511, 1957) indicates that a radial concentration gradient exists in flowing suspensions, peaking in the vicinity of the wall. It is to be expected, then, that the settling velocity will not be uniform across the tube. In the present experiments, however, the settling correction has been applied evenly over the central portion of the profile.

Diffusion Corrections

Through particle transport, whether by macromolecular diffusion or turbulent eddies, there will occur a "smearing" of the initial well-defined band of excited particles. In the laminar flow regime, the effect is sufficiently small to be neglected; for turbulent flow, however, this could be an appreciable factor. This is rather difficult to determine; and initially it has been assumed that it is sufficient to draw the profile, around a mean for the adjusted leading and trailing edges, with a width equal to that of the original activated band.

Some estimate of the magnitude of this effect may be possible from very recent work by Hanratty and Hisao (Engineering Experiment Station, University of Illinois, Technical Report No. 7, March, 1959) on the "Diffusion from a Source of Mass for Turbulent Flow of Water and of Slurries in a Pipe." In addition, the data of Laufer, as described by Townsend (Structure of Turbulent Shear Flow, Cambridge, 1956, p 212), showing a nonuniform

distribution in the turbulent intensity may enable some calculation of this correction as a function of position within the pipe.

An allied correction involves the increased width of the initial activated band due to movement of the particles through the light beam during the finite exposure time. Thus, at a Reynolds modulus of 80,000 in the 2.5-in. pipe, the original 0.25-in. band width was increased by 0.034 in. (approximately 13%).

Time Corrections

With the Hewlett-Packard counter, the time interval measurement is believed to be quite precise. For completeness, however, two factors contributing to errors in the time may be considered:

- (1) The stability of 100 kc crystal standard used as the time base; this is listed as $\pm 0.0005\%$.
- (2) The phasing between the timing pulse operating the electronic gate and the number of pulses passing through the gate is estimated at ± 1 count.

For a flow in the 2.5-in. pipe at $N_{Re} = 80,000$ (time interval = 49.12 milliseconds), this leads to a maximum timing error of $\pm 10.25 \mu\text{sec}$, or about 0.02%.

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(a)

(b)

(c)

(d)

SHUTTER SPEED: 1/50 sec

1/75 sec

1/200 sec

1/500 sec

Fig. 8. Instantaneous Velocity Profiles Showing Effect of Exposure on Profile Width. Flow in 2.5-in. Plastic Tube at $N_{Re} = 80,000$. $f/1.5$ Lens.

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Fig. 15. Instantaneous Velocity Profile Photograph
for Turbulent Flow in a 2.5-in. Plastic Pipe.

Fig. 20. Schematic Diagram of Flow System.

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Photo 23426

-13-

Fig. 21. $1/4'' \times 6''$ Wedge with a Half Angle of 8°

Unclassified
Photo 27736

Fig. 24. Demonstration of the Actinic Values of Five Different Phosphors

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