APPENDIX I

Fig. 9 shows for Run 1AB the theoretical acceleration of the water column against time, as well as the percentage of the total hydraulic head loss with respect to the acceleration head applied to the water column. As a consequence of the relatively short pipeline and due to the relatively large acceleration heads instigated, the total hydraulic losses are insignificant when the accelerations are large. The percentage of the total losses attains a significant value only in the intervals of time when the accelerations are nearly zero. These times however are very small in comparison to the times during which the large accelerations persist, and lead to the conclusion that the evaluation of the hydraulic losses is not critical. (This was substantiated when calculations employing drastic changes in friction factor, indicated negligible changes in the other parameters.)

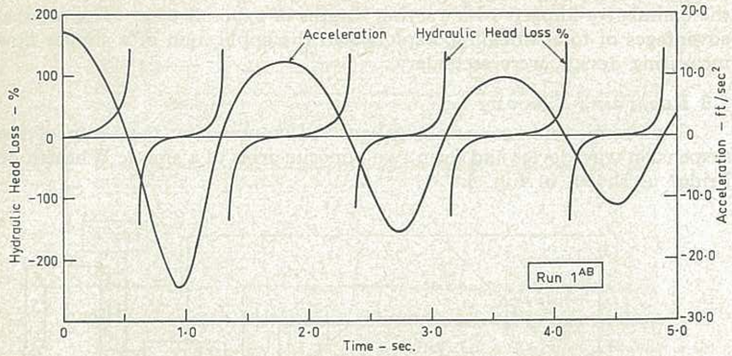

Fig. 9.—Variation of Hydraulic Losses.

APPENDIX II

Initial Laboratory Data

Run 1AB

S_{11}	54.0 ft.	H_{atmos}	33.8 ft.
S_{12}	3.4 ft.	H_A	73.6 ft.
S_{21}	10.0 ft.	H_1	33.8 ft.
d_1	0.166 ft.	X_1	6.00 ft.
d_2	0.168 ft.	T_1	528.0 °R.

A New Technique for Discrete Particle Study in Turbulent Flow

By B. B. Sharp, M.E., Ph.D., M.I.E.Aust. and I. C. O'Neill, M.Eng.Sc., B.C.E., M.I.E.Aust.*

Summary.—This paper describes the development of a new system for measuring the mean particle concentration distributions in turbulent pipe flow suspensions. The device incorporates a fine wire suspended across a pipe diameter and the entire instrument can be rotated about the pipe axis, enabling the entire cross section to be sampled.

The technique of measurement described was developed as part of an investigation into the behaviour of dilute discrete particle suspensions and the scope of this paper is limited to this application. Special problems of accuracy were involved and these were overcome with the aid of an electronic counter circuit.

Although the example described concerns spherical particles, equally satisfactory results have been obtained with large irregular nylon pellets —only particles of a fibrous nature have proved unsuitable.

1.—INTRODUCTION

The need for further experiments into the behaviour of discrete particles in turbulent flow was emphasised by Batchelor in the opening address at the last Australasian Conference on Fluid Mechanics (Ref. 1). Such studies have applications in the practical areas of hydraulic conveying, sediment transport in natural streams and environmental control.

The question of mean particle concentration distribution is of particular fundamental interest as much useful information regarding, for example, particle diffusivity, gravity influence and boundary effects can be inferred from such data.

The experimental techniques available for determining mean concentration distribution in turbulent pipe flow include visual observation, volumetric sampling, the use of a conductance probe and radiation detection methods. Two widely different optical methods have been described by Barnard and Binnie (Ref. 2) and by Segré and Silberberg (Ref. 3). The major disadvantage of all visual methods is that they are not feasible in many practical situations. Volumetric sampling along the lines used by Elata and Ippen (Ref. 4) in open channel flow would only be of practical value in pipe flows with relatively fine particles. Conductance probes such as the one apparently used by Durand (Ref. 5) and the one recently developed by Sharp and Fish (Ref. 6) suffer two main disadvantages for the present application—firstly, it is difficult to design a suitably small probe and, secondly, these probes require extensive experimental calibration if the signals are to be meaningfully interpreted. An example of a radiation detection method may be found in the work of Du Plessis (Ref. 7).

The purpose of this paper is to describe a new technique for studying the behaviour of turbulent suspensions, in particular the measurement of mean particle concentration distribution. The application of the method is part of an investigation into the behaviour of suspensions in turbulent pipe flow but the scope of this paper is limited to discrete particle observation.

Sharp (Refs. 8 and 9) described the development of a flow measuring device which depends for its operation on the fluid drag on a fine wire suspended across a pipe. This paper describes the adaptation of this equipment to the detailed detection of particle impacts along the wire. Using a retractable shield it is possible to vary the length of wire exposed to the flow, thus enabling relative frequencies of particle occurrence to be assigned to various positions along any pipe diameter.

2.—EXPERIMENTAL EQUIPMENT

2.1 Flow Circuit:

Fig. 1 illustrates schematically the flow circuit in which circulation was achieved by an open impeller type pump through a 2-in. dia. clear plastic pipe with a 1-in. dia. return pipe. The flow rate was measured by an electromagnetic flow meter and a continuous filtered water supply to the balance tank near the pump suction assisted in temperature control and compensated for gland losses.

The addition and removal of particles to the flow proved most convenient at a tee connection to the return pipeline where it passed through

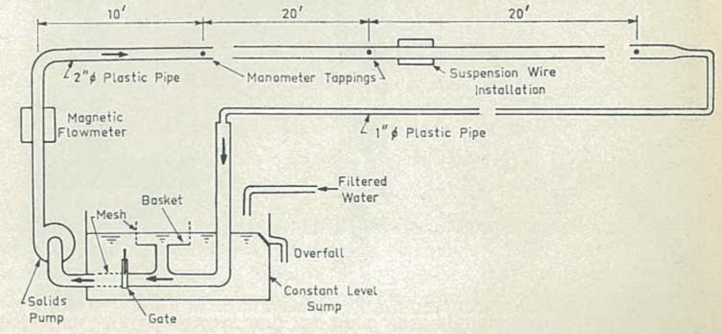

Fig. 1.—Schematic Diagram of Flow Circuit.

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the balance tank. The depression of pressure in the wake of a nozzle caused a small flow down a funnel and tube, thereby assisting the flow of particles from the storage container. Removal of the particles was achieved by closing a small gate just downstream of the injection point with the injection nozzle removed. (Further downstream of the gate a screen connection permitted flow to continue through the circuit from the balance tank.)

2.2 Suspension Wire:

The suspension wire device was located nearer the downstream end of the 2-in. pipe section and, as shown in Fig. 2, is similar in design to the original form developed by Sharp (Ref. 8). One important additional feature in this installation is the facility of complete rotation of a 6-in. length of the pipe incorporating the device as shown in Fig. 3. To prevent leakage a transparent plastic cylinder encases the tube and the shield is operated by a guide through a gland. A scale is engraved on the tubes for measurement of the shield position.

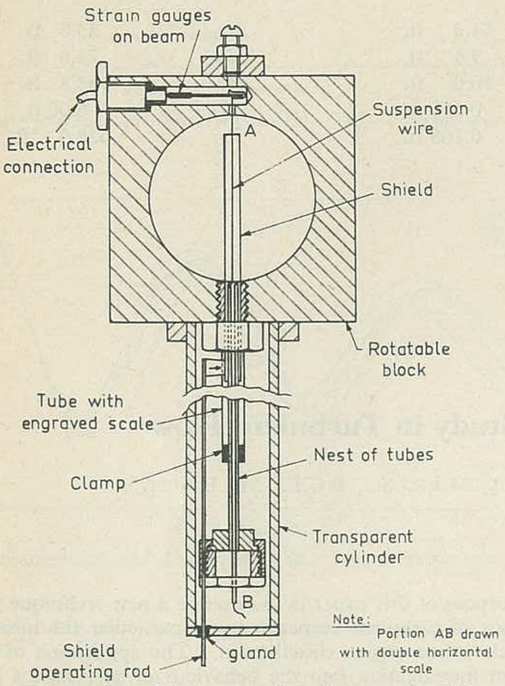

Fig. 2.—Detailed Construction of Suspension Wire.

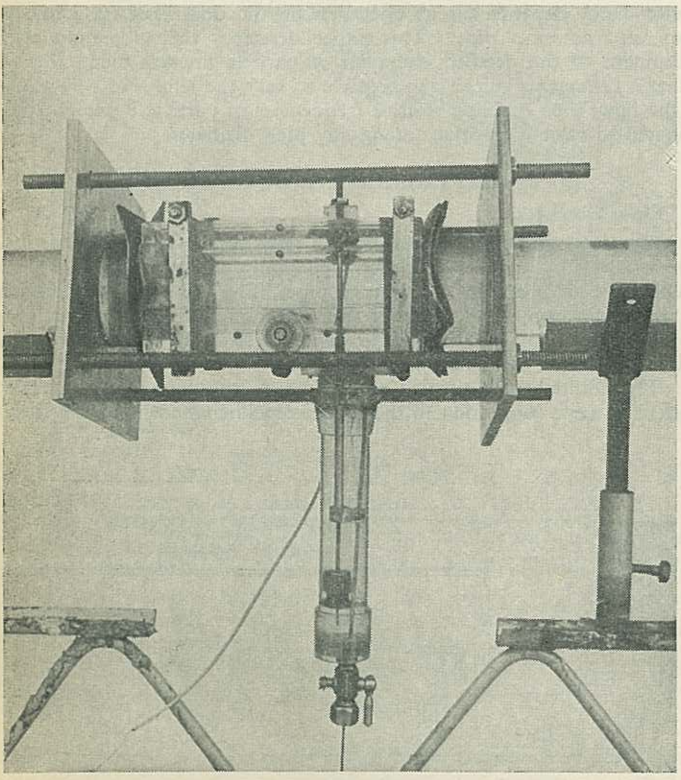

Fig. 3.—Overall View of Instrument In-Situ.

In this application partial shielding of the wire was used to determine the cumulative impacts over varying lengths of exposed wire. The original advantages of total shielding, exploited in the application of a similar flow measuring device, were secondary.

2.3 Recording Circuit:

Two semi-conductor strain gauges are mounted on the beam of the suspension wire device and form two opposite arms of a simple Wheatstone Bridge as shown in Fig. 4.

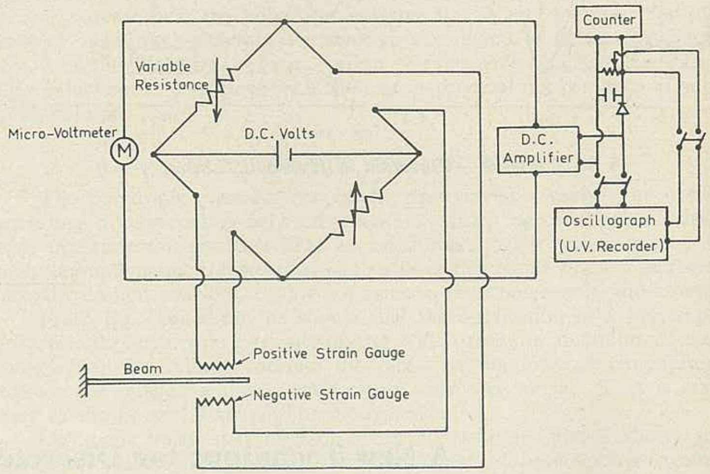

Fig. 4.—Basic Wiring Diagram.

Initially a record was obtained through D.C. amplifiers connected to an ultraviolet recorder. The frequency response of the most useful galvanometers was 500 Hz. and as the natural frequency of the suspension wire mechanical system was 390 Hz., each impact resulted in a ringing signal as shown in the ultra-violet trace in Fig. 5.

The circuit was modified later to use a counter (see later comment on sample length) and a form of "filtering" was required. As shown in Fig. 4, this circuit incorporated a rectifier (diode), RC low-pass filter and a voltage divider. The total output signal was fed to the counter and a small proportion of the same signal was fed to the galvanometer of the ultra-violet recorder.

In Fig. 6, the shaped signal due to the modified circuit is shown in a typical trace.

Event and timing marks of the ultra-violet recorder enabled the impacts registered by the counter to be checked with a sample record. For long periods the counter alone was used and timed with a stop watch.

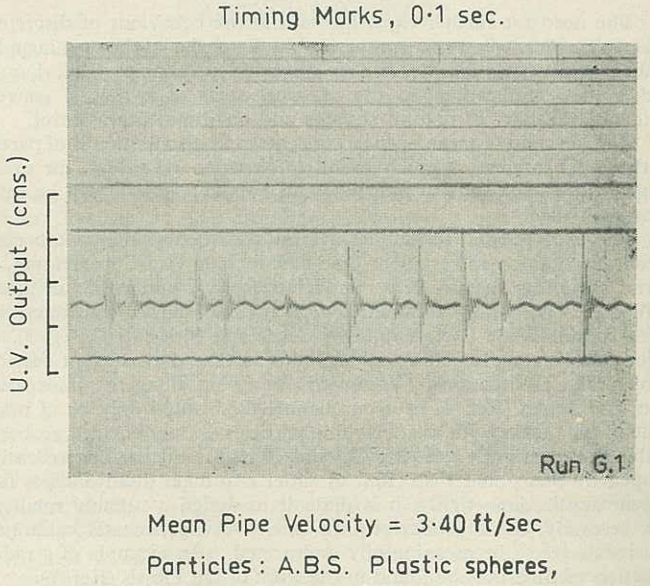

Fig. 5.—Typical Suspension Wire Trace, Indicating Particle Impacts.

The counter responded to negative going pulses above a certain low threshold value. The electrical components could be adjusted so that this value just excluded the maximum signals caused by turbulent flow effects on the wire.

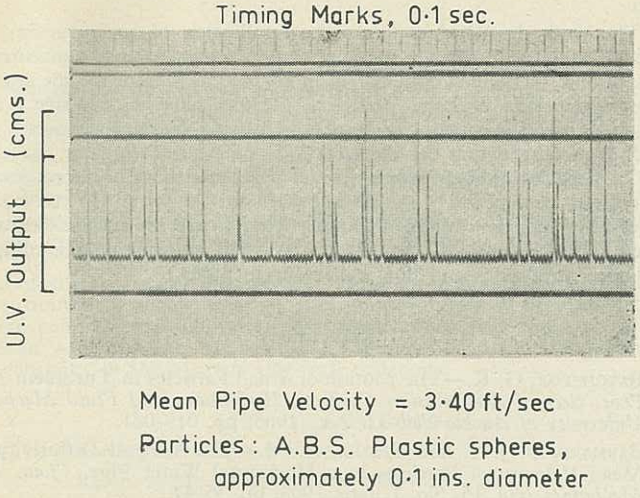

Fig. 6.—*Typical "Filtered" Suspension Wire Trace, Indicating Particle Impacts.*

The procedure involved checking a short ultra-violet record with a simultaneous count. Final readings were then taken when adjustments gave agreement by the two methods. It is possible that some very small impacts were of the same order as the turbulence and thus difficult to distinguish.

3.—PRELIMINARY TESTS AND MEASURING TECHNIQUE

Before particles were added, the system was started with the suspension wire completely shielded. Adjustments such as bridge balance and amplifier gain were made to the electronic circuit and a suitable initial tension was applied to the suspension wire.

A weighted amount of particles was carefully inserted into the system over a period of many circuit lap times, with no effort being made to provide precise delay times between individual particle insertions. The quantity of particles used in the present research programme was selected to satisfy two criteria.—

(i) Minimise the possibility of multiple impacts on the fully exposed wire.
(ii) Provide concentrations such that both mutual particle interference and modification of the turbulent flow field were negligible.

The flow was adjusted to the desired value and the system (including temperature) given some time to stabilise. Following this period, as a preliminary step oscillograph traces were taken for a few representative wire exposure lengths. Portion of a typical trace is shown in Fig. 5. These traces were quickly examined and the lengths of record, to provide a suitable accuracy of results, were estimated. Invariably the times involved were found to be beyond the practical utility of a recorded trace.

The problem of measuring much greater impact counts was overcome with the aid of an electronic counter and additional circuitry as shown in Fig. 4. The "filter" circuit was necessary to ensure that each impact was counted as a single signal. Fig. 6 shows a typical "filtered" trace, indicating that only the initial deflection of the beam associated with each impact is finally received as an abrupt voltage change.

During the relatively long counter runs, short synchronised comparisons of counter readings and oscillograph traces were obtained, as a check of the electronic circuit.

For a particular wire orientation runs were made for a series of wire exposures, each varying in length by a predetermined increment. However, the predetermined shield positions were set haphazardly in order to avoid systematic errors. The instrument was rotated through 180° and the traversing procedure repeated.

4.—DISCUSSION

4.1 General:

This paper considers only a typical example. The results shown in Figs. 7, 8 and 9 apply to conditions along a vertical diameter of a 2-in. dia. pipe. The particles used were plastic spheres of specific gravity 1.03 and approximately 0.10-in. dia.

4.2 Discussion of Impact Counting:

The lengths of time required for counting runs are influenced by the accuracies required of the final mean concentration distribution. From each preliminary representative oscillograph trace, both the sample mean and variance of the intervals between impacts can be quickly calculated. Determination of the mean impact frequency distribution along the wire involves the differences between two sample mean values, and the statistics of sample means can be used to give approximate relationships between probable sampling errors and impact count.

It would appear that two general conclusions can be drawn.—

(i) Long recorded traces are impracticable.
(ii) There are economic count times, beyond which the advantages in reduction of sampling errors are off-set by the enormous times of counting involved.

For the present example the economic times for counter runs were between approximately 3 and 4 min., measuring up to 6,000 impacts on runs where the wire was fully exposed.

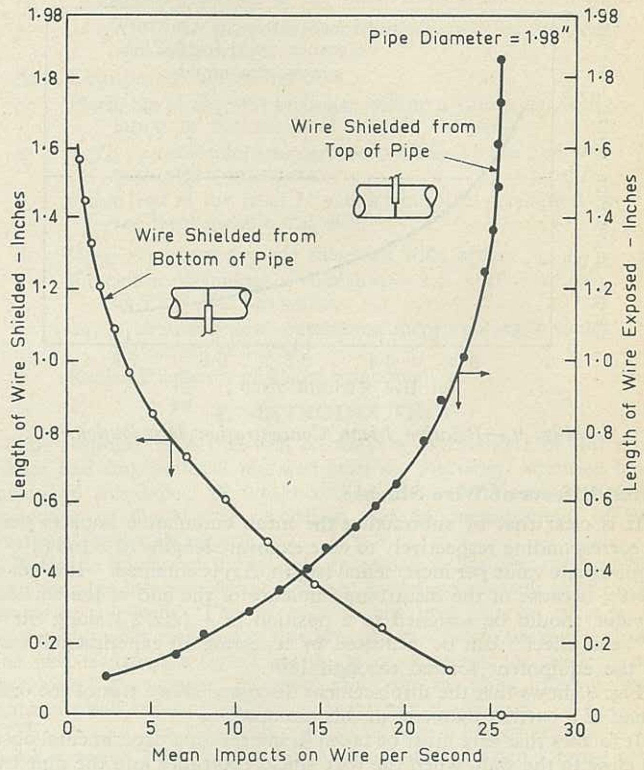

Fig. 7.—*Cumulative Impact Results.*

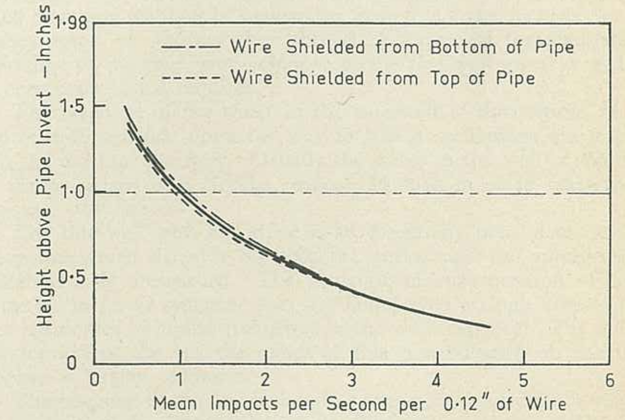

Fig. 8.—*Impact Distribution.*

Examination of the short synchronised oscillograph traces and counter readings indicated a negligible percentage of counts "lost" over the range of wire exposure lengths. It should be emphasised that the lowest possible level of "discrimination" is desirable and is limited only by the refinement of the recording equipment and the maximum signals caused by turbulent flow past the wire.

4.3 Reduction of Results :

A number of alternative techniques can be used for obtaining the impact frequency distribution from the cumulative impact results shown in Fig. 7. For example, a suitable curve such as a polynomial can be fitted by the method of least squares to smooth out any irregularities due to sampling errors, and the curve can be differentiated to obtain the frequency distribution.

In the example illustrated here the actual experimental observations were used to construct the curves (shown dotted) in Fig. 8.

End effects (discussed later) produced two distinct curves corresponding to the separate (opposite) vertical traverses performed. The curve (shown full) combines these results and can be considered as indicating the relative mean frequency of impacts occurring along the wire in a given time interval.

Because " concentration " is associated with the probability of occurrence of a single particle in unit volume, account must be taken of local mean fluid velocity in converting the resultant curve of Fig. 8 into the relative mean concentration distribution curve shown in Fig. 9.

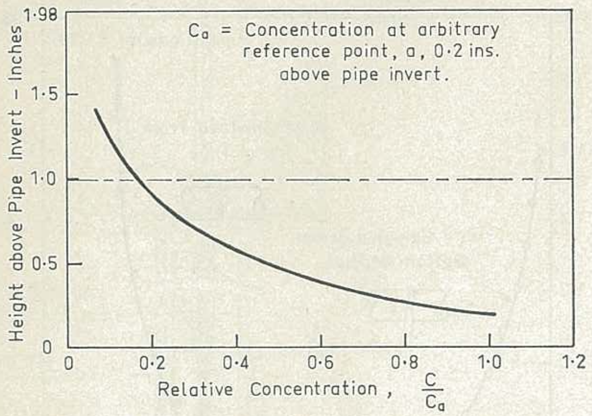

Fig. 9.—Relative Mean Concentration Distribution.

4.4 End Effects of Wire Shield :

It is clear that by subtracting the mean cumulative impacts per unit time corresponding respectively to wire exposure lengths of x and $(x + \Delta x)$, an appropriate value per incremental length, Δx, is obtained. It is not clear, however, because of the disturbing influence of the end of the shield, that this value should be assigned to a position $[x + (\Delta x/2)]$ along the wire. The " end effect " can be evaluated by repeating an experimental traverse with the equipment rotated through 180°.

Fig. 8 shows that the displacement discussed above was of the order of one half of a particle diameter in this example.

It follows that care must be taken in interpreting experimental observations close to the wall, when the wire shield protrudes into the pipe by less than half a particle diameter. Similar arguments apply when the length of wire exposed is less than $1\frac{1}{2}$ to 2 particle diameters.

CONCLUSIONS

The work described concerns the application of an intrument, and auxiliary equipment, for the measurement of mean particle concentration distributions. The technique has been adapted at present for the study of dilute suspensions of large particles. Results have shown that a satisfactory degree of accuracy can be obtained using these procedures.

It is envisaged that the device will be suitable for greater concentrations of particles although some special problems must be faced, such as the frequent occurrence of multiple impacts on the wire. In the extreme case of heavy concentrations of fine particles, where the suspension can be treated as a pseudo-fluid, the device may yield information regarding the rheological properties and flow behaviour in pipes.

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