Experiments in Fluids 9, 252–256 (1990)

Experiments in Fluids

Velocity measurements in slow flow by the conductance-tracer method

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Abstract. The conductance tracer velocity measurement method, which is usually employed for determination of mean velocity, is extended to point velocity measurement of the order of a few millimeters per second with accuracies of the order of 10%. Velocity is determined by the time required for a conducting solution to travel between two measuring stations. At each station the conductance between two electrodes is sampled and the resulting conductance time trace is analysed numerically. Cross talk and electrolysis problems are overcome by AC current, alternate switching conductance measurements. The leading edge criteria, suggested in this work, seem to be best suited for travel time determination in such flows. The existence of shear does not seem to have an influence on the validity or the accuracy of the measurement.

1 Introduction

The distinctive feature of the tracer method of velocity measurement is that a discrete quantity of foreign substance is injected into the fluid stream, after which a measurement is taken of the time interval for this substance to be carried to an observation point. This method was used to determine blood circulation parameters about 100 years ago by Herring and Stewart (Fox 1962). Allen and Taylor (1923) developed the Allen salt velocity method whereby conductance variations caused by salt solution, were detected at a point downstream of the injection point. Mason (1940) and Thomas and Dexter (1955) conducted laboratory experiments with the Allen salt velocity method and proposed procedures to improve its accuracy. In a series of investigations Hooper (1940, 1960, 1961) dealt with diffusive aspects of the salt method. He concluded that the accuracy of this method is superior to that of others and suggested that the time interval be inferred by the center of gravity of the conductance traces. Taylor (1922, 1953, 1954) provided the theoretical modelling and physical interpretation for the diffusion phenomena upon which the method relies. The ASME (1977) has since recognized the Allen salt trace method and established clear standards for its use. Following Hooper, the ASME recommends that time intervals should be determined from the center of gravity of the areas defined by the conductance traces.

When the foreign substance is a solution which is injected into a slow moving fluid in a pipe, the dispersion process involves both forced convection and molecular diffusion. Forced axial convection is governed by the velocity distribution in the pipe, while molecular diffusion which is maintained by the concentration gradient, acts in the radial as well as the axial direction. After the initial transition stage, an equilibrium between the convection and diffusion processes causes the dispersed cloud of the solution to have a radial distribution which moves with the mean velocity of the flow. If the time required to reach this equilibrium is short enough, the measured time interval between the injection of the solution and its detection downstream, can be used to measure the mean velocity of the flow. Such a method can therefore be used in a capillary flow, where molecular diffusion is sufficient to reduce the transition time in the small diameter pipe. In turbulent flows where random fluctuations of fluid particles accelerate the dispersion process, this method is applicable even for pipes with large diameter. However, if the mean velocity is very slow and the pipe is not a capillary, equilibrium is achieved far downstream from the injection point, making it impossible to use the tracer method to determine mean velocity. This is why in all the above mentioned references the tracer method is not recommended for slow flow measurements below $Re = 2{,}000$. Unfortunately most of the modern methods for velocity measurement are also not applicable for such flows. Even Laser Doppler Anemometry requires a minimum level of velocity to create a measurable Doppler effect. Therefore, in most instances where this type of very slow flow (of the order of few millimeters per second) occurs, some sort of a tracer method is used but usually with poor accuracy.

The development of a rapid inexpensive A/D converter on the one hand, and the need for reliable measurement of extremely slow flows on the other, were the motives behind this study which constitutes an attempt to extend the validity of the Allen salt tracer method to slow flows. In this work a conductance-tracer point velocity measurement is proposed

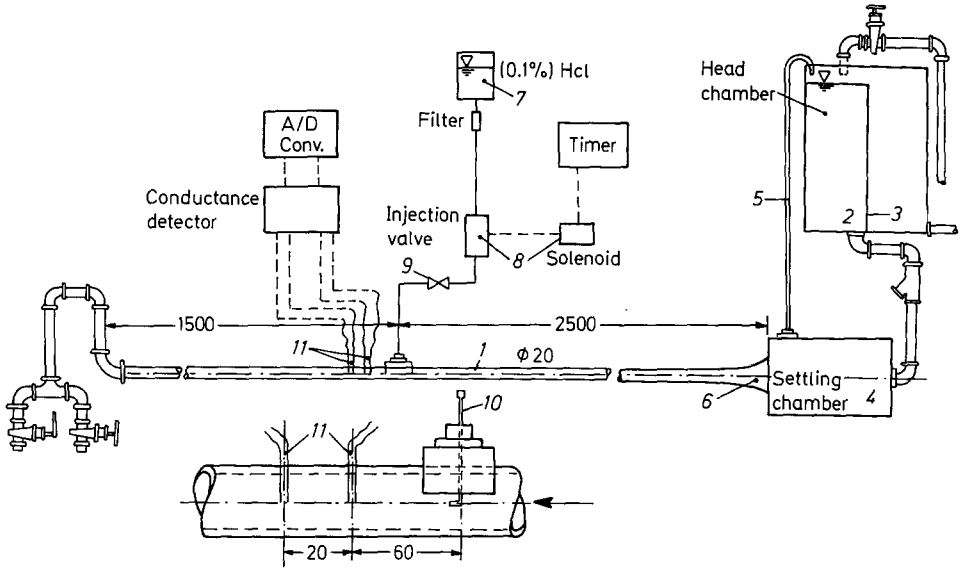

Fig. 1. Experimental set-up

for slow flows. This method enables velocity distribution measurement and, when the velocity profile is known, calculation of the bulk discharge velocity.

2 The conductance-tracer method

The conductance-tracer method determines the fluid velocity by injecting an electrical conducting solution, at a specific point in the velocity field, and measuring the time required for the solution to pass between two measuring stations.

This method is based on the following conditions: (a) the dispersion process near the injection point is dominated by convection. Effects of molecular diffusion may be neglected in both the longitudinal and radial directions. (b) The injection point and the two conducting detectors are on the same streamline. (c) The specific gravities of the conducting solution and the flowing fluid should be close to each other.

When these conditions are satisfied, the measured velocity is a point velocity in the velocity field. The mean velocity and the discharge can be calculated by integrating the point velocities across the flow cross-sectional area.

3 Experimental set-up

3.1 Flow system

A straight 4-m-long (1) (numbers in parentheses refer to the corresponding numbers in Fig. 1), 20-mm-diameter smooth plexiglass pipe was leveled and set in a temperature controlled room with water flow in the pipe initiated from a constant head tank (2). This $500 \times 400 \times 600\ \text{mm}^3$ tank had an inner partition (3) which acted as an overflow height control. Water was constantly kept above the partition level so that a small amount was always drained out of the system, thus maintaining a constant water head. From the head chamber (2), water entered a cylindrical ($\varnothing$ 200×400 mm) settling chamber (4) which was equipped with an air release pipe (5). A parabolic ($x^2 + 1.5\ y^2 = 1$) intake contraction (6) provided a smooth entrance from the settling chamber to the pipe.

Following Schlichting (1955), L_e, the entrance length required for the flow – with a given Reynolds number, R_e – to become fully developed, is given by:

$$L_e = 0.06 \cdot R_e \cdot D\,.$$

Thus, for any $R_e \leq 2{,}000$, the velocity profile at $X = 2.4$ m will always be fully developed and given by:

$$U = 2 \cdot U_m\,[1 - (r/R)^2]$$

where U_m is the mean velocity, r is the radial coordinate and R the radius of the pipe.

3.2 Injection system

The injection system consisted of a 500 cc solution container (7), a solenoid-operated valve (8) and a needle valve (9). The container was placed above the pipe to create the necessary head to drive the solution into the pipe once the solenoid valve opened. This valve was activated by a timer for adjustable duration between 0.01 and 1 s. Adjustment of the needle valve provided additional means for controlling the amount of solution injected at each shot. The solution was injected through a bent in a 25 gauge hypodermic needle (10), which was located 2.5 m from the entrance to the pipe. The bend of the syringe in the flow direction and the low discharge velocity ensured immediate adjustment of the solution velocity to the local surrounding water flow. The needle was capable of radial motion to provide injection at any desired radius.

0.1 HCl (hydrochloric acid) in distilled water [specific gravity 1.014 g/cm^3 coefficient of molecular diffusivity $13.1 \cdot 10^5$ cm^2/s and coefficient of electrical conductivity 391 $(\Omega \cdot \text{cm})^{-1}$] was used as the conducting solution. In most cases the amount of injected solution was approximately 10^{-3} cc.

3.3 Detection system

A detection device was composed of two platinum electrodes (0.25 mm diameter) placed 2 mm apart in the streamwise direction. With the exception of the tip, the electrodes were coated with a thin layer of insulating epoxy. The two detection stations were placed 20 mm apart in the downstream direction. All four electrodes were placed so that their tips coincided with the axis of the pipe. In order to reduce whatever effects the initial injection speed had on the flow stream, the first pair of electrodes was placed 60 mm away from the injection point. At this distance the maximum possible residue of injection velocity is less than 0.4% of the low discharge velocity (estimated at less than 20 mm/s).

When a DC voltage was imposed across the electrodes, a serious problem arose due to corrosion of the electrodes by electrolysis. To overcome this problem, 2.5 kHz AC voltage was used for conductance detection. The ohmic resistance between the electrodes was typically on the order of 5 kΩ. Cross-talk between the two stations was prevented by alternately switching back and forth between the two detection stations at a frequency of 1.25 kHz. Thus, when voltage was applied to one pair of electrodes, the other pair had an open circuit.

3.4 Data acquisition

The output of the two detectors stations was conditioned by amplification and offset to a range of ± 5 V and then sampled by a 12-bit A/D converter. The data were stored for subsequent processing. The sampling rate of the converter varied according to the expected velocity, so that at least 200 data points covered the transition time between the two detection stations. This meant a reciprocal relation between sampling rate and velocity so that the relative resolution was kept close to constant.

3.5 Velocity calibration

Flow visualization techniques were used to insure that the flow in the pipe was laminar. A continuous injection of dye through the injection system revealed that the flow was laminar for the range of measured velocities (0–90 mm/s). Before each run, the system was allowed to settle and stabilize after the needle valve (no. 9 in Fig. 1) was set. Ten measurements were taken of the mean velocity in the pipe using a measuring cup and stopwatch, five prior to the data taking and five subsequently. The maximum deviation between these velocities was less than 1%.

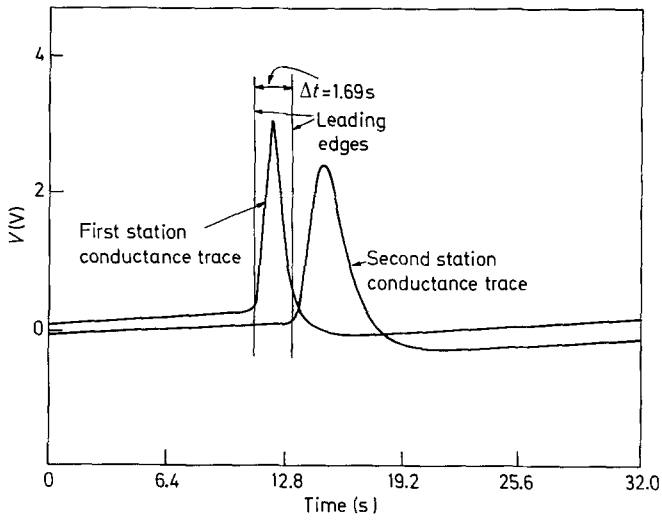

Fig. 2. Typical conductance traces

4 Experimental procedure

Prior to each experiment, the flow resistance needle valve was adjusted to the desired position (velocity) and temperature and flow conditions were allowed to set for a period of at least 30 min. The mean flow was then measured volumetrically and recorded. Centerline velocity, where electrodes were placed, was evaluated from the measured mean velocity, using the fully developed laminar velocity profile relation:

$$U_{cl} = 2 \cdot U_m \, .$$

A single switch activates both the solution injection system and the data-acquisition process. At each setting at least 30 successive runs were made. Data from the A/D converter and measured velocity were then stored on tape for subsequent processing.

5 Time markers determination criteria

The basis of any tracer velocity measurement method is the determination of the travel time between the detecting stations. The only ambiguity in this method is in the criterion which should be used to mark a time reference on the conductance traces. Figure 2 shows typical conditioned traces which were obtained from each run. The rise in electrical conductance is gradual from a base level to a peak, followed by a gradual drop. The location of a time marker on such a curve is an open question. Four "reasonable" marking criteria are: (i) maximum conductance point; (ii) center of gravity of areas under the conductance curve; (iii) center of areas under conductance curve; (iv) leading edge.

For criterion (iii) the marker is placed at the mid point which divides the area into two equal parts, one to the right and the other to the left of the marker. In the traditional Allen salt tracer method, only the first three criteria are

considered. Experiments with the Allen method have indicated that the best results are obtained with time intervals determined from the center of gravity of the conductance areas. Part of this work, where point velocity was to be measured, was to determine the most suitable time marker criterion. To do that, all four criteria were used to evaluate the velocity from the same data.

The area under the conductance curves for area-based criteria (i, ii, iii) is determined by numerically subtracting the long time average (prior to the injection) pedestal from the trace which was then (numerically) low pass filtered. The numerical filtering was done to eliminate high frequency noise and is the reason behind the gradual rise and decay of the traces shown in Fig. 2. The same conditioned traces are used to determine the time marker by criterion (iv). The leading edge marker is set arbitrarily at the time for which the conductance level first exceeds 0.5% of the conductance amplitude above the base level.

Table 1 summarizes typical results of the analysis for one set of experiments. This set was done with a volumetrically calibrated velocity of 0.77 mm/s and averaged over 30 successive experiments. It should be noted again that the results presented in Table 1 are from identical data, but with different analysis methods. The conclusion from the typical data shown in Table 1 is that for the type of flow described here, the most suitable time marker is achieved by using the leading edge criterion (iv). Deviations between calibrated velocity and measured velocity by this method are approximately 25% of the same deviation calculated by the conventional, first three methods. It is also interesting to note that the conventional methods yield results with very similar errors. The only method which yields a basically different result is (iv) the leading edge method.

Table 1. Summary of velocity evaluation by different methods, based on 30 runs with a calibrated velocity of 0.77 mm/s

Method of interpretation	Mean velocity (mm/s)	Standard deviation (mm/s)	Deviation of average (%)	Maximum deviation (%)
i	0.508	0.041	−34.0	−42.8
ii	0.597	0.066	−22.5	−35.3
iii	0.578	0.060	−24.9	−37.4
iv	0.718	0.039	−6.74	−17.4

Table 2. Results of velocity evaluation by leading edge criterion

Calibrated velocity (mm/s)	Avg. measured velocity (mm/s)	Standard deviation (mm/s)	Deviation of average (%)	Maximum deviation (%)	No. of runs
0.77	0.718	0.039	−6.74	−17.4	30
4.97	4.53	0.25	−8.83	−18.4	40
8.6	7.93	0.66	−7.76	−14.95	40
12.93	11.63	0.39	−9.88	−16.6	30
16.1	14.77	0.43	−8.23	−14.51	30
16.75	15.05	0.29	−10.14	−13.65	40
20.52	19.18	0.263	−6.55	−8.93	40
22.3	20.64	0.97	−7.16	−11.42	40
25.2	22.04	0.338	−12.53	−15.69	40
40.2	38.11	2.5	−5.19	−10.31	40
48.4	44.25	1.98	−8.57	−13.29	40
60.63	56.09	3.17	−7.48	−15.55	40
74.0	66.8	3.38	−9.78	−16.4	40
95.0	88.8	9.4	−6.52	−25.0	30

6 Velocity evaluation

Table 2 summarizes experimental versus calibrated velocity measurements for the range of velocities between 0.77 and 95 mm/s. All the measured data in this table were obtained by using the leading edge criterion (iv) to mark the reference time on the conductance time trace. This was done after the method had been proven to be superior to the others. The deviation between the calibrated and measured velocities is typically on the order of 10%. The maximum deviations, which occur within the runs of a single setting, are larger and on the order of approximately 15%. These accuracies are excellent when considering the extremely slow flows associated with them. However it is interesting to note that the measured velocities are always smaller than the actual, calibrated ones. Furthermore, when the average of the absolute values of deviation was calculated, the result in absolute values was very close to the reported negative deviation between average velocity and the calibrated one. This points to the systematic error which exists in the determination of a too-long travel time lapse. Such an error can be generated by the measurement system and/or by the analysis procedures. This indicates that the error associated intrinsically with this method is only about one half of that reported. The other half is due to the systematic error which is most probably associated with this particular experiment. This error may involve an error in measurement of the distance between the two measuring stations or, alternatively, if the distance between the electrodes in each station is not identical, the resulting travel time may systematically be erroneous.

7 Off centerline measurements

In order to determine the possible effects that the presence of shear might have on the results of velocity measurements obtained by the described method, off centerline velocity measurements were taken. Table 3 summarizes typical results. Calibrated velocity was obtained by measuring the mean velocity by the previously described procedure and using a fully-developed parabolic velocity distribution to calculate the velocity at the radial location point. Typical deviations between actual and measured velocities in Table 3 are approximately the same as those given in Table 2 for the centerline where no shear exists. Thus, it is probably safe to

Table 3. Off centerline velocity measurement

r/R	Calibrated velocity (mm/s)	Measured velocity (mm/s)	Deviation of average (%)	Calibrated velocity	Measured velocity (mm/s)	Deviation (mm/s, %)
0.0	24.8	23.4	−6.0	13.6	12.4	−9.7
0.3	22.6	20.2	−11.9	12.4	1.24	−2.5
0.6	15.9	16.7	4.8	8.7	8.1	−7.4

conclude that the presence of shear does not affect the results obtained by the present sensors.

The amplitude of the conductance trace may serve as an indicator of the location of the measuring station. For the tracer method to yield reliable velocity results by point measurements, the injection as well as measuring stations should be placed on the same streamline. If the geometry is such that a streamline is a straight line, then the location of all three points on the same line is a relatively easy task. However, when the geometry is curved, the appropriate location of the tips of the probes in the measuring station could be achieved by a trial-and-error process which is aimed at locating the point of highest conductance level, which should coincide with the streamline passing through the injection point. Therefore, the conductance tracer method should also be applicable for slow velocities with curved geometries.

8 Concluding remarks

Measurement of velocities on the order of a few millimeters per second is a very difficult task in which all common methods of measurements fail. The proposed conductance tracer method, which in this work yielded results of acceptable accuracy, is most probably the only measurement method which is still applicable, provided careful attention is paid to the choice of the conducting solution, measurement-station location, and correct method of data interpretation.

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Received November 17, 1989