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FLOW MEASUREMENT USING A CONDUCTIVITY FLOW METER — INITIAL INVESTIGATION

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ABSTRACT

The limitations of existing salt velocity flow measurement techniques are reviewed and the use of a new automatic method called the Conductivity Flow Meter is described. During trials in a laboratory flume the variables associated with the new system were examined to assess their affect on performance and a series of tests carried out to investigate the precision and accuracy of the meter. The results show the Conductivity Flow Meter to compare favourably with other salt–velocity techniques and current meters and indicate that it could find wide application in flow measurement both in closed conduits and open channels.

INTRODUCTION

Existing salt–velocity methods of discharge measurement based on monitoring changes in artificially induced electrical conductivity require the direct recording of the passage of the conductivity cloud using conductivity sensitive electrodes or the indirect technique of obtaining samples from the flow at known time intervals for subsequent analysis so that concentration–time graphs may be plotted. The resulting traces appear as a series of "humps" and from these the average velocity of flow may be determined. Both techniques involve the use of cumbersome equipment or time consuming sampling and analysis.

This work describes the development of a new conductivity flow meter designed to overcome these problems.

REVIEW

Allen and Taylor (1924) originally devised the salt–velocity technique and while it has found wide application for flow gauging in closed conduits, its application in open channel flow measurement has mostly been limited to time of travel investigations over long gauging reaches (Buchanan, 1964; Calkins and Dunne, 1970).

The original technique for closed conduits involves the introduction of large quantities of brine, approximately 5 litres per 1.5 m^3/s, into the flow to be gauged. This mixes within the flow to form a region exhibiting an electrical conductivity greater than the normal background conductivity. The cloud passage through the system is indicated at two predetermined points using electrodes connected to a recording ammeter. Subsequent trace analysis produces the time of travel between the electrode stations which are a known distance apart; and hence the mean velocity of flow can be determined and the discharge.

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Due to turbulent diffusion the two traces will not be identical, and to determine the time of travel it is necessary to choose a characteristic point on the traces which can be considered to travel with the mean velocity of flow. Taylor (1954) suggests, on theoretical and experimental grounds, that this point should be the peak of each trace. However, it has been found that when applying the technique to pipe flow it is often difficult to ascertain trace peaks with any great accuracy. Young *et al.* (1955) have shown that choosing the centre of area of traces as the characteristic point gives more consistent results than using the peaks. In an attempt to simplify the sometimes arduous task of trace analysis, Young and Wilson (1958) produced their "mid–point of half–maximum ordinate" method, which was applied to traces obtained by photographing oscilloscope records of the conductivity cloud. This method of trace display, a continuation of work performed by Hall (1943) and the subsequent analysis, was found to give accuracy comparable with alternative techniques, while greatly reducing the time required for after–test evaluation. Winternitz (1957, 1958) has also investigated alternative methods of physical trace analysis.

Leslie and Hunter (1959) devised a system for automatic trace evaluation by modifying the simplified method of Young and Wilson (1958). The results obtained were found to compare favourably with those given by conventional "centre of area" methods. However, although exhibiting considerable potential, the equipment was expensive and cumbersome.

In open channels, the salt–velocity technique is usually applied using either conductivity probes to map the conductivity–time curve or by an alternative method which reduces the complexity of the field equipment. This alternative approach involves collection of samples from the flow at known time intervals during the passage of the tracer past down–stream stations. The samples are chemically analysed and concentration–time curves constructed. Although requiring only simple field equipment this technique is much more time consuming. Trace analysis may also pose problems in open channels because of asymmetry in trace shape (Fischer, 1968). 'Centre of area' analysis will produce accurate results when traces are approximately symmetrical as produced in pipe flow, but not when such symmetry is lacking as in many open channel applications.

From the above discussion it will be appreciated that a simple automated system would be particularly useful in both pipes and open channels. Such a system has been devised by John (1974) called the Conductivity Flow Meter (C.F.M.).

In this case, two conductivity cells are required at each station, as shown in Fig.1. Fig.2 shows the traces formed by the conductivity cloud passing one such station. In situation (i) both cells will register background conductivity only. At (ii) the upstream cell of the pair is beginning to pick up the increased conductivity of the cloud. By (iii) both cells are covered by the cloud, with the upstream cell registering the higher conductivity reading. At (iv) the conductivity at both cells is the same, while a moment later at (v) the downstream cell is registering a higher conductivity than its upstream partner for the first time. It is at this point that the timer is switched either on or off, depending upon which station is concerned. In (vi) and (vii) the cloud is seen passing downstream until at (vii) both cells are again measuring the background conductivity. This is the basic idea employed in the C.F.M. and this note describes initial investigations into its use in open channels.

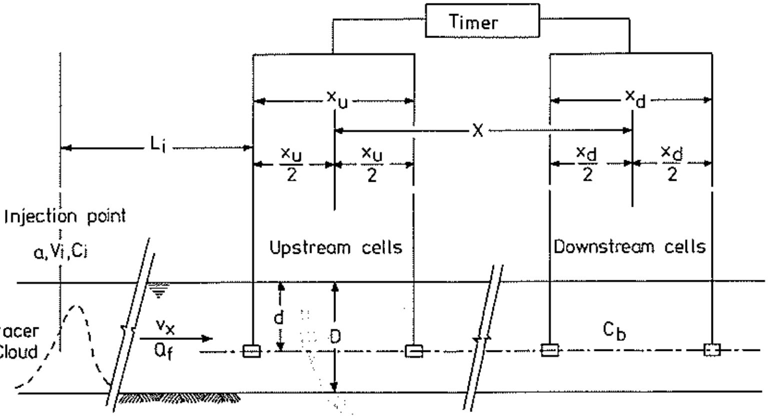


FIG.1 – Variables associated with the Conductivity Flow Meter method of flow measurement.

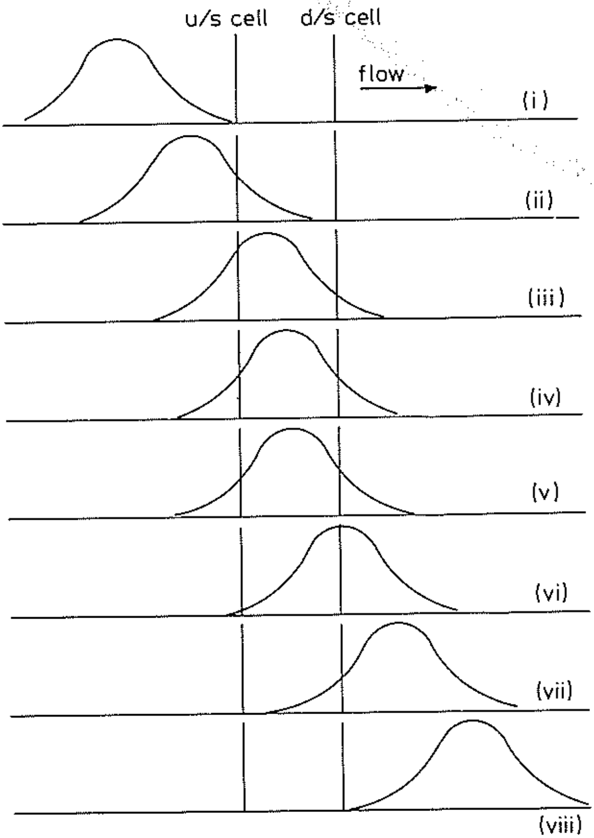


FIG.2 – A typical conductivity cloud passing a Conductivity Flow Meter cell station.

EQUIPMENT DESIGN AND OPERATION

There follows a brief summary of the design and operation of the C.F.M. Detailed descriptions may be found in John (1974) and John *et al.* (1976).

Beaker type conductivity cells consisting of two carbon ring electrodes set in resin filled plastic were modified for use in flowing water.

The electronic system incorporated a sensitivity device which dictated the amount the input from the downstream cell had to be greater than that from the upstream cell before switching occurred. This eliminated any false switching caused by changes in the background conductivity of the flowing water or any short term irregularities in conductivity on the trace limbs.

A six digit crystal controlled timer unit with numerical indicator display was used for time of travel measurement.

Sodium carbonate was used as the tracer solution, as opposed to the more conventional sodium chloride, as it is less corrosive and would be more acceptable than common salt in many practical gauging situations. The tracer solution was injected into the flow via a 15 mm diameter tube using adjustable foot bellows to allow different volumes of air to be expelled. The amount of air discharged determined the extent to which the tracer was initially dispersed within the flow.

The procedure for the determination of the time of travel was as follows. The inputs from the cells were balanced and the sensitivity set. The required value for the latter was found by a process of trial and error during the period of circuit development. The tracer was then introduced, and as the subsequent cloud passed the upstream cell station, the timer was started as previously described. As the cloud passed the downstream station, the timer was stopped in the same 'way, and the time of travel displayed. The mean velocity of the water, v_x, at the cell depth in question was then determined by dividing the distance between the centre points of the cell pairs, X, by the time of travel, t_t. Hence $v_x = X/t_t$.

SYSTEM VARIABLES

Initially it was necessary to investigate the many variables associated with the salt–velocity technique as illustrated in Fig. 1. These variables can be classified into three main groups, those associated with:

(a) Flow within the channel.
(b) Cloud formation and dissipation.
(c) The Conductivity Flow Meter.

This initial work describes the application to open channel flow and accordingly the calibration tests which were carried out in a laboratory flume.

(a) Flow within the channel: A glass sided flume 300 mm square in cross section and 10 m long was used. The maximum channel flow rate, Q_f, was 0.03 m^3/s and with flow depth, D, at 190 mm (this being the minimum depth required for the efficient use of the cells) the maximum v_x obtainable was of the order of 0.55 m/s. Point velocities within the flow were measured using a miniature propeller current meter which the manufacturer's claim to have an accuracy of ± 2% in the range 0.075 m/s – 0.15 m/s and ± 1% from 0.15 m/s – 1.50 m/s.

(b) Cloud formation and dissipation: The "ideal" trace is one of fairly uniform, smooth shape, with conductivity levels just sufficient to operate the relays. It should form as quickly as possible following the injection of the tracer, with the desired shape remaining as long as possible while changing as little as possible.

For any combination of the volume, V_i, and concentration, C_i, of the injected tracer solution, and the background conductivity of the flowing water, C_b, the volume of air used in the injection, a, will determine the amount of mixing which occurs at the injection point; that is the degree to which the tracer is dispersed within the flow. The local turbulence will then dictate how quickly the cloud develops, how smooth the trace becomes, and the speed with which the cloud dissipates.

To investigate cloud shape and behaviour, a potentiometric chart recorder was connected to four conductivity cells which were placed at equal intervals along the flume channel at the geometric centre of flow, that is the point where the diagonals of the flow cross section crossed.

Tests were first performed to establish if the direction of the injection tube had any effect upon trace shape. With Q_f and D held steady at 0.015 m^3/s and 200 mm respectively, various combinations of V_i, C_i and a were employed, firstly with the tube outlet facing upstream and then downstream. The results showed that the traces produced with the outlet facing upstream were marginally more uniform in shape. This was probably due to the increased turbulence caused by the out rush of air when injection took place against the direction of flow. It was also noticed that the speed with which the bellows were operated had a distinct effect on trace shape. A rapid depression of the bellows produced better traces than when the expulsion of air was more prolonged. The reason for this was probably that in the second case the tracer solution had already passed downstream by the time much of the air was being expelled. For all remaining tests where this method of introduction was employed, the tracer was injected using a rapid depression of the bellows, with the outlet facing upstream.

An extensive series of tests was performed to determine the combination of variables producing the best traces for use with the C.F.M. in the laboratory flume. Eleven combinations of Q_f and D were employed to give values of flow velocity ranging from 0.10 m/s to 0.55 m/s. In each case 45 combinations of the following were tested:

V_i – 20; 30; 40 ml
C_i – 15 000; 30 000; 45 000 μmhos/cm
a – 15 x 10^4; 50 x 10^4; 150 x 10^4; 230 x 10^4 mm^3

Tracer was also introduced by pouring to establish that the bellows method was indeed superior as far as cloud formation was concerned. With C_b kept at approximately 150 μmhos/cm, some 500 sets of traces (four per set) were obtained. Cloud behaviour was as predicted by dispersion theory. Generally, peaks were not well developed with many traces having multiple peaks. However, it is the sloping limbs which are of importance in this case, and on the whole these were well formed and fairly symmetrical. Peak heights decreased and cloud length increased with distance travelled downstream and in all cases traces were fairly well developed at about 3 m from the injection point. Increases in C_i or V_i increased peak height, with trace length being affected to a lesser degree. As v_x and Q_f increased, so peak height increased, but at very low velocities traces became irregular. For values of a greater than 50 x 10^4 mm^3 there was very little difference in trace shape. Pouring of the tracer into the flow resulted in very tall, narrow traces due to lack of dispersion at the injection point.

From the above observations, the following values were chosen for use with the C.F.M. and the flume tests.

C_i = 45 000 μmhos/cm

V_i = 40 ml

a = 100 x 10^4mm^3

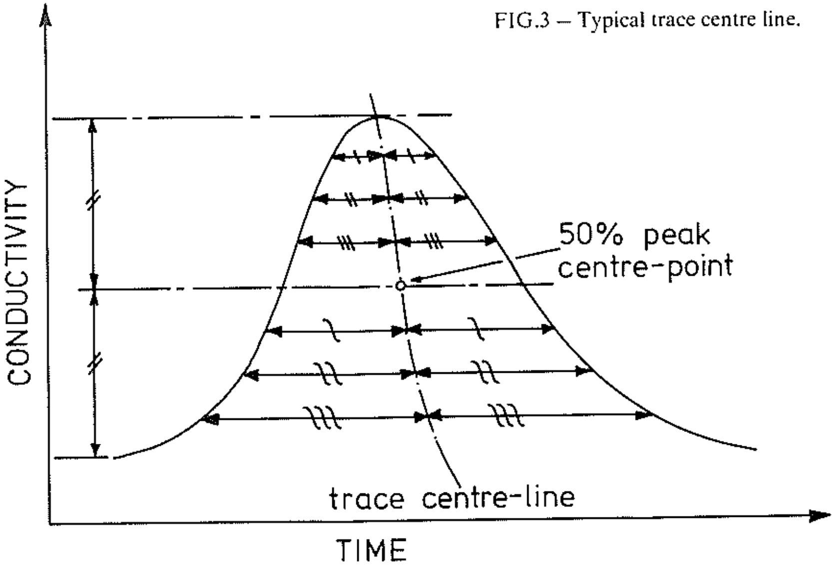
L_i = 3 m

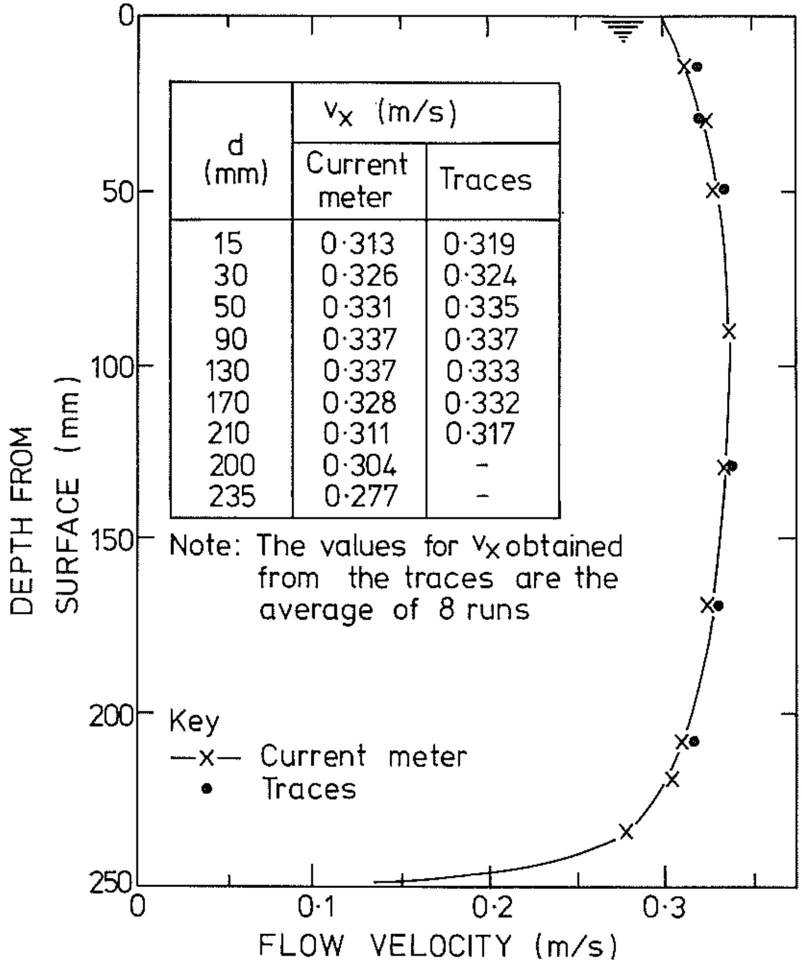
It must be stressed that the above values are not meant for universal application, being determined for use in the particular channel concerned.

(c) Conductivity Flow Meter: The variables associated with the flow meter requiring investigation were sensitivity, S, distance between the cells at the upstream and downstream sections, x_u and x_d respectively, distance between mid-points of cell pairs, X, i.e. the gauging length, the depth of immersion of the cell measured from the surface, d, and the time of travel, t_t.

The Conductivity Flow Meter is used to determine the mean flow velocity at a particular depth over a predetermined gauging length. Therefore, since the conductivity cloud is dispersed over a wide area of the flow cross section, in addition to longitudinally, it is important that the trace centre line (Fig.3), or the particular point on that line being employed in the trace analysis (hereafter termed a trace centre point), travels with the same velocity as that of the fluid at the depth in question. To investigate this, two cells were positioned 4 m apart at the centre of the channel width and connected to the potentiometric chart recorder. The times of travel were then determined at various depths within the flow midway between the vertical sides of the flume by introducing the tracer and analysing the resulting traces. The method of analysis used involved finding the centre point of each trace at 50 per cent of the peak value (Fig.3), Leslie and Hunter (1959) having demonstrated that the 50 per cent level exhibited least scatter in the results. This method of analysis was valid because traces were fairly symmetrical. By measuring the distance between centre points on the chart, and

FIG.3 – Typical trace centre line.





d (mm)	v_x (m/s) Current meter	v_x (m/s) Traces
15	0·313	0·319
30	0·326	0·324
50	0·331	0·335
90	0·337	0·337
130	0·337	0·333
170	0·328	0·332
210	0·311	0·317
200	0·304	-
235	0·277	-

Note: The values for v_x obtained from the traces are the average of 8 runs

FIG.4 – Flow velocity profile as obtained using the current meter and potentiometric recorder traces.

knowing the chart speed, the time of travel was easily found. The vertical distribution of the horizontal velocities was then plotted to give the mean velocity profile over the 4 m gauging length. This was compared with that constructed using the current meter at various sections between the cells. The results of this test are shown tabulated and graphed in Fig.4. The two profiles are seen to be very similar and shows that the trace centre line follows the flow velocity profile closely.

The relationship between x_u, x_d, X and S was found to be of considerable importance when considering the accuracy of the C.F.M. If the background conductivity was constant, and the conductivity traces perfectly smooth, the sensitivity could be set at a very low value so that the triggering point would be almost coincident with a point on the trace centre line. The small delay between the cells reaching parity of output, and the downstream cell obtaining the required increase in output to produce switching (S), would be almost identical at both measuring stations and the resulting t_t would be extremely accurate.

However this 'ideal' situation has been shown not to exist, and subsequently S has to be somewhat larger than would be preferred. This was determined by trial and error over a long testing period during the time when the circuitry was being developed.

Fig.5 illustrates the effect of altering x_u or x_d to obtain different x_u/x_d ratios. x_1 and x_2 are two values of x_u (also applies to x_d) applied to the same trace, with $x_2 > x_1$, and $S_1 = S_2$. The difference in the triggering points is shown. This figure also shows how the greater x_u or x_d become, the lower will be the conductivity level at which switching occurs.

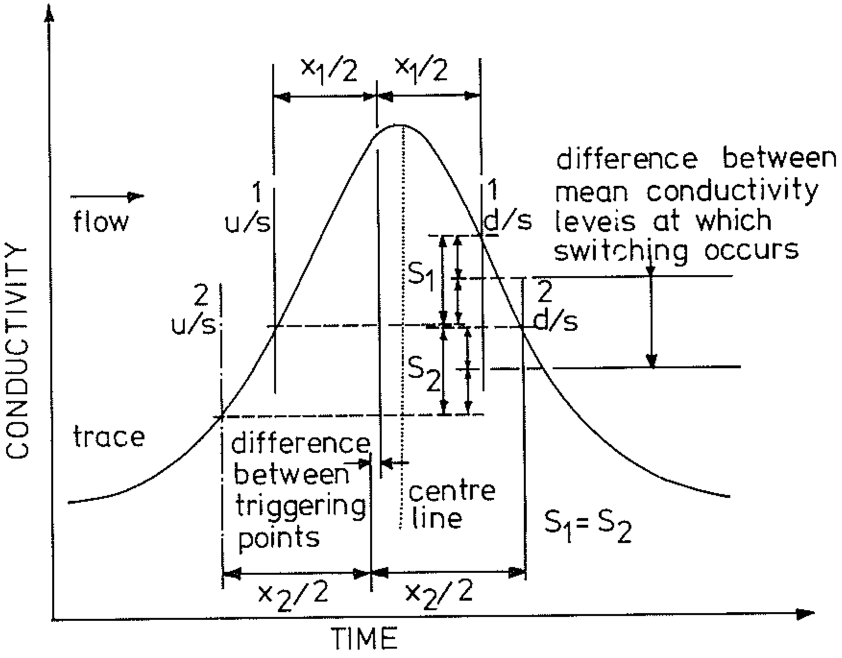


FIG.5 – Effect of altering x_u or x_d on the cell station triggering point.

The laboratory study of the relationship between t_t and x_d as X increases was carried out as follows. From examination of the traces produced in the earlier tests it was found that with $L_i = 3$ m, the trace length at the 50 per cent level at the upstream station would vary between about 0.30 m and 0.56 m, with the mean value being approximately 0.45 m. With this in mind, $x_u = 0.3$ m and 0.5 m were chosen for the tests. This provided a reasonable difference between the x_u's investigated so that any trends caused by the variation of this parameter should become evident, while also encompassing the mean value. In each case the average of five runs gave the time of travel corresponding to various values of x_d ranging from 0.20 m to 0.90 m. Three values of X were used, i.e. 2.0 m, 3.5 m, and 5.0 m. Fig.6 shows a typical set of results in graphical form, a complete set being documented by John (1974).

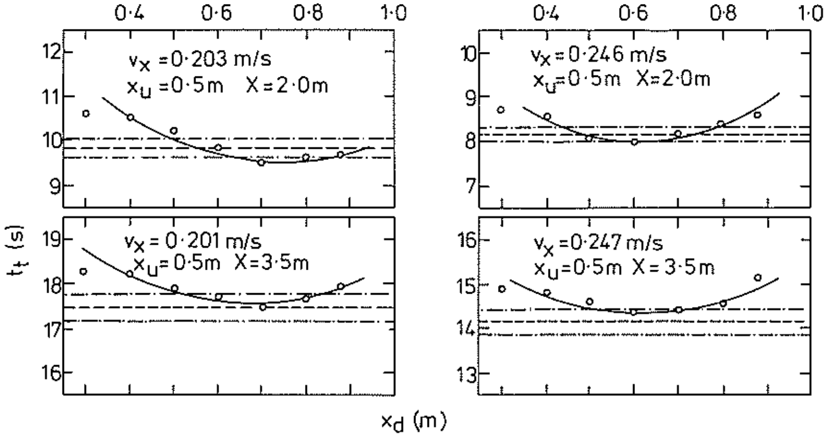


FIG.6 — Typical graphs of t_t against x_d for various combinations of v_x, x_u, and X. The value of v_x given is that obtained using the current meter. The corresponding value of t_t and ± 2% band width are indicated by the broken lines.

Most of the graphs show the minimum t_t value becoming greater as X increased. The pleasing aspect of the graphs when taken as a whole was their shallowness. This meant that a reasonable degree of accuracy could be expected for a wide range of x_d. The average range of x_d was 0.38 m to 0.75 m when $x_u = 0.3$ m, and 0.51 m to 0.76 m when $x_u = 0.5$ m.

After considering the points discussed above, it was decided that if values of X in the region of 3.5 m were investigated, the combination of $x_u = 0.40$ m and $x_d = 0.60$ m should produce accurate results.

To conclude, the results of the preliminary tests indicated that the following values should be given to the various parameters for use in the final testing period. $L_i = 3.0$ m, $x_u = 0.40$ m, $x_d = 0.60$ m, $X = 3.5$ m, $a = 100 \times 10^4 \text{mm}^3$, $V_i = 40$ ml, $C_i = 45\,000$ μmhos/cm.

C.F.M. ACCURACY AND PRECISION

The purpose of the following tests was to ascertain the accuracy and precision which could be expected using the Conductivity Flow Meter.

Test Series No.1 was designed to compare directly flow velocities obtained by the C.F.M. (employing two gauging lengths) with those given by the miniature current meter and the conventional salt–velocity technique using manual trace analysis. Eight flow rates were employed, giving flow velocities ranging from about 0.10 m/s to 0.50 m/s. In each case, the mean value of v_x at the geometric centre of flow was determined in the following ways:

(i) 30 runs using the C.F.M. at each of two X values i.e. 3.0 m and 4.0 m.

(ii) 30 runs using the potentiometric chart recorder over the same 3.0 m gauging length as used in (i) above. The traces were analysed using the single centre point method at 50 per cent of the peak value.

(iii) Using the miniature current meter by averaging 3 (for $X = 3.0$ m) or 4 (for $X = 4.0$ m) point velocities obtained from 100–second sampling periods, so that any inaccuracies caused by short term fluctuations in flow would be

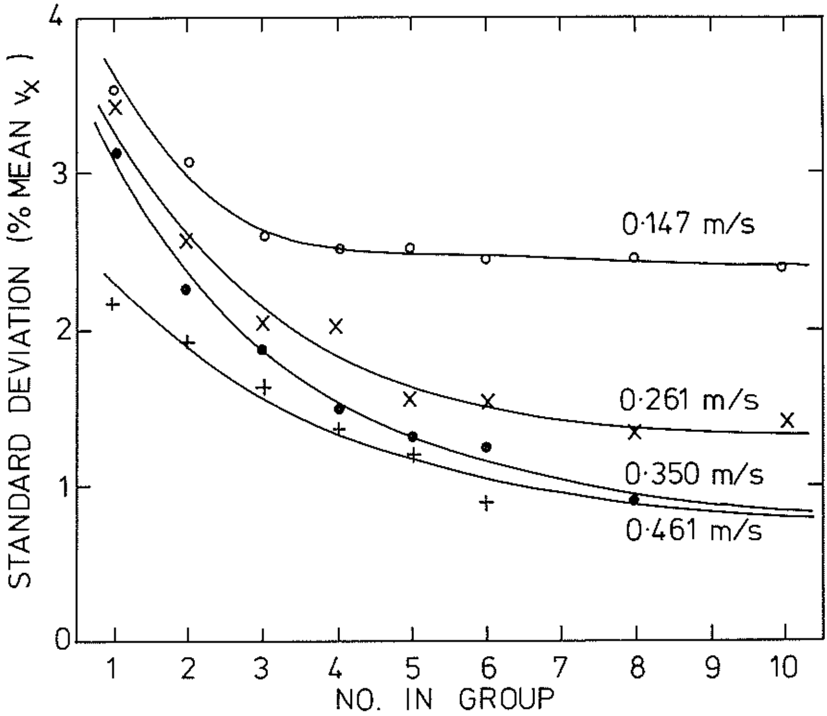


FIG.7 – Effect on flow velocity measurement of averaging groups of consecutive readings. The v_x value obtained from all 100 tests is shown above each line.

minimised. This test was repeated before and after every 30–run sequence, and the average value taken as the reference value of v_x for that sequence. The results of the above tests are shown in Table 1.

Test series No.2 was performed to investigate the variation in the results obtained by the three techniques used in Series No.1. Four flow rates were used, giving mean flow velocities of about 0.15 m/s, 0.27 m/s, 0.36 m/s and 0.47 m/s. In each case the following gaugings were performed:

(i) 100 runs using the C.F.M.

(ii) After each C.F.M. gauging, 3 consecutive 10–second sample current meter readings were taken, and listed as No.1, No.2 and No.3. By obtaining the average of each trio of 10–second gaugings a 30–second sample reading was also calculated.

(iii) 30 runs using the chart recorder over the gauging length of 4.0 m.

The results of these tests are shown in Table 2.

By analysing filmed conductivity traces Young and Wilson (1958) obtained results within ± 1 per cent of the reference values both in the laboratory, (compared with a weighbridge) and in the field (compared with current meters). In field based tests in conduits, Winternitz (1957, 1958) compared the conventional pen trace technique with a multiple current meter system consisting of thirteen meters. Results showed differences ranging from ± 1 per cent at high velocity (approx. 2.6 m/s) to a maximum of −3 per cent at lower velocities

TABLE 1 – Results of *Test series No.1.* Comparison of flow velocity measurement using the current meter, C.F.M. and manual trace analysis methods.

X = 3.0 m					*X = 4.0 m*		
mean v_x (m/s)			*% difference*		*mean v_x (m/s)*		*% difference*
(a) *Current meter*	*(b)* *C.F.M.*	*(c)* *50 % peak*	*(d)* $\frac{b-a}{a} \times 100$	*(e)* $\frac{c-a}{a} \times 100$	*(f)* *current meter*	*(g)* *c.f.m.*	*(h)* $\frac{g-f}{f} \times 100$
0.101	0.107	0.104	+5.94	+2.97	0.100	0.106	+6.00
0.164	0.165	0.164	+0.61	0	0.166	0.168	+1.20
0.259	0.252	0.257	–2.70	–0.77	0.261	0.254	–2.68
0.303	0.297	0.300	–1.98	–0.99	0.304	0.299	–1.64
0.376	0.372	0.377	–1.06	–0.27	0.378	0.373	–1.32
0.382	0.364	0.376	–4.71	–2.57	0.380	0.369	–2.89
0.442	0.434	0.457	–1.81	–3.39	0.460	0.451	–1.96
0.496	0.492	0.494	–0.81	–0.40	0.495	0.494	–0.20

TABLE 2 – Results of *Test series No.2* designed to establish the variability exhibited by the current meter, C.F.M. and manual trace analysis methods.

Current meter												*C.F.M.*			*Chart recorder*					
10 s samples									*30 s sample*			*x = 4.0 m*			*peak*			*50% peak*		
No. 1			*No. 2*			*No. 3*														
mean	*s.d.*		*mean*	*s.d.*		*mean*	*s.d.*		*mean*	*s.d.*		*mean*	*s.d.*		*mean*	*s.d.*		*mean*	*s.d.*	
(m/s)	*(m/s)*	*% mean*	*(m/s)*	*(m/s)*	*% mean*	*(m/s)*	*(m/s)*	*% mean*	*(m/s)*	*(m/s)*	*% mean*	*(m/s)*	*(m/s)*	*% mean*	*(m/s)*	*(m/s)*	*% mean*	*(m/s)*	*(m/s)*	*% mean*
.150	.006	4.00	.149	.006	4.03	.150	.005	3.33	.150	.005	3.33	.147	.005	3.54	.155	.004	2.58	.153	.004	2.61
.270	.003	1.11	.270	.004	1.48	.271	.004	1.48	.270	.002	0.74	.261	.009	3.44	.267	.009	3.37	.266	.008	3.01
.359	.005	1.39	.359	.005	1.39	.360	.005	1.39	.359	.004	1.11	.350	.011	3.14	.360	.017	4.72	.355	.010	2.82
.472	.006	1.27	.475	.004	0.84	.475	.003	1.71	.474	.003	0.63	.461	.010	2.17	.471	.012	2.55	.469	.010	2.13

(approx. 2.0 m/s). This increased accuracy at high velocities was confirmed by Leslie and Hunter (1959) when applying both their manual (pen trace) and automatic methods. Although in this present study the C.F.M. and 50 per cent peak trace analysis recorded the largest differences (compared with the miniature current meter) at lower velocities and reduced values at the higher, the trend was not generally present when considering the results as a whole. It is probable that a large proportion of the 6 per cent difference at the flow velocity of approximately 0.10 m/s was due to the relative inefficiency of the current meter at low velocities. This conclusion is substantiated by examination of Table 2 which shows that the scatter in the current meter readings was much greater at lower velocities than at the higher values. The significance of this point is that the accuracy which can be obtained by the C.F.M. would appear to be affected to a lesser extent as the flow velocities become very low.

A trend apparent in both Winternitz's and Leslie and Hunter's work, and which was repeated in this study, involved the tendency for the salt–velocity techniques to underestimate flow velocity, particularly at the upper end of the velocity range.

The advantage to be gained by collecting large numbers of readings was investigated by dividing the data in Test Series No.2 into groups of 2, 3, 4, 5, 6, 8, and 10 consecutive readings. The standard deviation of the mean of these groups about the 100 run mean was then plotted against the number of readings in the groups. These results are shown in Fig.7. The graph shows the degree of scatter for identical group sizes decreasing as velocity increased. It also shows how the scatter in the results at any v_x value decreases as the number in the group increases, although in each case as the group size increases the advantage to be gained by a further increase in size becomes less. For example, at $v_x = 0.147$ m/s to average more than four consecutive readings would not reduce the standard deviation about the mean by any significant degree. At the high velocities however, an average of about eight runs would be required before standard deviation started to level out.

CONCLUSIONS

Considering the simplicity of both the basic idea and the electronics required for its operation, the results obtained using the C.F.M. were most promising. Although the more sophisticated automated system of Leslie and Hunter (1959) would appear to be more accurate, the authors doubt whether the slight improvement in accuracy is a fair return taking into account the extra cost, complexity and bulk of the equipment, and the expertise required for its operation. The test results showed that the C.F.M. is not yet as accurate or precise as some alternative salt–velocity methods, which themselves are often less accurate than many other methods. However, when the C.F.M. results are compared with those obtained using the current meter it must be remembered that the tests were performed in a glass sided flume where the latter will usually be superior. In natural channels, where roughness elements will be far more pronounced the C.F.M. could well prove to be as efficient as the more conventional device. The benefit of obtaining the mean of a number of tests has been demonstrated above and the ease with which results can be obtained using the C.F.M. make it an attractive form of salt–velocity measurement. As Leslie and Hunter (1959) point out, it is a facet of human nature that large numbers of tests are not performed if the acquisition of data is laborious. There is thus a great advantage to be gained from the use of automated equipment which gives results quickly and easily. An additional advantage of automation is that it permits the evaluation of results during gauging.

When compared with current meters, use of the modified conductivity cells is attractive in that they involve no moving parts, will function in heavily silt laden water and are unaffected by organic debris smaller than the aperture size employed (14 mm in this case). As with all salt–velocity techniques, the C.F.M. may be used in flows exhibiting high degrees of turbulence. In common with other direct velocity–area discharge gauging procedures it suffers from the need to measure mean cross sectional flow area between sampling stations, but the short gauging reach required by the C.F.M. could make it more attractive than other methods of this type.

Even in its present A.C. powered form, transportation is fairly easy and modification to D.C. operation should make it possible to manually transport the necessary equipment over considerable distances.

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NOTATION

The following symbols are used in this paper

a	volume of air used in the introduction of the tracer
C_b	background conductivity of the flowing water
C_i	conductivity of the tracer solution
d	depth of immersion of a conductivity cell measured from the surface
D	depth of flow
L_i	distance between the point of tracer injection and the first cell the tracer passes
Q_f	flume discharge
S	sensitivity of switching circuit
t_t	time taken for a characteristic point in the conductivity trace to travel between cell stations i.e. time of travel
V_i	volume of tracer introduced
v_s	mean flow velocity between stations
x_u	distance between cells at the upstream station
x_d	distance between cells at the downstream station
X	distance between mid–points of cell pairs

REFERENCES

Allen, C. M. and Taylor, E. A. 1924: The salt velocity method of water measurement. *Mechanical Engineering January 1924:* 13-16 and 51.

Buchanan, T. J. 1964: Time of travel of soluble contaminants in streams. *Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers 90* (SA3): 1-12.

Calkins, D. and Dunne, T. 1970: A salt tracing method for measuring channel velocities in small mountain streams. *Journal of Hydrology (Netherlands) 11* (1970): 379-392.

Fischer, H. B. 1968: Dispersion predictions in natural streams. *Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers 94* (SA5): 927-943.

Hall, L. S. 1943: Open channel flow at high velocities. *Transactions of the American Society of Civil Engineers 108:* 1394-1434.

John, P. H. 1974: An investigation into some less conventional methods of streamflow measurement. Unpublished Ph.D. thesis U.W.I.S.T., Cardiff. 284 p.

John, P. H.; Johnson, F. A. and Sutcliffe, P. 1976: A conductivity flow meter. *Journal of Hydraulic Research 14 (1):* 37-44.

Leslie, W. H. P. and Hunter, J. J. 1959: New equipment for salt velocity flow measurement. *Mechanical Engineering Research Laboratory (East Kilbride, Scotland) Fluids Report No. 62:* 11 p.

Taylor, G.I. 1954: The dispersion of matter in turbulent flow through a pipe. *Proceedings of the Royal Society 223:* 446-468.

Winternitz F. A. L. 1957: Comparison of flow measuring techniques at Kinlochleven Hydro–electric Station – Preliminary tests. *Mechanical Engineering Research Laboratory (East Kilbride, Scotland) Fluids Report No. 59:* 13 p.

Winternitz, F. A. L. 1958: Comparison of flow measuring techniques at Kinlochleven Hydro–electric Station – Final tests. *Mechanical Engineering Research Laboratory (East Kilbride, Scotland) Fluids Report No. 65:* 17 p.

Young, L.; McMillan, C. E. and Scott, R. W. W. 1955: Salt velocity flow measurements in a one–inch diameter pipe. *Mechanical Engineering Research Laboratory (East Kilbride, Scotland) Fluids Report No. 33:* 10 p.

Young, L. and Wilson, G. 1958: Developments in salt–velocity flow measurements. *Mechanical Engineering Research Laboratory (East Kilbride, Scotland) Fluids Report No. 60:* 13 p.