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COMPARATIVE FLOWRATE MEASUREMENTS AT THE CANEVA GENERATING PLANT UNIT 2

2-3 April 1996

by

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Abstract

A comparative flow measurement test was performed on unit 2 at the Caneva generating plant. The test was the seventh in a wide programme sponsored by ENEL to compare the acoustic flow-measuring method with the currentmeters method, accepted by IEC code.
This last test compared the acoustic method also with the code accepted pressure-time method and was essentially conducted in accordance with the IEC 41/1991 and ISO 3354 (1988) codes.
The data presented in this report confirme the good results of the acoustic method and its advantages if compared with the currentmeters method.

Resumé

Une essai comparative de mésure du debit a été effectuée dans l'unité 2 à la central de generation de Caneva.
L'essai a été la septième d'une série de recherches supportées par ENEL pour comparer la méthode a ultrasons avec la méthode des moulinets, acceptée par le code CEI.
Cette dernière essai a comparé la méthode acoustique aussi avec la méthode, acceptée par les normes CEI, pression-temps et a été effectuée d'accord avec les normes CEI 41/1991 et ISO 3354 (1988).
Les données présentées dans cet rapport confirment les bons resultats de la méthode acoustique déjà obtenues dans les précédentes expériences et les avantages en comparaison a la méthode des moulinets.

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1. Introduction

Since ENEL needs to know the flowrate in the hydroelectric production plants in order to manage offtake works in safe conditions, as well as to optimize production, there has always been a continual interest in the study of the different flowrate measurement methods, with particular attention focused on those which can guarantee precise and reliable results.
Of the different methods applied to penstocks, ENEL Hydraulic and Structural Research Center (CRIS) has carried out numerous studies and experiments on the currentmeter method, the saline dilution method, the pressure-time method and, more recent, the acoustic method.
The latter has already been successfully tested by CRIS over the last few years [1]÷[6] with the first applications in penstocks and then in open channels. The currentmeter method has been the main method for a comparison with all the applications in pipes and channels.
Acceptance tests of the turbine of the second group of the Caneva hydroelectric plant (TV), after the latter had been completely rebuilt in the penstock and the hydraulic and electric machinery, created an opportunity to further investigate the comparison between currentmeters and ultrasonic and it was also possible to use the pressure-time or "Gibson" method at the same time.
In the Caneva hydroelectric plant there are 2 horizontal axis 18.7 MW groups equipped with Francis turbines each fed with a maximum flowrate of 20 m^3/s conveyed by a 2.8 m diameter penstock (one per group).
This report presents the most significant results of a comparison between three different flowrate measurement methods, a study which has involved three ENEL departments.

2. Flowrate measurement using currentmeters

The length chosen as the flowrate measuring section is located in the straight stretch, which extends for 72.5 diameters, between vertices V_1 and V_2 , (Fig. 1), at a distance of 59.5 diameters from the upstream vertex V_1 and 13 diameters from the downstream vertex V_2; these are conditions which fully comply with the ones provided in standards IEC 41: 1991 [7] and ISO 3354 (1988) [8] which were referred to for the positioning of the 21 currentmeters on cross bars, composed of 4 arms with a 35 x 75 mm ovoid section, arranged in a St. Andrew's cross, Fig. 2.
The currentmeters used were made by SIAP with a propeller diameter of 120 mm, and a pitch of 0.25 m; they were calibrated over the period May-October 1993 in the calibrating tank of the Hydraulics Institute of Padua University with the same type of arms and vices as the ones to be used in the tests.
In the first two tests, which were carried out on the afternoon of 2 April, the current meters occupying positions n° 7 and n° 13 (Fig. 2) did not give out any impulses, while the one at position 18 did not function properly, as it gave out a number of

considerably anomalous impulses compared to the other three positioned on the same circle.
Since anomalies were observed in the third test in the currentmeters located at positions 2, 3 and 17 at the maximum flowrate of 20 m^3/s, the pipe was emptied to check the state and working conditions of the currentmeters.
The situation observed is clearly documented in the photos in Fig. 3.
Two propellers were in fact blocked by material transported by the current, the electrical system of one currentmeter broken down, and others had weeds wound round the propellers which reduced their speed.
The cross bar was cleaned, all the currentmeters were checked for good working order and then testing was started again. The data reported in this paper only refers to the seven tests carried out after this intervention.
Flowrate was calculated using J. Coffin's well-known cubic curves method which is in excellent agreement with the graphic methods proposed by the ISO Standard 3354.
The values of J. Coffin coefficients k_i, which appear in Tab.1, depend on the geometric position of the currentmeters along the radius alone, with the exception of coefficient k_5 which multiplies the mean velocity of the outermost circle, in which exponent n of the wall law appears; this is found to be equal to 9.5 when the graphic method provided in Annex E of ISO 3354 is applied.
Diametrical velocity profiles are given, by way of example, in Figs. 4 and 5 for four of the seven tests to show that the body of the velocities is almost stable depending on flowrate.
In all the tests the upper radii A and C of Fig. 2 were always characterized by lower velocities than the lower radii A' and C', as Fig. 6 clearly illustrates, along with the isovels of the same tests reported in the previous figures.
The above-mentioned ISO Standard states that the flow may be considered sufficiently "regular" to allow for the application of the Standard if the asymmetry index Y, defined in paragraph 3.1.9. of the same is lower than or equal to 0.05. The old IEC Standard, publication 41, 2nd edition, 1963, which was used for reference up to a short time ago, prescribed that "measurements carried out with cross-bars with four arms may be considered sufficient if the flowrates, calculated separately for the two diameters, do not differ by more than ±2 from their mean".
These two "satisfactory" flowrate measurement indices were calculated for all the tests and are indicated in Tab. 2 which shows regular flowrate conditions with index values far below the limit values.
The mean discharges indicated in Tab. 2 are not to be used for calculating turbine efficiency since it is necessary to take into account the blockage effect created by the cross bar and currentmeters which is known to bring about an overestimation of the flowrate.
In fact the ISO Standard states that when the relative obstruction exceeds 2% and is lower than 6% (the limit for the application of the Standard), it is necessary to reduce the flowrate value measured by the currentmeters by a correction factor which takes the blockage effect of the currentmeter-supporting cross bar and the currentmeters themselves into account.
The expression indicated in Annex B leads to a 0.5% reduction in the flowrate measured by the currentmeters.

3. Flowrate measurement using an acoustic flowmeter

A few diameters upstream of the currentmeter flowrate-measuring section 16 acoustic transducers were installed on two vertical planes; each one had 4 acoustic paths arranged symmetrically to the axis of the pipe at distances of ±0.30902R and ±0.80902R, as provided by the IEC Standards 41/1991 (Appendix J) when the Gauss-Jacobi flow field integration method is adopted.
The ultrasonic section had a 50 diameter straight length upstream and a 22.5 diameter one downstream which is theoretically more than sufficient to eliminate any dissymmetry in the body of velocity, and is equal to 5 times the 10 and 3 diameter values recommended by the IEC Standards.
The topographic method was used for the configuration of the installation geometry and the diameter of the measuring length was obtained in n° 5 sections as shown in Tab. 3 which also indicates the characteristic geometric parameters of the installation, as well as the ovality of the pipe which was below 1%.
All together a total of seven comparison tests were carried out with a flowrate contained between 9 and 20 m^3/s, corresponding to a velocity of 1.4 and 3.2 m/s.
ENEL CRIS developed and tested the data logging and processing software which makes it possible to calculate flowrate for each of the two measurement planes (normal and crossed) as well as the mean velocity of the single acoustic paths. This information supplies indications about the flow field trend and shows up any dissymmetries.
The most significant results of the flowrate measurements carried out with the acoustic flowmeter are given in Tab 4 which shows the normal plane flowrates, the crossed plane ones, the compensed flowrate and the mean velocity, the single velocities of the four acoustic paths and their relations to the mean velocity.
First of all it was observed that the difference in flowrate between each plane and their mean value did not exceed 0.13% with a mean difference value taken from the seven tests as an absolute value equal to 0.06%; this confirms that in fully-developed normal flow conditions when the straight stretchs of pipe are adequately long (>20 ϕ), a single measuring plane is sufficient provided that it has 4 acoustic paths.
The acquisition of individual velocities confirmed the distribution of the flow field supplied by the currentmeters, i.e. velocity a few per cent higher in the lower semicircle. For the outer acoustic paths there is a 9% (n° 1 and n° 4) difference while for the inner ones it is 4.6% (n° 2 and n° 3).
The mean of the ratios x_i of the two outer acoustic paths was equal to 0.9085, while the mean of the two inner paths was equal to 1.0350. If the radial profile of the velocity follows Von Karman's law of power $V = V_0\ (1\text{-}r/R)^{1/n}$ where n is equal to 9.5 as stated in the previous paragraph, the theoretical values v_i / v_m for the outer and inner paths are 0.9155 and 1.0333, respectively, which differ by 0.8% and 0.2% from the measured ones.
It should be noted that the tests, carried out on the pipe in group n° 1, with the same configuration as the acoustic flowmeter, led to exactly the same results regarding the flow field distribution.
The flowrates calculated for each of the two semicircles reveal a slightly more marked nonuniformity with the acoustic flowmeter than with the currentmeters, shown in Tab. 5 where the flowrates of the two semicircles were expressed in a % of the total flowrate.
On average, with the ultrasonic method 48.6% of the discharge passed through the upper semicircle and 51.4% through the lower one, whereas with the currentmeter

method the corresponding values were equal to 48.8% and 51.2%, respectively. The overall inaccuracy in the flowrate measurement carried out using the flowmeter was equal to 0.16% and this was obtained from the contribution of the following terms:

a) inaccuracy in the time measurement	ε_t	= 0.03% (inaccuracy of 20 ns)
b) inaccuracy in the angle measurement	$\varepsilon_{\cos\vartheta}$	= 0.01% (inaccuracy of 20')
c) inaccuracy in the length measurement	ε_L	= 0.05% (inaccuracy of 1mm)
d) inaccuracy in the area measurement	ε_A	= 0.1% (a 1 mm inaccuracy in the radius measurement)
e) inaccuracy of the integration method	ε_i	= 0.1%

4. (Gibson) Pressure-time method

The Gibson method calculates the flowrate by integrating the pressure difference measured at the ends of a straight stretch during the closure of a wicket gate. For Caneva, the section chosen for the experiment is immediately upstream of the ultrasonic measuring section, which is also along the straight length contained between vertices V_1 and V_2.
For each section two diametrically-opposed pressure taps were installed at an angle of 45° to the vertical axis and a distance of 36.85 m between the two sections was established.
The 13-diameter-long measuring stretch had a straight length 34 diameters upstream and 25.5 diameters downstream.
A Honeywell transducer with an impressed current outlet and a 10 m range was used for the measurement of the differential pressure. It was calibrated in the interval -0.2÷0.8 m with the sample scale in class 0.04%, and was placed at the very center of the measuring section, so that it was possible to obtain the same length of pipes with a 10 mm diameter upstream and downstream.
Before each test the pipes were visually checked for air bubbles.
In all the tests the product of the distance between the two piezometric sections times the mean velocity in the pipe was always above the value 50 m^2/s prescribed by the Standards.
In order to avoid fluctuations in the flowrate, the velocity regulator was placed under a load limiting device and flowrate stability was checked after each variation in the load from the acoustic flowmeter indications.
Shutdown of the group occurred through the closing of the distributor to the technical minimum; then the shutdown of the machine was actuated by the closure of the rotative valve and the by-pass of the same. These steps were taken so as not to set off a synchronous discharge and to limit mechanical stress.
The measuring system , comprising the differential transducer and datalogger, fully complied with the relative Standards.
The response time was below 1 ms, the sampling frequency was 100 Hz and the differential pressure data was processed by numerical filtering using a low-pass filter of 0.13÷0.18 Hz.
The area between the differential pressure signal and the load loss recovery line was calculated using a program which was developed and tested at the DPT Measuring and Testing Department (Servizio Misure e Prove DPT) of Venice.

The overall time for data acquisition for each test was about 300 seconds, comprising an interval of 10 seconds before the start of the test, a closing time of 40 seconds for the distributor, and 60 seconds for the rotative valve, completing closure operations of the by-pass within 240 seconds.
Only five comparison tests were carried out with the Gibson method and the other methods described above and Figs. 7 and 8 show an example of signal recording for two of these five tests.

5. Results of the comparison

Seven comparison tests were carried out with the current meters and acoustic flowmeter with flowrates contained between 9 and 20 m^3/s; in the case of the Gibson method, however, the comparison was limited to five tests only.
The difference from the currentmeter method, which was used as the reference method, is shown in Tab. 6 which highlights that in five of the seven tests the acoustic flowmeter supplied slightly lower flowrates than the current meters did; as for the Gibson method, two tests gave negative differences and three tests positive ones.
The results given by the acoustic flowmeter differ from the ones obtained in tests carried out in the past with the same reference method, for which positive differences were generally obtained. The difference in absolute value between the two methods nevertheless remains the same as was seen in previous ENEL experiences, contained within the order of 0.1÷0.3% .
The Gibson method also gave excellent results with differences from the current meter results, which never exceeded 1% despite the low differential pressure values due to the high closing time of the flowrate regulation system.
The comparison tests between the multipath flowmeter, which uses 8 acoustic paths, 4 for each of the two crossed planes, and the currentmeters, once again confirms the validity of the acoustic method, which is fully entitled to being included in the code as the principal method, provided that multipath systems are adopted.
In conclusion it can be said that the hydraulic conditions which are ideal for the use of currentmeters, are equally valid to adopt the multipath acoustic flowmeter. In favour of the latter method and the Gibson method is the fact that in the event of a malfunction it is possible to operate without having to empty the pipe, which was unfortunately necessary in the last Caneva experience.

Acknowledgements

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Particular thanks to all the personnel ENEL DPT SMP (Measuring and Testing Department) of Venice and Rome who recorded the measurements with the pressure-time and currentmeters methods with interest and enthusiasm.
I would also like to express my warmest thanks to the CRIS-UIGI personnel who collaborated in organizing and carrying out the tests, as well as processing the data.

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[7] IEC 41/1991: "Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines.

[8] ISO 3354 (1988): "Measurement of clear water flow in closed conduits-velocity-area method using currentmeters in full conduits and under regular flow conditions.

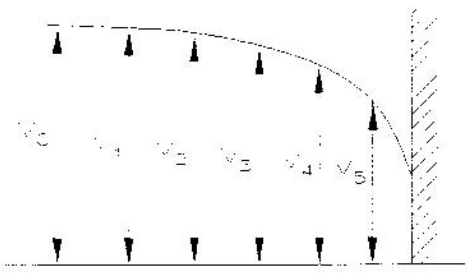
Tab. 1 - Discharge calculation by numerical J. Coffin method

Run nº	V_0 (m/s)	V_1 (m/s)	V_2 (m/s)	V_3 (m/s)	V_4 (m/s)	V_5 (m/s)	Mean Velocity V_m (m/s) 1)	Discharge Q (m/s) 2)
1	1.601	1.575	1.527	1.461	1.374	1.249	1.433	8.803
2	1.881	1.858	1.801	1.726	1.625	1.472	1.691	10.387
3	2.128	2.113	2.053	1.968	1.853	1.681	1.926	11.833
4	2.467	2.446	2.384	2.286	2.157	1.958	2.237	13.743
5	2.798	2.772	2.701	2.582	2.437	2.215	2.531	15.551
6	3.155	3.130	3.048	2.916	2.751	2.504	2.858	17.561
7	3.604	3.563	3.483	3.338	3.155	2.874	3.269	20.082

1) Mean velocity = $\frac{Q}{\pi R^2}$ *computed by Coffin method*

$v_m = k_0 v_0 + k_1 v_1 + k_2 \cdot v_2 + k_3 v_3 + k_4 v_4 + k_5 v_5$

$k_0 = 0.05380$
$k_1 = 0.21840$
$k_2 = 0.16619$
$k_3 = 0.17510$
$k_4 = 0.17561$
$k_5 = 0.20161 \quad n = 9.5$



2) Discharge blockage effect non corrected

Tab. 2 - Determination of diametral discharges and calculation of the index asymmetry

Run n°	Discharge relative to diameters [1)] A-A' (m³/s)	C-C' (m³/s)	Q_{mean} [1)] (m³/s)	Difference [2)] ε (%)	Asymmetry index [3)] y
1	8.762	8.844	8.803	-0.47	0.024
2	10.369	10.405	10.387	-0.17	0.025
3	11.820	11.846	11.833	-0.11	0.026
4	13.731	13.755	13.743	-0.09	0.029
5	15.506	15.597	15.551	-0.29	0.030
6	17.448	17.673	17.561	-0.64	0.032
7	19.983	20.182	20.082	-0.49	0.029

1) Discharge blockage effect non corrected

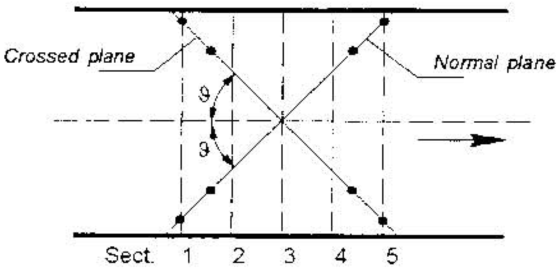
2) $$\varepsilon = \frac{Q_{A-A'} - Q_{mean}}{Q_{mean}} \times 100$$

3) $$y = \frac{1}{v_m}\sqrt{\frac{\sum_{i=1}^{4}\left(v_i - v_m\right)^2}{3}}$$

i = radius number

V_i = mean velocity at i radius

Tab. 3 - Geometrical elements of the multipath acoustic flowmeter installtion



Section n°	ϕ_m (mm)
1	2797.5
2	2798.3
3	2795.8
4	2798.0
5	2797.5

ϕ_{mean} = **2797.4**

Path n°	L (m)	ϑ	cos ϑ	
1	2.191	45° 05' 39"	0.70594	Normal plane
2	3.681	45° 04' 48"	0.70612	Normal plane
3	3.687	45° 04' 09"	0.70625	Normal plane
4	2.192	45° 03' 32"	0.70638	Normal plane
1	2.191	45° 05' 12"	0.70604	Crossed plane
2	3.680	45° 04' 03"	0.70627	Crossed plane
3	3.688	45° 02' 18"	0.70664	Crossed plane
4	2.192	45° 03' 43"	0.70634	Crossed plane

$$Ovality = \frac{D_{max} - D_{min.}}{D_{mean}} \times 100$$

Penstock ovality determination

Section n°	D_{max} (mm)	$D_{min.}$ (mm)	D_{mean} (mm)	Ovality (%)
1	2806	2790	2797.5	0.57
2	2806	2789	2798.3	0.61
3	2802	2788	2795.8	0.50
4	2806	2791	2798.0	0.54
5	2805	2792	2797.5	0.46

mean value **0.54**

Tab. 4 - Most significant results of the discharges measurements by multpath acoustic flowmeter

Run n°	Q_{nor} 1) (m^3/s)	Q_{cros} 2) (m^3/s)	Q_{com} 3) (m^3/s)	ε 4) (%)	v_m 5) (m/s)	v_1 (m/s)	v_2 (m/s)	v_3 (m/s)	v_4 (m/s)	v_1/v_m	v_2/v_m	v_3/v_m	v_4/v_m
1	8.781	8.777	8.779	+0.02	1.428	1.247	1.439	1.517	1.349	0.873	1.007	1.062	0.944
2	10.336	10.631	10.349	-0.13	1.684	1.451	1.705	1.784	1.597	0.862	1.013	1.059	0.948
3	11.773	11.745	11.759	+0.12	1.913	1.656	1.934	2.029	1.813	0.866	1.011	1.061	0.948
4	13.654	13.663	13.659	-0.04	2.222	1.933	2.257	2.345	2.101	0.870	1.016	1.055	0.946
5	15.440	15.448	15.444	-0.03	2.513	2.165	2.545	2.659	2.394	0.862	1.013	1.058	0.953
6	17.416	17.438	17.427	-0.06	2.835	2.474	2.859	3.000	2.702	0.873	1.008	1.058	0.953
7	19.943	19.928	19.936	+0.04	3.244	2.820	3.279	3.431	3.085	0.869	1.011	1.058	0.951
									Mean values	**0.868**	**1.011**	**1.059**	**0.949**

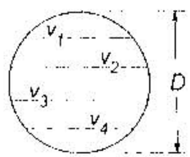
1) Normal plane discharge

2) Crossed plane discharge

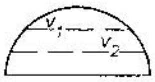
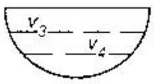
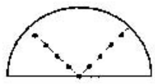
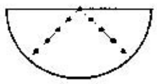
3) Compensed discharge

4) $\varepsilon = \frac{Q_{nor} - Q_{com}}{Q_{com}} \times 100$

5) $V_m = \frac{Q_{com}}{A}$ $\quad A = \frac{\pi D^2}{4}$



Tab. 5 - Discharges flowing in the two semicircle upper and lower of the penstock, % of total flowrate

Run n°	ULTRASONICS		CURRENTMETERS	
	 (%)	 (%)	 (%)	 (%)
1	48.5	51.5	49.0	51.0
2	48.6	51.4	48.9	51.1
3	48.5	51.5	48.9	51.1
4	48.8	51.2	48.8	51.2
5	48.6	51.4	48.7	51.3
6	48.5	51.5	48.7	51.3
7	48.6	51.4	48.8	51.2
Mean values	**48.6**	**51.4**	**48.8**	**51.2**

Tab. 6 - Results of the tests comparing three methods: currentmeters, ultrasonic, pressure-time

Run n°	$Q_{currentmeters}$ [1] (m³/s)	$Q_{ultrasonic}$ (m³/s)	Q_{Gibson} (m³/s)	ε_1 [2] (%)	ε_2 [3] (%)	ε_3 [4] (%)
1	8.759	8.779	8.841	+0.2	+0.9	+0.7
2	10.335	10.349	-	+0.1	-	-
3	11.774	11.759	11.805	-0.1	+0.3	+0.4
4	13.674	13.659	-	-0.1	-	-
5	15.473	15.444	15.544	-0.2	+0.5	+0.6
6	17.473	17.427	17.431	-0.3	-0.2	+0.0
7	19.982	19.936	19.872	-0.2	-0.6	-0.3

1) Discharge blockage effect corrected: correction = 0.5%

2) $$\varepsilon_1 = \frac{Q_{ultrasonic} - Q_{currentmeters}}{Q_{currentmeters}} \times 100$$

3) $$\varepsilon_2 = \frac{Q_{Gibson} - Q_{currentmeters}}{Q_{currentmeters}} \times 100$$

4) $$\varepsilon_3 = \frac{Q_{Gibson} - Q_{ultrasonic}}{Q_{ultrasonic}} \times 100$$

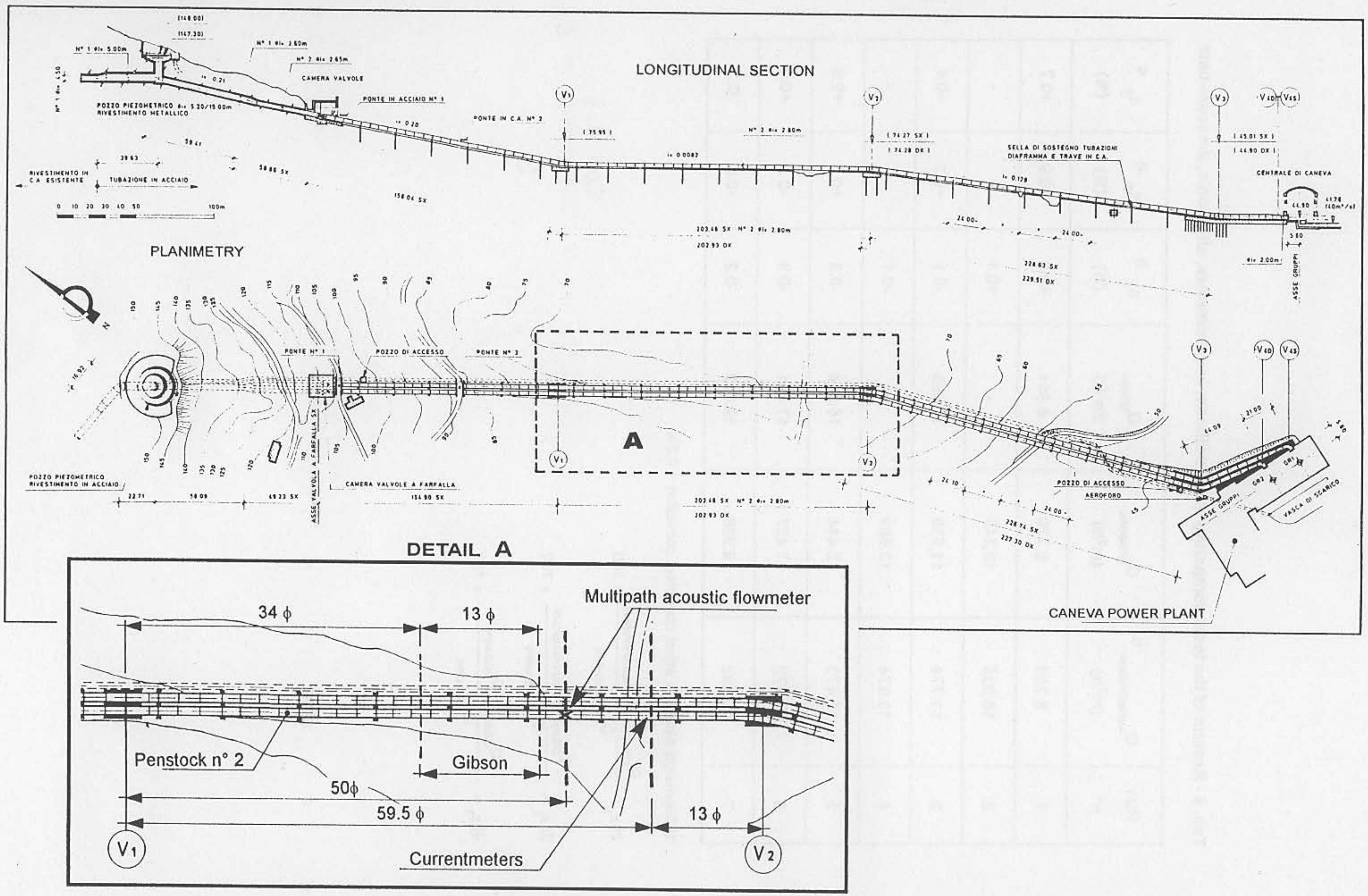
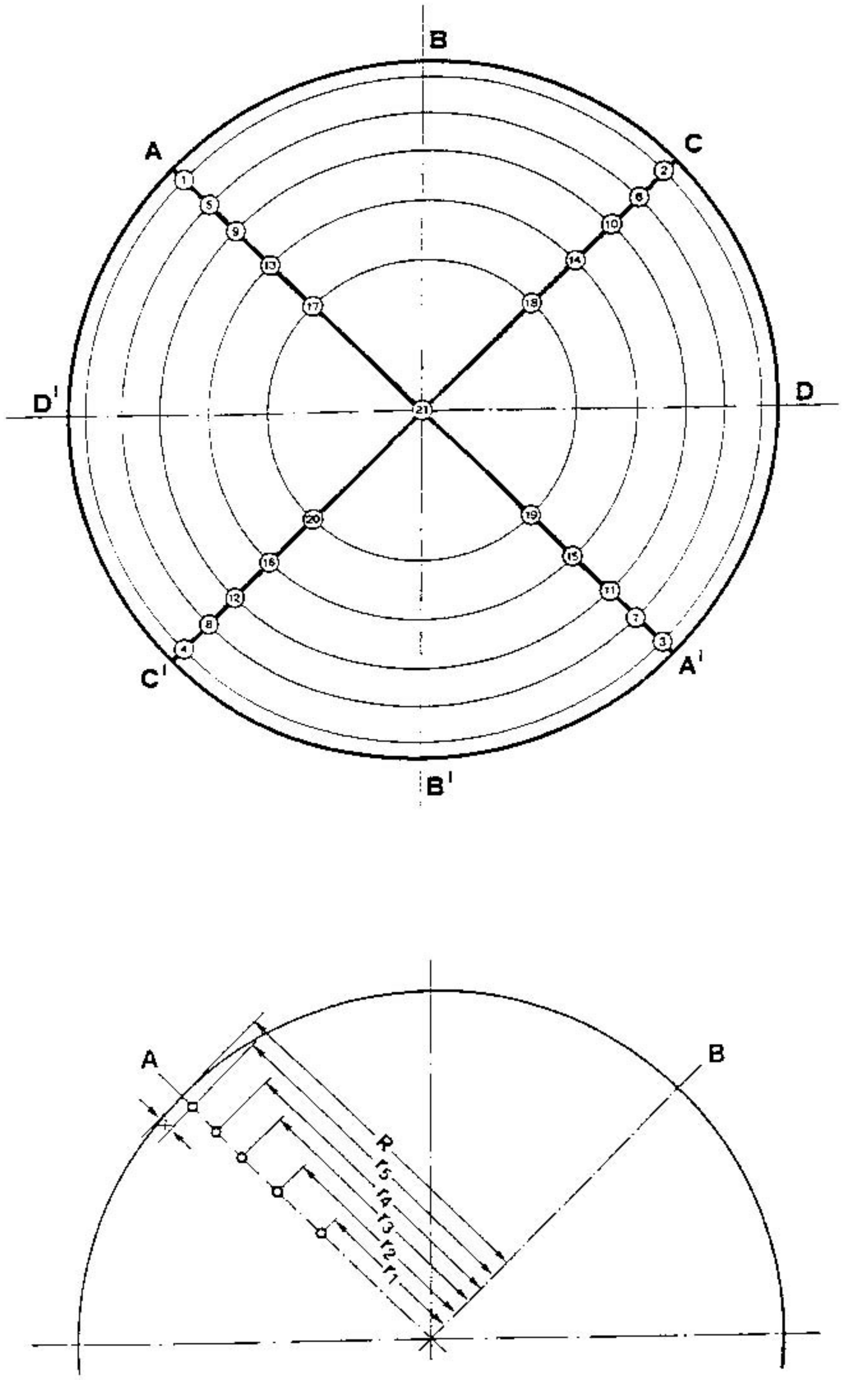


Fig. 1 - Caneva power plant - Location of test equipment (currentmeters, acoustic flowmeter, Gibson pressure taps).



R = 1398.4 mm x = 75 mm

r_1 = 584.0 mm r_2 = 827.0 mm r_3 = 1014.8 mm

r_4 = 1170.3 mm r_5 = 1310.5 mm

Fig. 2 - Position of currentmeters on fixed cross bars in Caneva Unit 2 penstock.

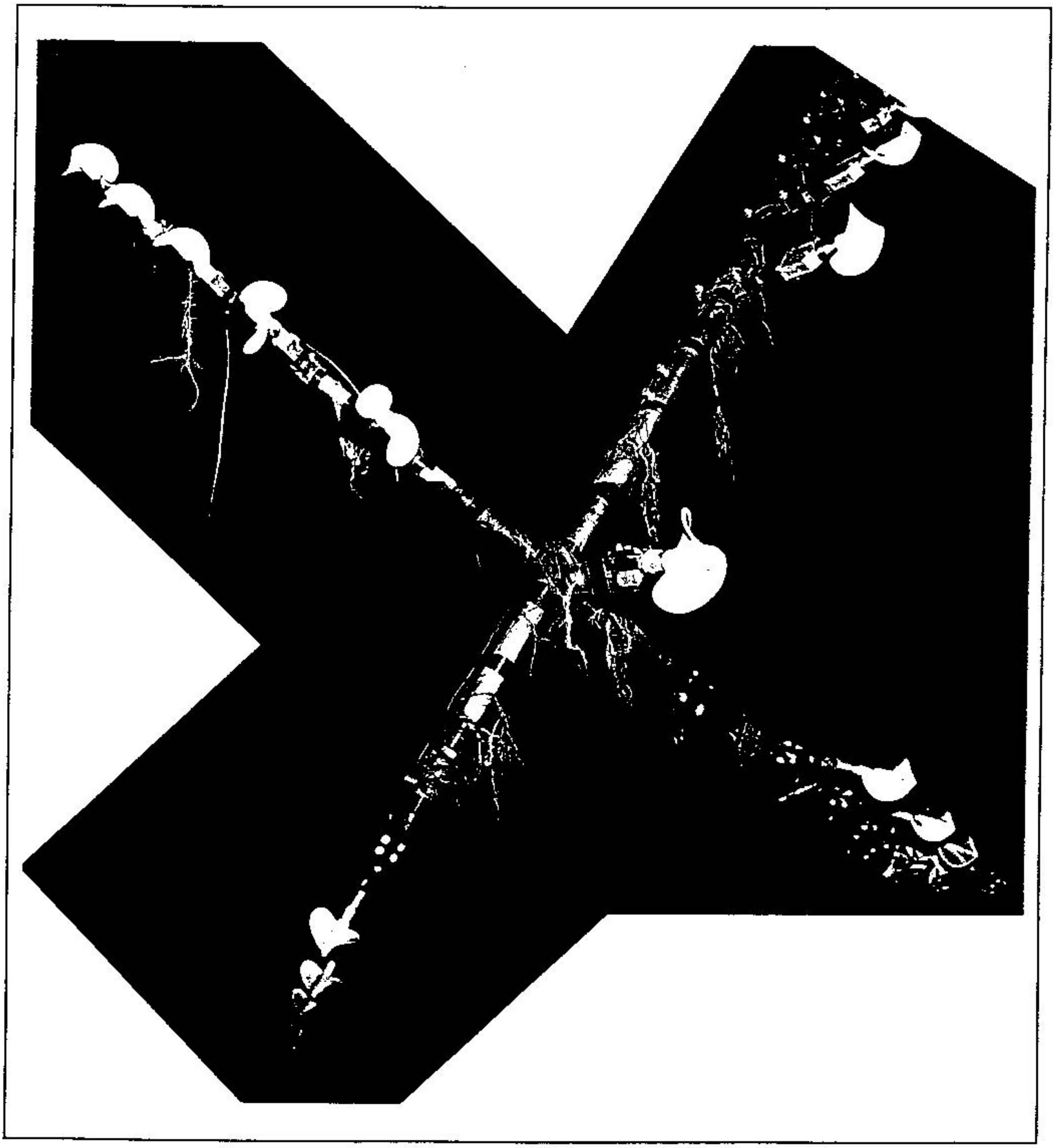


Fig. 3 - Situation of currentmeters and cross bars found after three tests carried out the first day - 2 April.

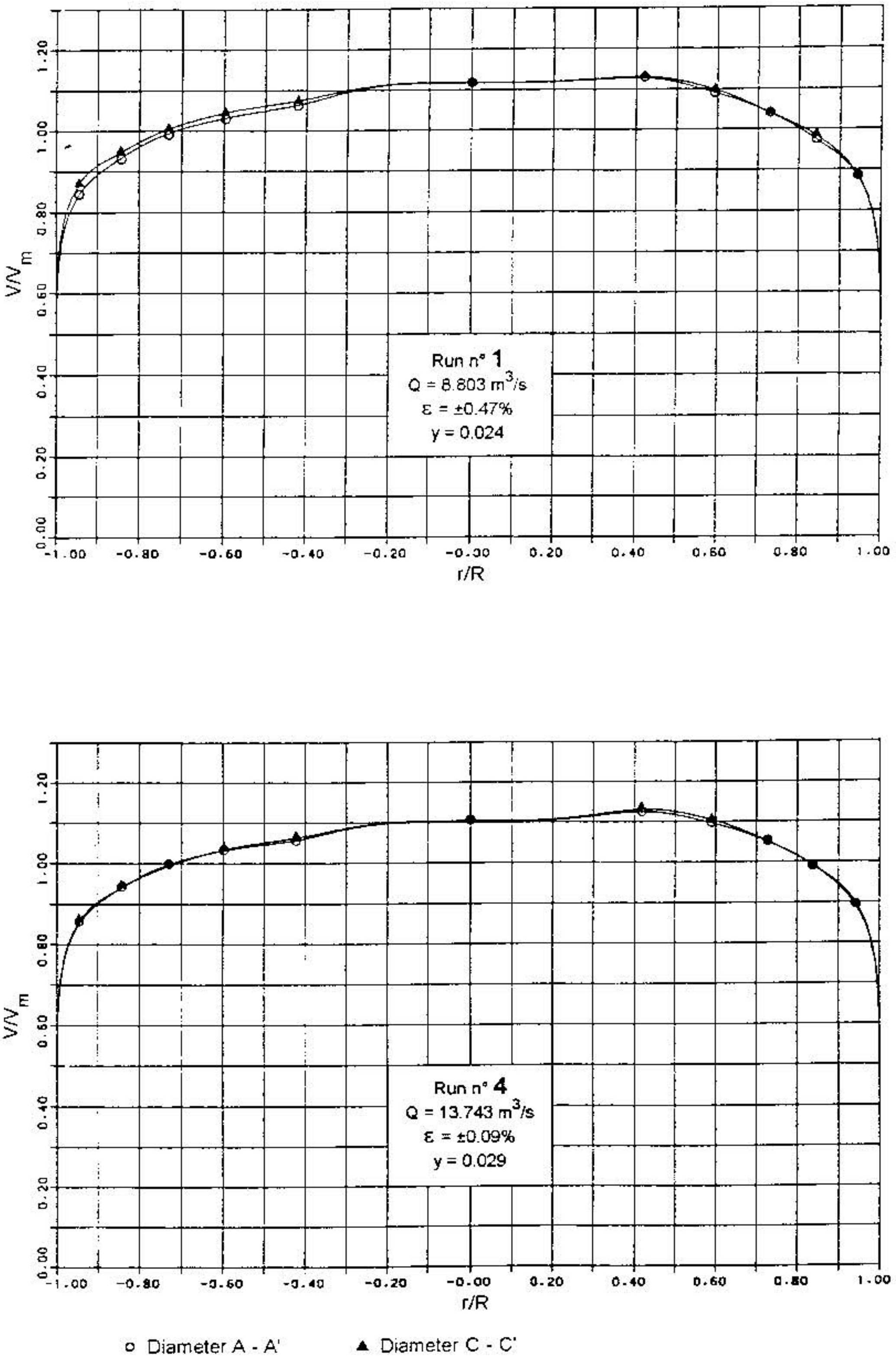


Fig. 4 - Diametral adimensional velocity profiles - Runs n° 1, 4.

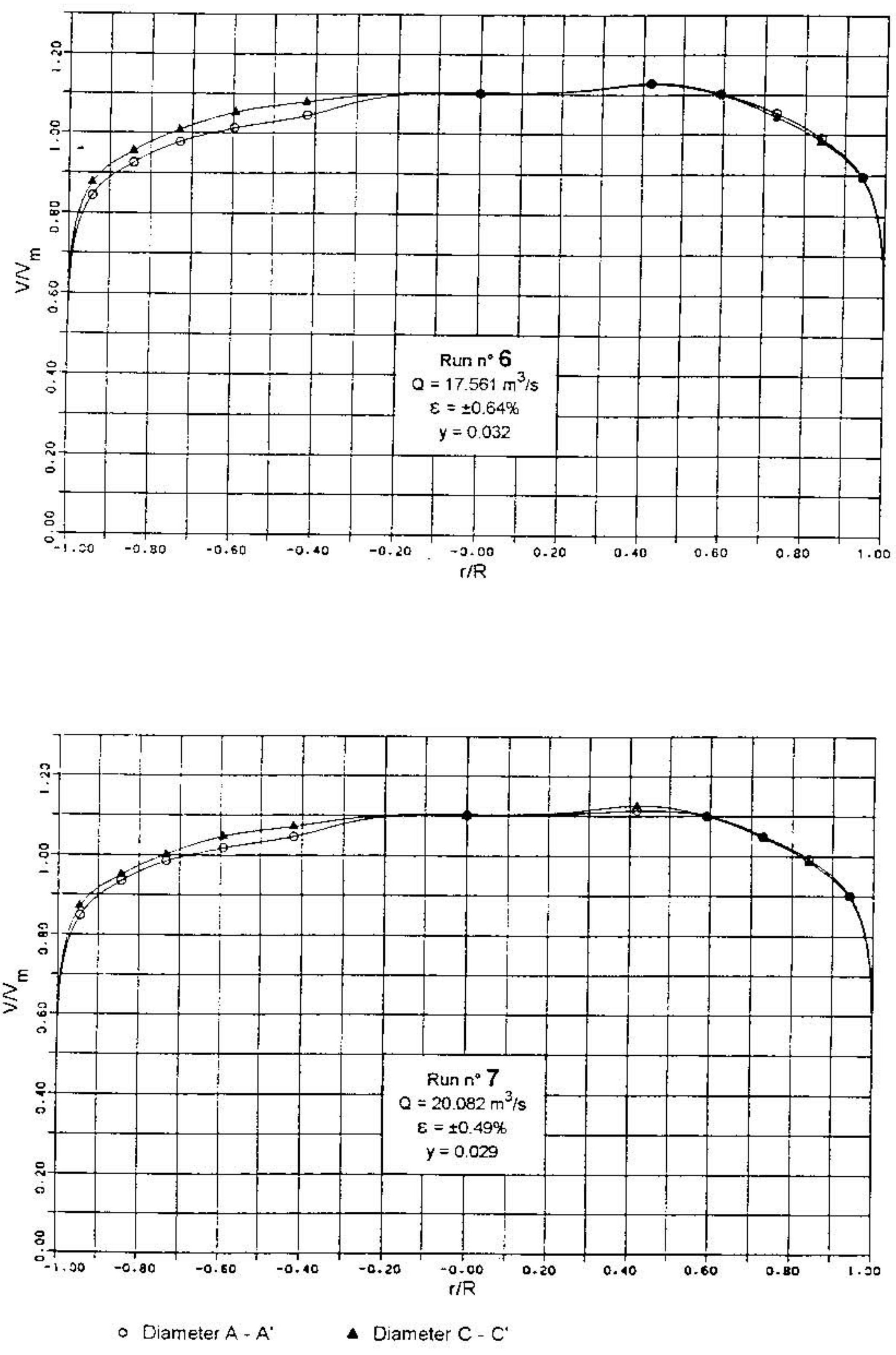


Fig. 5 - Diametral adimensional velocity profiles - Runs n° 6, 7.

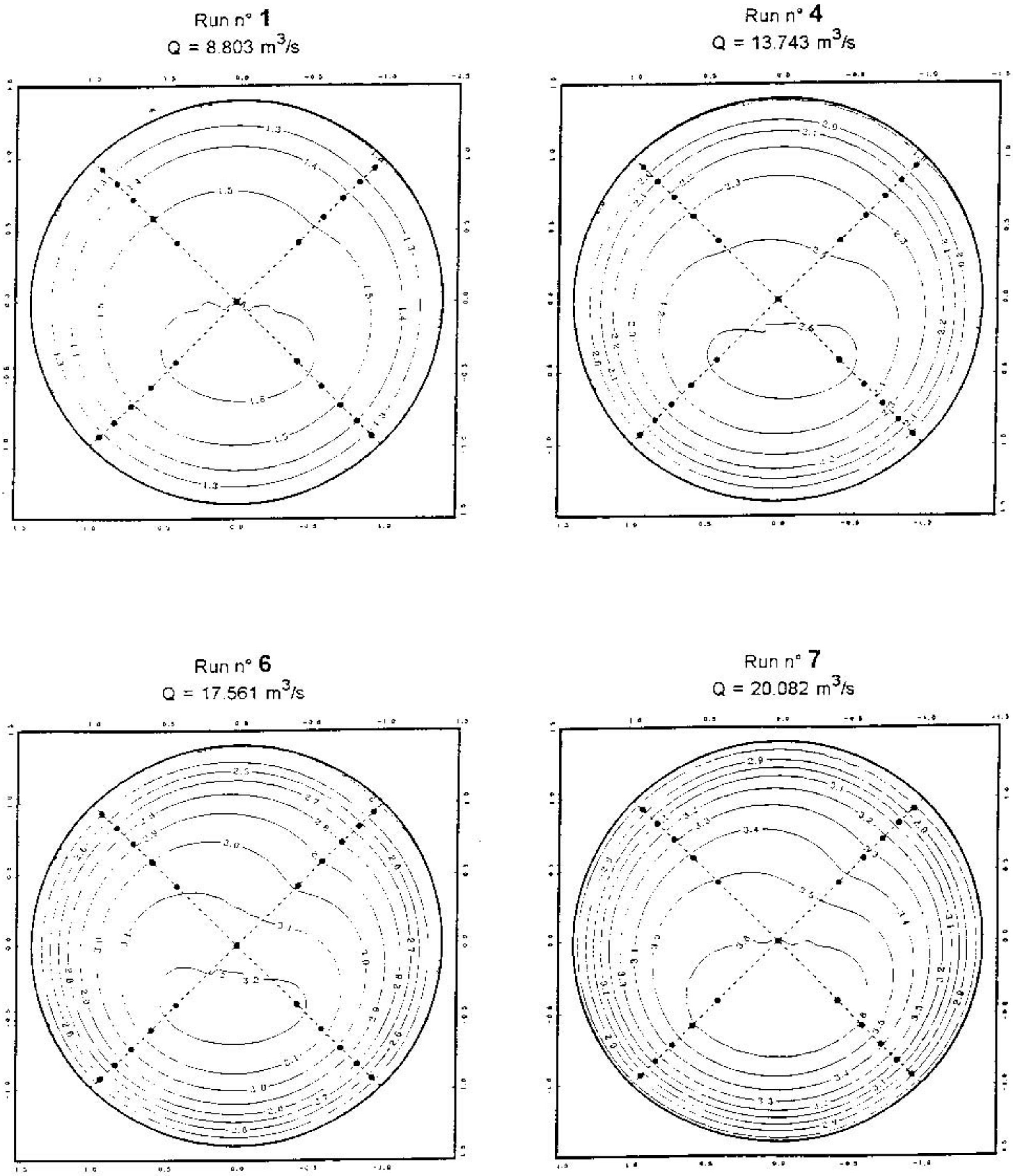


Fig. 6 - Isovel at four different discharge measurements.

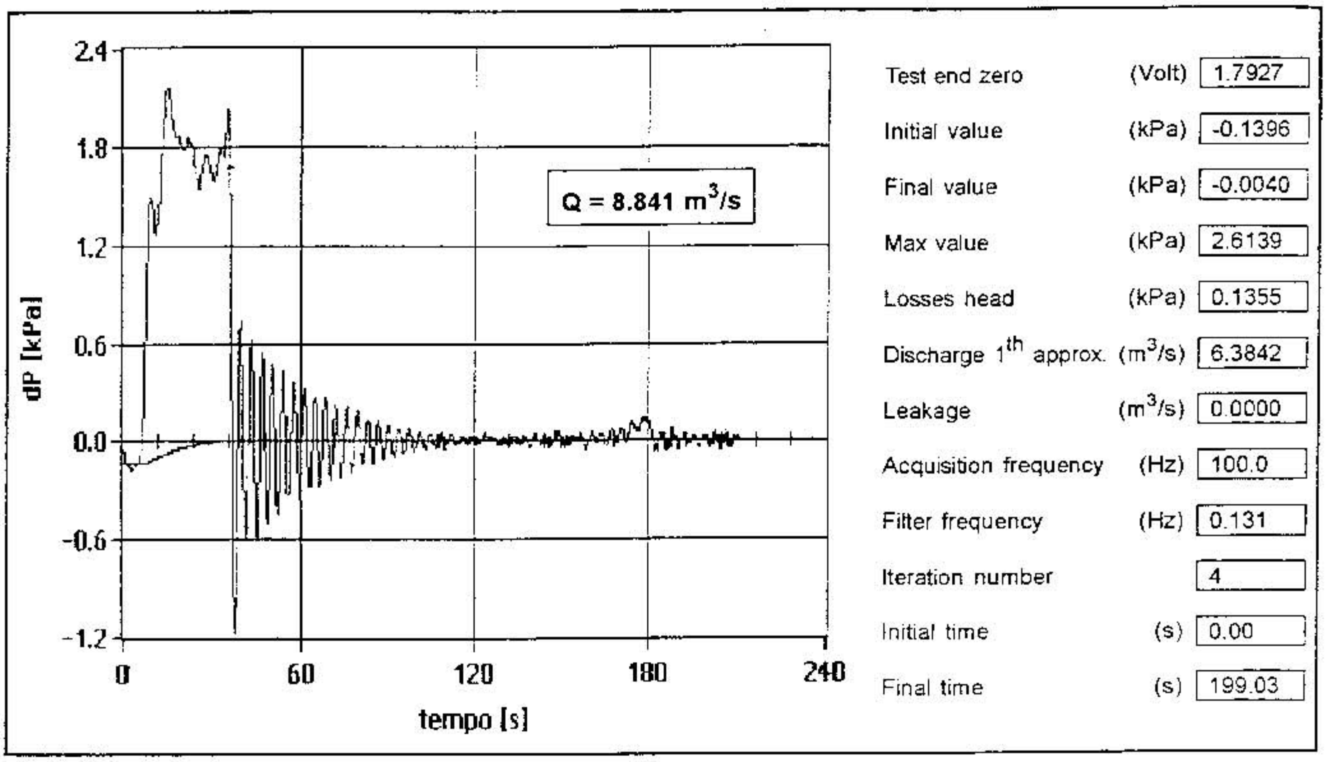


Fig. 7 - Pressure-time method - Run n° 1.

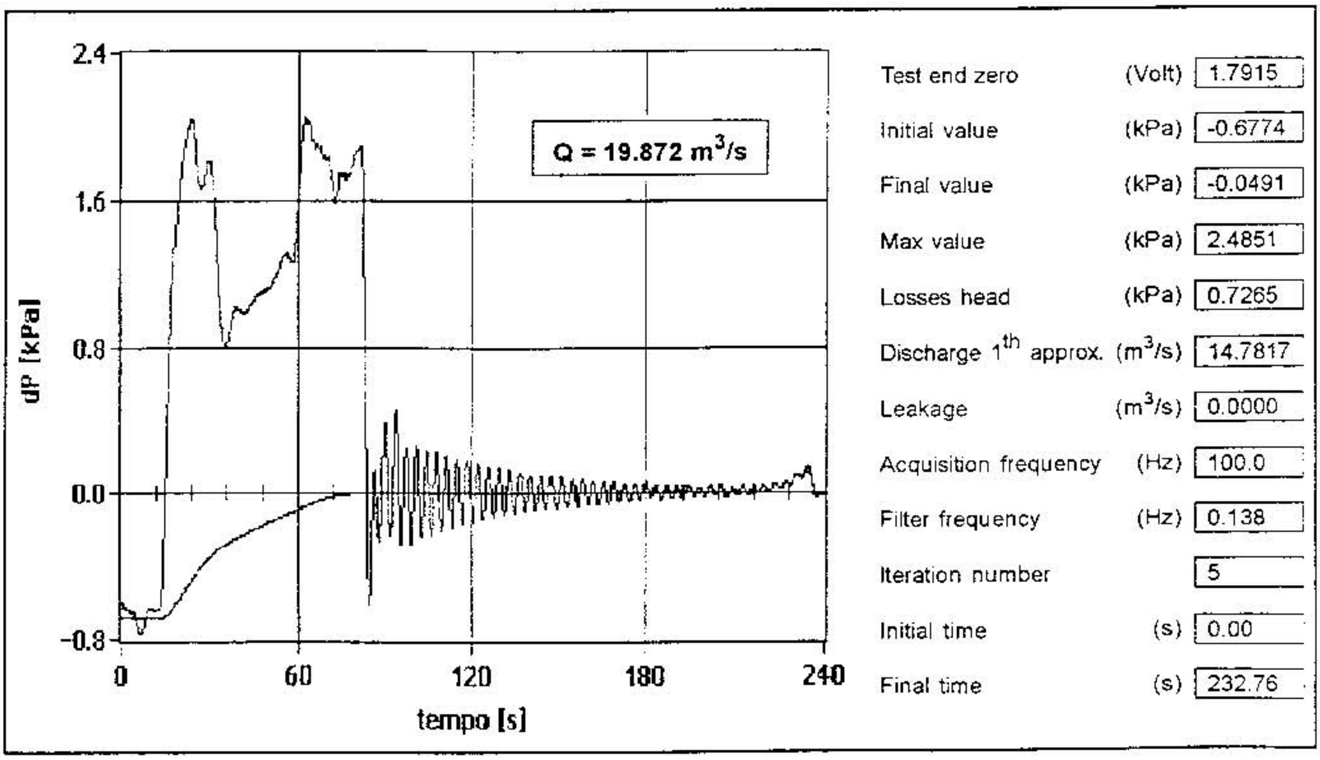


Fig. 8 - Pressure-time method - Run n° 7.