Comparison of discharge measurements in penstocks using current meters to test machinery efficiency in generation and pumping conditions

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The current meters method has used as the primary method for measuring discharge to assess the efficiency of binary-set hydraulic machinery (reversible unit) or ternary-set machinery (motor-generator, turbine and storage-pump). In this case, a single section is chosen for discharge measurement in order to curb costs and reduce the duration times of the tests, providing this is feasible for the particular plant involved. While this choice complies with the Standards regarding the availability of a straight stretch upstream and downstream of the section with reference to the presence of disturbances and singularities, it can sometimes result in flow field conditions that differ between the two operations, i.e. the generation and pumping. Moreover, when the discharge measurement section is located downstream of the hydraulic machinery, very disturbed conditions occur with a flow that is not fully developed.

This report refers to recent results obtained at a hydroelectric plant equipped with a reversible unit, in which the flow fields differed considerably between the two different operations, with a rotational flow occurring in the pump, which led to an underestimation of the discharge and generated unreliable efficiency values. This underestimation is due to the use of normal propellers, not self-compensating, which record a velocity that is lower than the axial component of the velocity when the flow direction differs from the axis of the current meter.

This result was also observed on earlier occasions, and this led us, in certain cases, to select different sections for the two operations (generation and pumping). This obviously entails longer testing times; on the other hand, it eliminates any doubts about the validity of the test results.

COMPARISON OF THE VELOCITY DISTRIBUTION IN CIRCULAR PENSTOCKS MEASURED WITH CURRENT METERS TO ASSESS THE EFFICIENCY OF HYDRAULIC MACHINERY IN GENERATING AND PUMPING OPERATIONS

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The current meter method is the main method to be used for measuring discharge in order to assess the efficiency of turbines, pumps and reversible turbines. In the case of reversible units or ternary-set units, in order to reduce costs and the duration of the tests, a single section is selected for discharge measuring operations when possible (which depends on the plant layout) and this is generally located in the pipes upstream from the turbine. When this method is used, a considerable difference in the regularity of the flow field may sometimes occur between the two operating conditions (i.e. generating and pumping mode), despite the fact that, in both cases, standards regulating the distance of the measuring section from disturbances upstream and downstream are strictly observed. In fact, when discharge measurements are carried out downstream of machinery, particularly disturbed flow conditions may occur, which are very different from a fully-developed flow, a necessary condition for the correct use of current meters equipped with usual, not self-compensating propellers.
This report refers to the results obtained at several hydroelectric plants, where rotational flow conditions occurred during the pumping operation leading to an underestimation of the discharge.
This condition, which is highlighted by a reduction in velocity at the centre of the penstock, with a shifting of the maximum velocity towards the wall, means that the mean axial velocity does not occur where the relative radius is r/R=0,76, which is characteristic of a fully-developed flow, but for higher values and as a result there is an underestimation in the discharge which increases as the deviation does. In the cases examined, both the difference value between the discharges calculated on the two diameters, as well as the asymmetry index prescribed in the standards, are fully observed.
This paper estimates the error as a function of the relative r/R radius where the mean axial velocity occurs and an index for a fully-developed flow is proposed, establishing a limit that should not be exceeded. The author believes that in order for a discharge measurement taken in a penstock to be considered valid, the value of the relative r/R radius where V/Vm=1 should be roughly 0.76, or the fully-developed flow index below 0.02.

1. INTRODUCTION

In acceptance tests for hydraulic machinery, the standards prescribe that whenever discharge measurements are performed using current meters, there should be a sufficiently long straight stretch of penstock upstream and downstream of the measuring section, equal to 20 and 5 diameters, respectively. This will guarantee that there is a "fully developed" distribution of the velocity, such that no changes in the profile will occur in the subsequent section of flow.

The flow is considered "fully developed" when the following conditions are fulfilled:

a) the profile reveals a rotational symmetry (concentric isovel)
b) the maximum velocity is at the centre of the penstock
c) the ratio between the mean velocity and the maximum velocity complies with the value that can be calculated using the theoretical formulae described below in paragraph 2.

It has often been observed that, while the requirements for using current meters as measuring instruments are strictly complied with and the effects of disturbances in the straight sections of the penstock before and after the measuring section should therefore not be expected, the velocity profile does not always correspond to the "developed" distribution.

In the case of a turbulent flow, the velocity distribution depends on the Reynolds number and on the roughness of the conduit.

Apart from the roughness and the Reynolds number, the flow field in a given section depends largely on the layout of the penstock before this section, i.e. on the disturbances and any distinctive features present upstream of this section (bends, valves, section changes, bifurcations, hydraulic machinery, etc.), which would produce asymmetries in relation to the axis of the penstock, as well as rotational movement.

This leads to the problem of establishing the length of the "mitigating" straight section, i.e. for a return to a fully developed flow, particularly when there are helicoidal flows such as those produced by hydraulic machines or bends in a pipe. In these cases, the straight stretches of penstock should be longer than the lengths recommended by the standards to guarantee the "mitigating" effect, i.e. so that the tangential component disappears from the velocity.

If the current meters are used correctly, then the flow should be stationary and the velocity profile developed as much as possible - that is to say, a flow that runs parallel to the axis of the penstock with rotational symmetry. Only when these conditions are guaranteed can it be said that the current meters are being used properly, particularly when usual propellers, and not self-compensating, are being used. In practice, however, the physical conditions existing in the hydroelectric plants can sometimes limit the choice of the section to be used for measuring operations and as a result the flow is not always fully developed.

2. VELOCITY DISTRIBUTION IN CIRCULAR PENSTOCK

In order to represent the velocity distribution of a fully developed flow, different expressions have been used. One of the better known ones is the simple power formula, known as the Prandtl formula:

$$\frac{V}{V_o} = \left(\frac{y}{R}\right)^{\frac{1}{n}} \qquad (1)$$

where:
- Vo represents the velocity on the axis of the penstock
- y the distance from the wall= R-r
- n a coefficient which depends on the roughness of the penstock and the Reynolds number

This expression is suitable in the vicinity of the wall, but it does not reproduce the velocity distribution close to the axis of the penstock very well.
Another expression is given by the Karman and Prandtl formula

$$\frac{V}{V^*} = \frac{Vo}{V^*} + \frac{1}{k}\ln\frac{y}{R} \qquad (2)$$

where:
- V* is the roughness velocity
- k is an index of the roughness of the pipe.

The law (2) of velocity distribution in circular penstocks has been improved thanks to studies carried out by Prof. E. Marchi [1] which have led to the following expression:

$$\frac{V}{V^*} = \frac{Vo}{V^*} + \frac{1}{k_1}\ln\frac{y}{R} + \frac{1}{k_2}\Phi\left(\frac{r}{R}\right) \qquad (3)$$

where Φ(r/R) values are indicated in the following table:

r/R	(r/R)	r/R	(r/R)	r/R	(r/R)	r/R	(r/R)
0,05	0,0311	0,40	0,0316	0,80	-0,1198	0,96	-0,1967
0,10	0,0480	0,50	0,0021	0,85	-0,1433	0,98	-0,2066
0,20	0,0595	0,60	-0,0340	0,90	-0,1673	0,99	-0,2116
0,30	0,0520	0,70	-0,0751	0,93	-0,1820	1,00	-0,2166

In his report, [2] Grego has envisaged being able to represent the curve V/Vm=f(r/R) with an analogous expression to (3), where Vm represents the mean velocity in the penstock. Starting from the experimental flowrate measuring data, which were obtained in fully-developed flow conditions [3], he developed the following expression:

$$\frac{V}{Vm} = 1{,}1523 + 0{,}09211\ln\frac{y}{R} + 0{,}1858\Phi\left(\frac{r}{R}\right) \qquad (4)$$

from which it can be deduced that the adimensional velocity is equal to 1,1523 on the axis of the penstock, and 1 for r/R=0,764, which is in complete agreement with E. Marchi's findings.

3. EFFECTS OF DISTURBANCES THAT PRODUCE A HELICOIDAL FLOW

In helicoidal flows, which are characterised by the appearance of tangential velocity components, it is possible to distinguish two zones in the penstock. In the external part, the following formula is valid:

$$V_t\, r = cost \qquad (5)$$

whereas in the part around the axis, the following relation is valid

$$V_t / r = cost \qquad (6)$$

Between the two zones, there is a separation and as far as the axial velocity is concerned, the maximum shifts towards the wall of the penstock, thus differing from the distribution that is observed with a fully-developed parallel flow.
The tangential components appear downstream of the runner of the reaction turbines (Francis and Kaplan) and the centrifugal pumps. Even bends or a combination of bends may produce helicoidal flows which require long straight mitigating stretches of pipe.
A disturbance-mitigating lenght is the distance, in a straight stretch of a penstock, measured from the disturbance to the end of it, by which section which the velocity profile should not differ from the final one by more than 1%. With an increase in the roughness of the penstock, the length of the mitigating stretch tends to decrease and the mitigating process leading to the formation of the developed profile is achieved more rapidly.
Nikuradse gives 40 diameters as the necessary straight stretch for an efficient mitigating effect in both smooth conduits and rough ones. In general, however, longer mitigating lengths than those envisaged by Nikuradse are required.
Rough assessments regarding the influence of bends on the mitigating section indicate penstock lengths of between 50 and 70 diameters. Gregorig [4] maintains that 50 diameters are not sufficient to re-establish a fully-developed flow after a bend.
The distance required for the rotating effect to completely disappear should be estimated as equal to at least 100Ø of straight stretch.

4. ACCEPTABILITY REQUIREMENTS FOR DISCHARGE MEASUREMENTS

The standards regarding acceptance tests on hydraulic machinery prescribe that, in order to get good results in discharge measurements in penstock, it is necessary to fulfill the following conditions:

a) choose a measuring section in a straight stretch with 20 diameters upstream and 5 diameters downstream of a general disturbance
b) difference ε_D between the discharges computed for each diameter do not differ by more than ±2% of their mean
c) asymmetry index Y of the flow field (defined in ISO3354 paragr.3.1.9) of less than 0.05.

It is a fact that compliance with these requirements does not guarantee the quality, and therefore the acceptability, of the discharge measurements. In fact, profiles with rotational symmetry, typical in the presence of a helicoidal flow and a long way from the definitive fully-developed flow ones, are in strict compliance with all three conditions stated above.
Satisfactory criteria for discharge measurements in circular penstocks have already been indicated in an earlier report [2] as the mean velocity in the section corrisponding to the value 0.76 of the relative radius.

It has been verified that this condition occurs when the straight stretch upstream of the measuring section is much longer than the 20 diameters required by the standards, which is in agreement with observations by other authors in the literature.
It is necessary to use straight stretches that are much longer than 20 diameters when measurements are performed using current meters in the sections that lie after hydraulic machinery, as this could produce rotational components.
It is clear that the issue of looking for a secure method for judging whether a measurement is valid or not is still ongoing and not entirely solved. The evidence that is presented below confirms what has already been affirmed in a previous report [2], i.e. that if the mean velocity falls to around the relative radius 0.76 and the other conditions are observed, this confirms the acceptability of the discharge measurement. On the other hand, if there is a helicoidal flow, the current meters will underestimate the discharge and the further it is from the reference value of 0.76, the greater the error.
Available data has made it possible to estimate the degree of uncertainty in the measurement whenever the above requirement is not met, and in such a situation it is necessary to anticipate the possibility of establishing an agreement between supplier and customer regarding a higher tolerance on discharge measurements and therefore on machine efficiency.

5. AVAILABLE DATA AND RESULTS

The presence of helicoidal flows is particularly evident when discharge measurements are taken in pipes downstream of hydraulic machinery. This condition occurs when a single measuring section is chosen for tests on reversible units or on ternary-set groups. The most common solution is to perform measuring operations in the diversion systems and this entails choosing the section upstream of the turbine and downstream of the pump.
In this case, flow conditions are generally regular for the turbine with a fully-developed flow, while the flow could have a rotational component during pumping operations, though this decreases after a certain number of diameters that is much higher than the one prescribed in the standards. It should be pointed out that modern penstocks are welded and are undoubtedly smooth from the viewpoint of hydraulic behaviour. This condition magnifies the phenomenon of rotational flow and in order for it to disappear, it would be necessary to have a straight section of over 100 diameters; this is confirmed by some of the cases described in this paper.
It would therefore be wiser to avoid performing measuring operations using current meters downstream of hydraulic machinery since the latter could produce tangential components.
Five plants were studied and discharge measurements were taken during generating and pumping operations, using current meters equipped with usual propellers, and not self-compensating, mounted on fixed cross-bars which generally have four arms. For a plant with a tunnel diameter of almost 6m, eight arms were used with 57 current meters mounted on them. A comparison between generating and pumping operations was made using the same discharges whenever possible, taking into consideration the following parameters:

a) type of operation of the machine
b) penstock diameter
c) mean velocity in the section
d) Reynolds number
e) number of diameters of straight section upstream and downstream of the measuring section

f) number of current meters
g) comparison between the diametrical discharges ε_D
h) asymmetry index Y
i) relative radius r/R for V/Vm=1
j) ratio between the velocity on the axis of the penstock and the mean velocity Vo/Vm
k) difference between the measured performance and the one guaranteed for the hydraulic machine
l) tolerance on the measured performance
m) fully-developed flow index, which represents the deviation of the measured velocity distribution from the theoretical law, defined by the formula (4)

The latter index, which is actually the author's proposal for inclusion in the standards as an acceptability index for discharge measurements in circular penstocks, will be defined below.

The characteristic parameters of the discharge measurements for the five plants under investigation are shown in Table 1.

It should be pointed out that, with the exception of plant D in the pumping operation, all the other cases have a number of diameters in the straight stretch upstream and downstream of the measuring section that are well above the number required in the standards. In all the tests, the acceptability indexes for discharge measurements in both generating and pumping operations, i.e. the comparison between diametrical discharges ε_D and the asymmetry index Y, are lower than the values stated in the standards, namely 2% and 0.05, respectively.

The results are very different, however, if the relative radius r/R is taken into consideration, which is where the mean velocity occurs, as well as the ratio between the velocity on the axis of the penstock and the mean velocity. In the case of plant A, perfectly identical flow conditions occur in generating and pumping operations, with measured performance values in perfect agreement with the guaranteed one.

Whenever there is a helicoidal flow and therefore velocities that are inclined in relation to the axis of the penstock, the usual propellers underestimate the axial component of the velocity with a consequent overestimation of the machine's performance in the turbine operation and an underestimation in the pumping operation. This result is clearly shown in the table, since it can be seen that when there is a helicoidal flow, the difference between the measured performance and the guaranteed one exceeds the tolerance that is envisaged for the measured performance. The presence of a helicoidal flow is clearly indicated by the high value of the ratio r/R where V=Vm as opposed to the value 0.76, the index of a fully-developed flow.

Figures 1 and 2 give the velocity distribution curves expressed adimensionally for all the examined cases as a function of the relative radius. A decrease in velocity at the centre during the pumping operation is due to the rotational components which give the axial velocity distribution the characteristic appearance of a helicoidal flow.

Examining the different plants, the following considerations can be made regarding some anomalous results in the pumping operation.

In plant B, the test performed during the pumping operation was repeated, but this time after moving the measuring section closer to the tunnel intake, thus obtaining results that are perfectly comparable with the ones obtained during the generating operation. The test revealled a 10% error in discharge compared to the previous situation.

In the case of plant C, performance measurements were carried out on the four multistage centrifugal pumps to obtain the same distributions of the velocity profile as the four Pelton units, with the exception of unit 1, which is the closest to the measuring section. This result is illustrated in the diagram of Figure 1 where the velocity distribution profiles of units 1 and 2 have been compared during the pumping operation.

A comparison of the performances of the pumps of the four units has shown the same value for units 2,3 and 4 and a reduction of 2.5 percentage for the pump of unit 1 compared to the other pumps; this must have been due to the underestimation of the discharge as a result of the presence of a helicoidal flow.
For plant D, the configuration of the penstock restricted the available length of straight pipe to only 11 diameters in the pumping operation. However, both a comparison between the diametrical discharges and the asymmetry index satisfy the requirements prescribed in the standards, while the value of the relative radius for V/Vm=1 clearly denotes the presence of a rotational flow, with a degree of uncertainty in the flowrate measurements in the order of 4%. This value was estimated on the basis of a direct comparison between measurements taken in the channel and measurements taken in the conduit in a section (chosen downstream of a pump) which had a straight stretch with a number of diameters that was lower than the number prescribed in the standards (8 diameters instead of 20). These results, presented by the author in his paper [3], are indicative of a 15° inclination in the flow, as indicated by the tests conducted in the calibrating tank by G. Benini[5].
The tests performed on plant E confirm the results given by plant D regarding pumping operations in terms of uncertainty. In this case, however, even the tests in the generating operation, for both the Pelton turbine and the reversible unit, indicate an underestimation of the velocity in the central zone.

6. INDEX OF A FULLY-DEVELOPED FLOW

The velocity distribution curve in circular penstocks may be represented very efficiently by expressing the adimensional velocity as a function of the logarithm of the relative distance from the wall. The same experimental curves of Figures 1 and 2 are shown in Figures 3 and 4 together, with the theoretical distribution curves derived from the equation (4). The diagrams indicate that in the presence of a helicoidal flow, the measured velocity exceeds the theoretical one for r/R greater than 0.7, while it is inferior for r/R smaller than 0.7. The difference between the two curves increases as the helicoidal flow becomes more accentuated, i.e. the greater the value of r/R for V/Vm=1.
For the tests under examination, the measured V/Vm values and the corresponding r/R values were considered and the squares of the differences between the measured adimensional velocities were calculated, including the one in the centre and the ones on the circles concentric with the pipe axis, as well as the theoretical velocities. For the fully developed flow index, the square root of the sum of these differences was assumed and it was divided by n where n represents the number of concentric circles.
The following expression was adopted:

$$I_{fdf} = \sqrt{\frac{1}{n}\sum_{i=0}^{n}\left[\left(\frac{V_i}{Vm}\right)_{mis} - \left(\frac{V_i}{Vm}\right)_{teor}\right]^2} \qquad (7)$$

The values calculated in all the examined tests indicate I_{fdf} values of between 0.002 and 0.2 for a fully-developed flow, as in the case of tests performed during generating operations; in the presence of a helicoidal flow, however, the values rise to 0.04 and even up to 0.1. We propose, as acceptability index of discharge measurements in penstock, a value of r/R for V=Vm of between 0.75 and 0.77 and a fully developed flow index, according to expression (7), of less than 0.02. For r/R values of above 0.77, it is necessary to increase the degree of uncertainty in the discharge measurement, as shown in the diagram in Figure 5.

It is therefore believed that while the asymmetry (shift of the maximum velocity from the centre) remains secondary to the effects of uncertainty on the discharge measurements, the presence of a helicoidal flow, when usual propellers are used, leads to an underestimation in the discharge measurement and this can be seen in the examples reported.

7. CONCLUSIONS

The cases examined for comparison between the discharge measurements performed on a single section in order to measure the efficiency of hydraulic machinery during generating and pumping operations show that:

a) the asymmetry of the velocity distribution is subordinate to the presence of tangential components
b) Reynolds is not important
c) the mitigating section required gets much longer when there are rotational components
d) in the presence of a helicoidal flow, the length prescribed in the standards for a straight section between the disturbance and the discharge measuring section for the use of current meters is insufficient
e) on the mitigating stretch, the following parameters are involved:
- the Reynolds number
- the roughness of the pipe
- the diameter of the pipe
- the effect of the disturbance on velocity distribution

f) tests carried out in the power plant by T. Harald [6], confirmed by the results presented herein, indicate that a pronounced helicoidal flow does not undergo an important mitigating effect after only 40 Ø, but rather it is necessary to reach at least 100 Ø.

In a previous report [2], the author verified the fact that if the adimensional velocity profile from a flowrate measurement taken in a penstock assumes the unitary value of r/R=0,76, the discharge measurement can be considered a good one.

Nevertheless, in order to obtain this type of result, it is necessary to have lengths of straight pipe that are longer than the ones required in the standards. Should the experimental data differ from the law (4), it is necessary to formulate estimation criteria for the error commited. The relation presented here represents an attempt that was already established as an objective to reach this result, but described in a previous paper [2] and supported by experimental data.

We can therefore ascertain that, when the value of $(r/R)_{V/Vm}=1$ exceeds 0.76, the discharge is underestimated and the further away it is from this value, the greater the underestimation.

A fully-developed flow index has also been indicated and its limit, set at 0.02, should not be exceeded in order for the discharge measurements to be considered acceptable. This index, along with the value of the relative radius where the mean velocity occurs (and which should be between 0.75 and 0.77) represents, in the author's opinion, a necessary and sufficient condition for discharge measurement acceptability.

Finally, an estimation of the error was carried out, and it was always negative, occurring when there is a helicoidal flow. In this case the velocity, measured using current meters equipped with usual, not self-compensating, propellers, is underestimated.

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Table 1- Discharge measurement comparison in generating and pumping operation

Power plant	Operation	Machine	Test n°	pipe diameter	Velocity	Reynolds	diameters number		Current-meters n°	Discharge comparison ε_D	Asymmetry index Y	$(r/R)_{V=Vm}$	Vo/Vm	1) $\Delta\eta$	Tollerance	I_{fdf}
				(m)	(m/s)		upstream	down_stream		(%)				u.per %	u.per %	
A	generating	Francis	1	2,150	2,486	5,3*10^6	132	132	13	0,15	0,003	0,749	1,166	-0,7	2	0,00959
A	pumping	pump	2	2,150	2,517	5,4*10^6	132	132	13	0,35	0,007	0,756	1,149	-0,9	3	0,00249
B	generating	Francis	3	5,810	2,291	1,3*10^7	181	22	57	0,22*	0,009	0,759	1,166	0,3	1,5	0,00644
B	pumping	pump	4	5,810	2,344	1,4*10^7	22	181	57	0,07*	0,044	**0,914**	0,970	**-11,5**	1,5	**0,10592**
B	pumping	pump	5	5,810	2,405	1,4*10^7	214	16	57	0,16*	0,006	0,759	1,163	-1,3	1,5	0,00836
C	generating	Pelton	6	4,000	0,842	3,4*10^6	125	125	25	0,45	0,010	0,757	1,140	-1,5	1,5	0,00644
C	pumping unit 1	pump	7	4,000	0,838	3,4*10^6	125	125	25	0,17	0,006	**0,812**	1,081	2) -2,5	1,5	**0,04103**
C	pumping unit 2	pump	8	4,000	0,864	3,4*10^6	125	125	25	0,18	0,006	0,757	1,141	not determined	1,5	0,00525
D	generating	Francis	9	4,480	1,193	5,3*10^6	149	11	25	0,59	0,019	0,754	1,129	2,0	1,5	0,01059
D	pumping	pump	10	4,480	1,050	4,7*10^6	11	149	25	0,19	0,017	**0,846**	1,025	-2,7	1,5	**0,06353**
E	generating	Pelton	11	3,600	3,472	1,2*10^7	71	88	25	0,45	0,041	0,774	1,093	0,5	1,5	0,02441
E	generating	reversible	12	3,600	0,930	3,3*10^6	71	88	25	0,13	0,032	0,780	1,110	2,1	1,5	0,02399
E	pumping	reversible	13	3,600	0,767	2,8*10^6	88	71	25	0,29	0,006	**0,850**	1,071	-2,0	1,5	**0,05643**

* discharge comparison between S. Andrews and greek cross

1) difference between measured and guaranteed efficiency

2) efficiency difference between unit 1 and the other three units

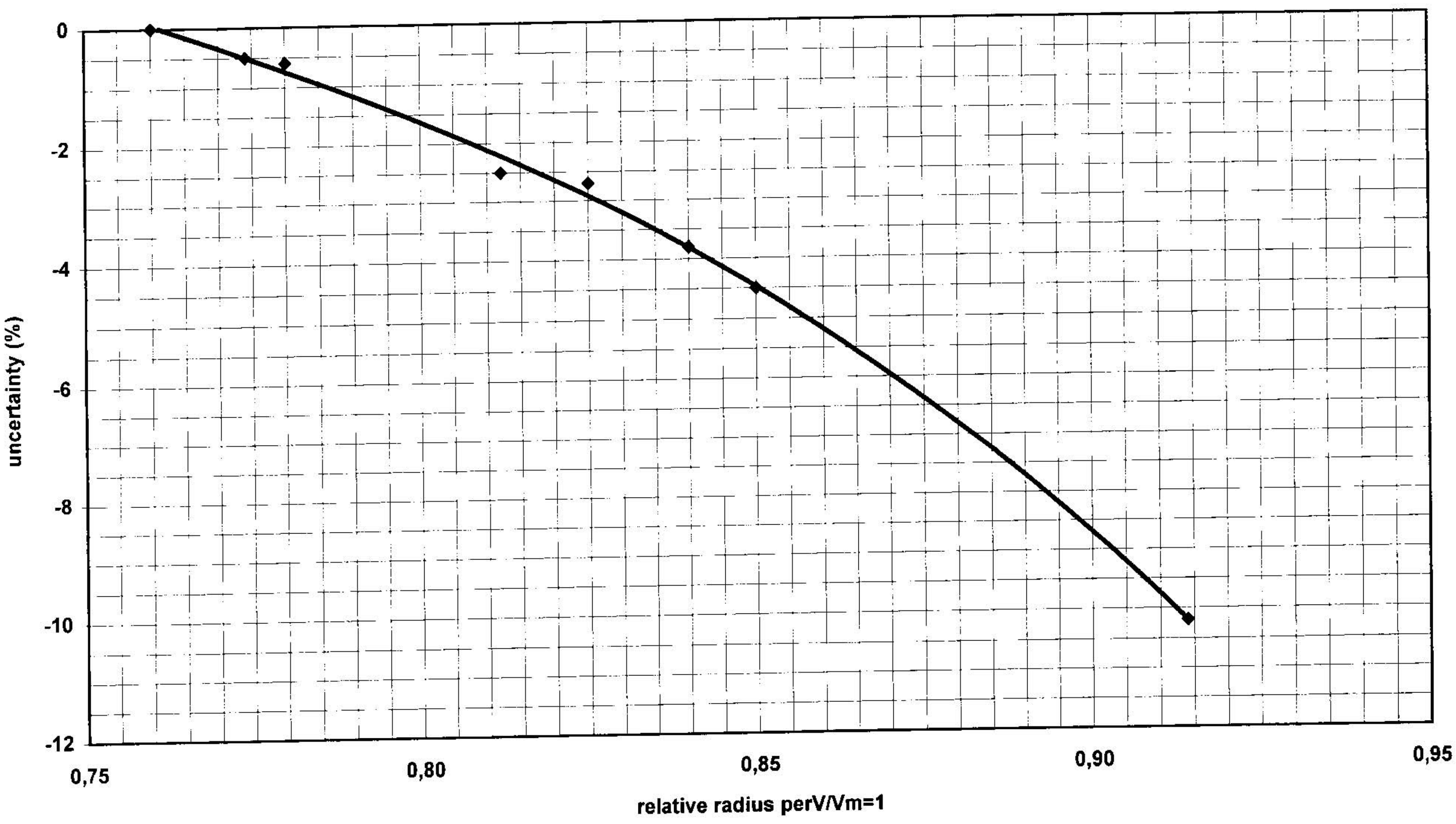


Fig.5 - Discharge measurement uncertainty, in presence of a helicoidal flow, by versus relative radius (r/R) per V/Vm=1

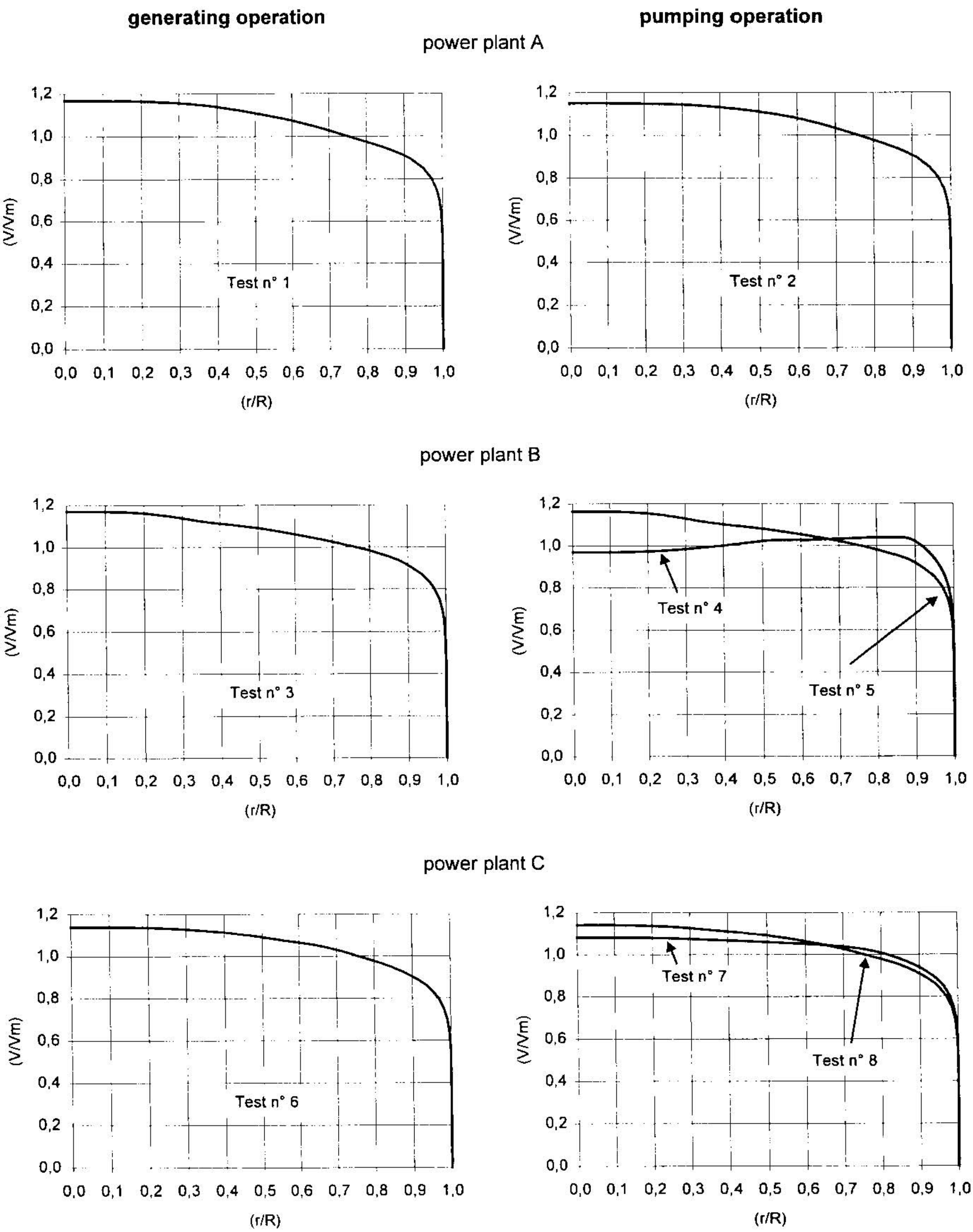


Fig. 1 - Adimensional velocity distribution (V/Vm) versus relative radius (r/R) - Power plants A, B and C.

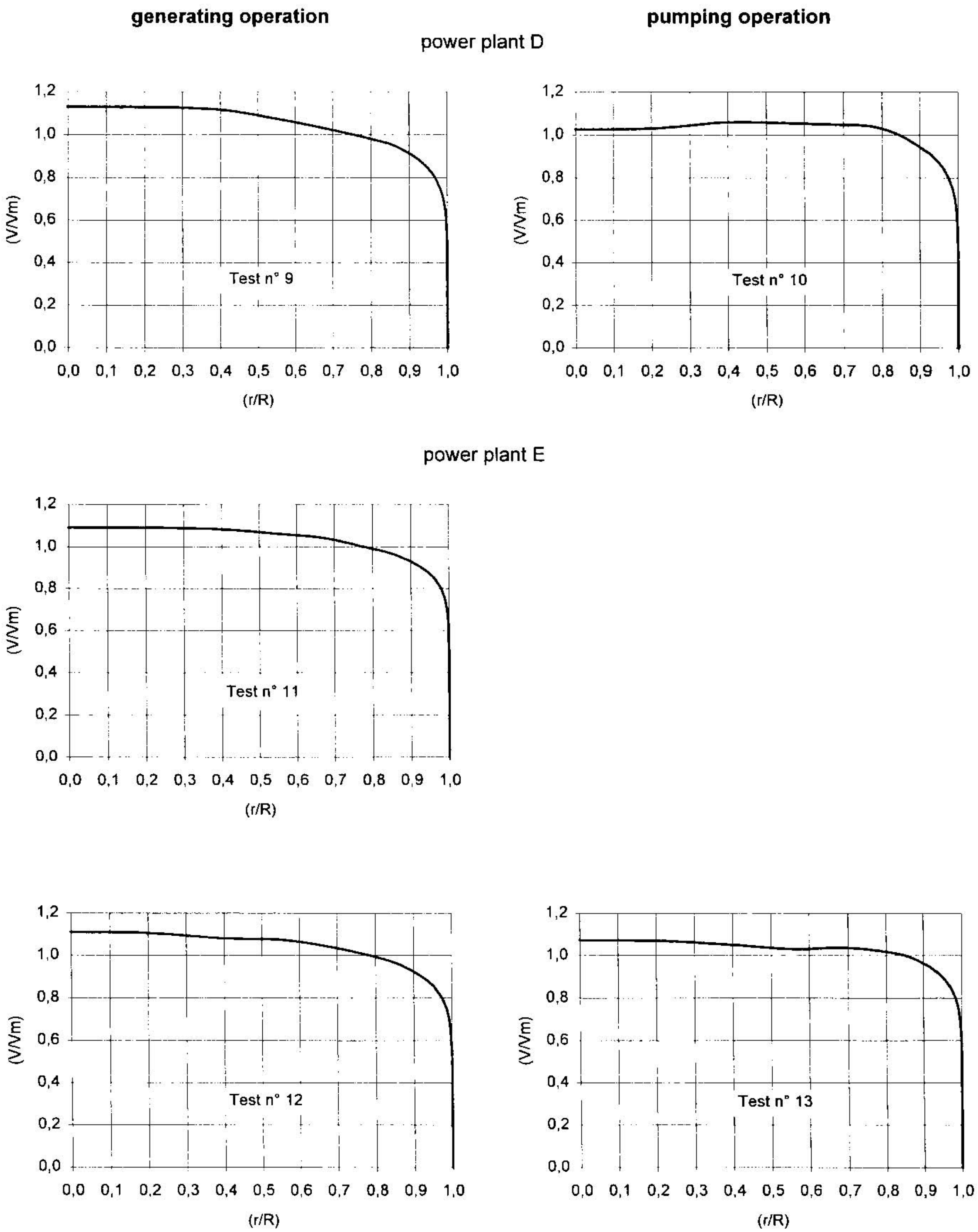


Fig. 2 - Adimensional velocity distribution (V/Vm) versus relative radius (r/R) - Power plants D and E.

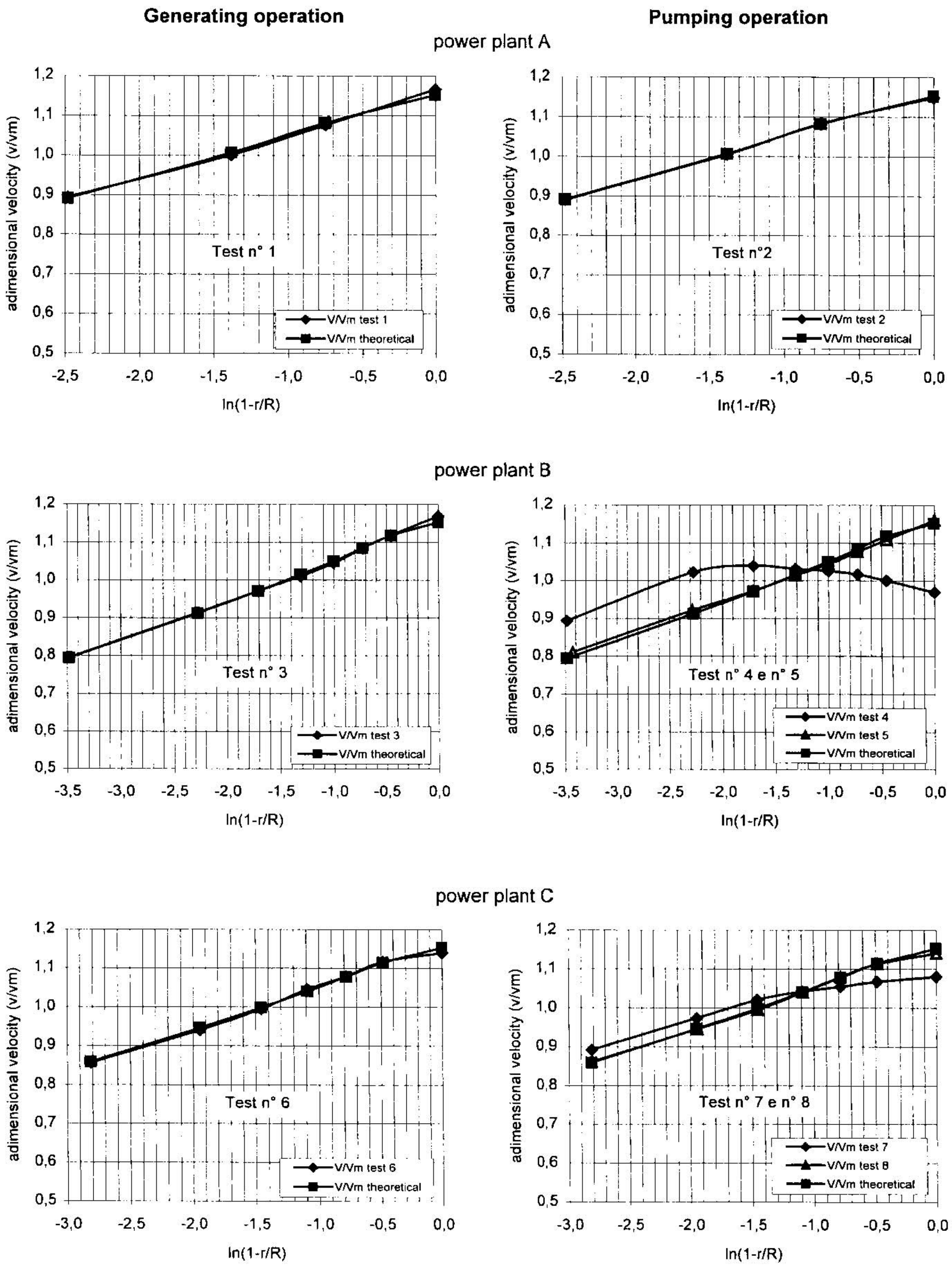
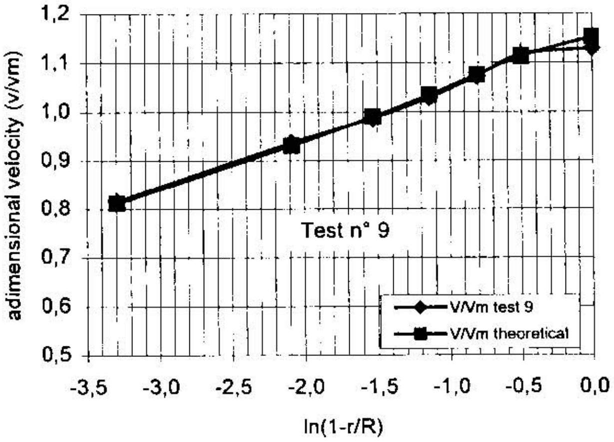
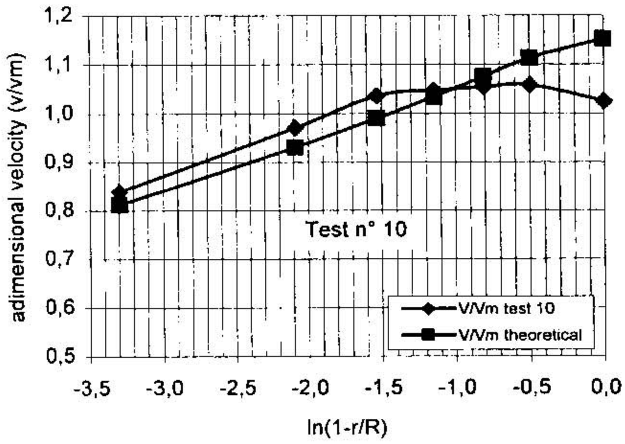


Fig. 3 - Measured and theoretical adimensional velocity distribution versus logarithm of relative distance from the wall - Power plant A, B and C.

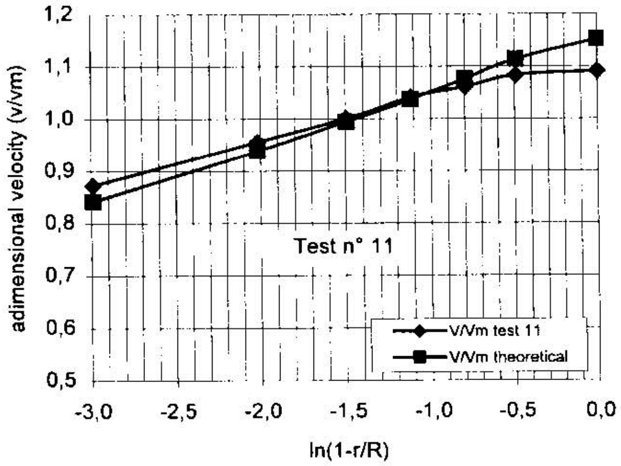
Generating operation **Pumping operation**

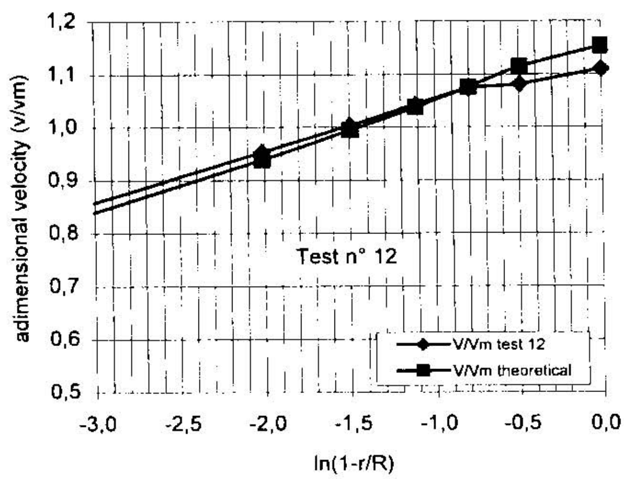
power plant D





power plant E





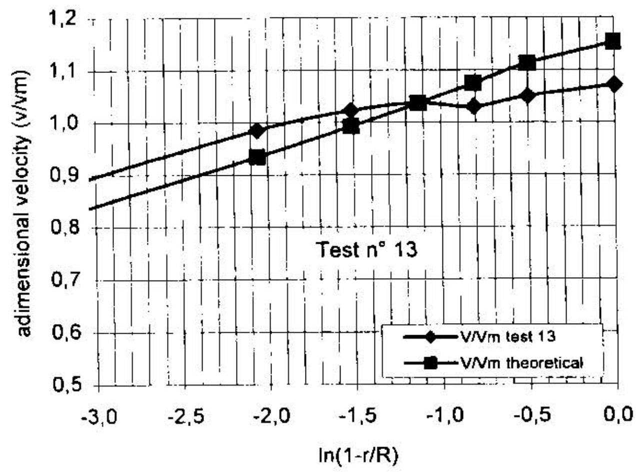


Fig. 4 - Measured and theoretical adimensional velocity distribution versus logarithm of relative distance from the wall - Power plants D and E