CURRENT METERS MEASUREMENT IN AN ASYMMETRIC FLOW CONDITIONS IN CLOSED CONDUIT TO VERIFY TURBINE EFFICIENCY AFTER ITS REFURBISHMENT

Zdenek Cepa
Head of Department of Hydraulic Machinery Tests and Diagnostics
CKD Blansko Engineering, Czech Republic
zdenek.cepa@cbeng.cz

ABSTRACT

This paper concerns Unit No. 2 at HPP Doblar in Slovenia after refurbishment. The improvement in performance of the new turbines could be measured with acceptable accuracy. Documentation of the previous acceptance tests has not been found. Thus, the velocity profile as a function of discharge was not known from the old reports. Should this be difficult due to the length of the common part and surge tank connected, discharge measurement can be conducted, provided care is taken of the net volume of water exchanged between the duct and the surge tank within duration of measurement and practically no leakage through the other turbines. Finally it was decided to install current meters in the Unit No. 2 short penstock, downstream of a surge tank and elbow. The presence of the elbow causes the flow to change direction due to inertial forces that produce asymmetrical flow. The core of the maximal velocities is shifted to the peripheral wall of bend. Therefore, it was proposed to perform complete current meter measurement, taking into account asymmetric flow conditions together with Winter-Kennedy measurement, despite of the fact we considered to be too expensive. The primary goal of acceptance tests was to establish an approximate absolute efficiency level and second one to calculate average weighted turbine efficiency to check if guarantee values have been met. Additionally, the influence of air admission through the shaft on output power, absolute turbine efficiency and draft pressure pulsations was investigated.

INTRODUCTION

HPP Doblar 1 is an accumulation-derivation an underground Hydro-Power Plant on the Soca river in Slovenia. Three new vertical Francis turbines of 13.76 MW, each at maximum net head of 46.91m head and discharge of 33 $m^3.s^{-1}$ replaced the old ones, which had been in operation since the year 1939. Equipment complete replacement was urgently necessary for reliable and safe operation. It was decided to replace the runners, spiral cases and generator in all three units, replacing one runner each year starting in 2010/2011. Unit #3 was to have the first replacement runner.

The elevated storage reservoir is connected with underground surge tank and spillway by the common tunnel of diameter 5.6 m and length 3567 m, downstream the common surge shaft of diameter 8.0 m was built. Each turbine is supplied from the common surge shaft by individual penstock of diameter 3.0 m with elbow 130^0 inclination followed by short straight cylindrical segment and conical contraction just upstream of the spiral casing inlet. Turbine rotation is clockwise from coupling view. Discharge leaving turbine enters a tail water surge tank and horse shoe profile 5x3.76 m discharge tunnel of length 90.0 m to the riverbed. It was decided that replacement of the turbines of all three units to improve efficiency and the maximum power output including generator together would make rehabilitation profitable.

1. DESCRIPTION OF THE TESTS

The measurements should be performed on the Unit #2, which has the favourable flow conditions comparing to the other ones, at three net heads: 46.91, 41.9 and 37.69 meters. The last net one, a minimum net head, could not be achieved even if Unit # 3 was in full discharge operation (Unit # 1 was under refurbishment at that time). There was a large discrepancy between measured net head and the guaranteed one, so an adjustment was made using model curve [2], [6]. The tail water level was affected by the number of units in operation at the station and actual flow rate in the river. During the measurement, the adjacent units were not in operation for the heads 46.91 and 41.9 meters.

2. CURRENT METERS INSTALLATION

The diameter of the current meters section was 3039 mm (see Figure 1) and time period of measurement was 300 seconds during that the other relevant quantities were acquired.
When there is a reason to believe that flow may be asymmetric, the uncertainty of flow measurement is reduced more by increasing the number of radii along which measurements are made then by increasing the number of points per radius. In our case 31 current meters are available for installation in a conduit using five on each of six radii, see Figure 2 and Table 1.

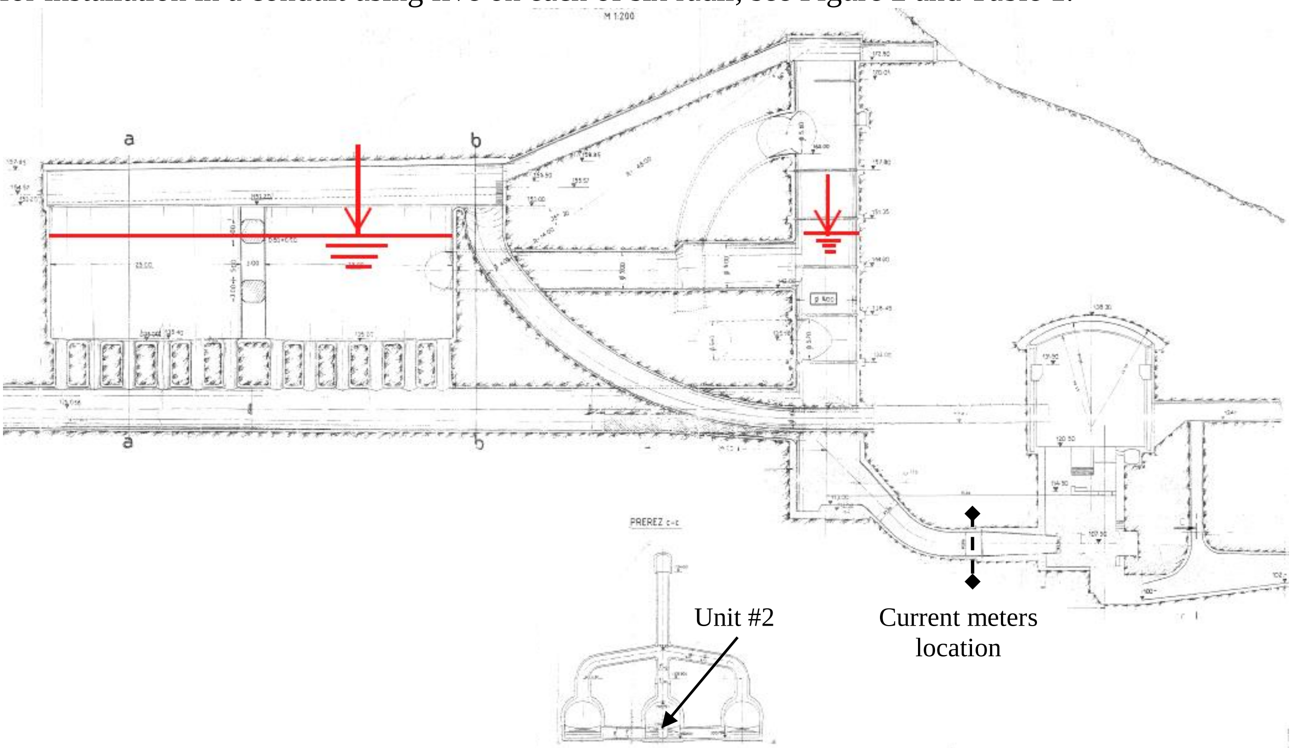

Figure 1: Location of the current meters 6th arms supporting cross in the flow passage system

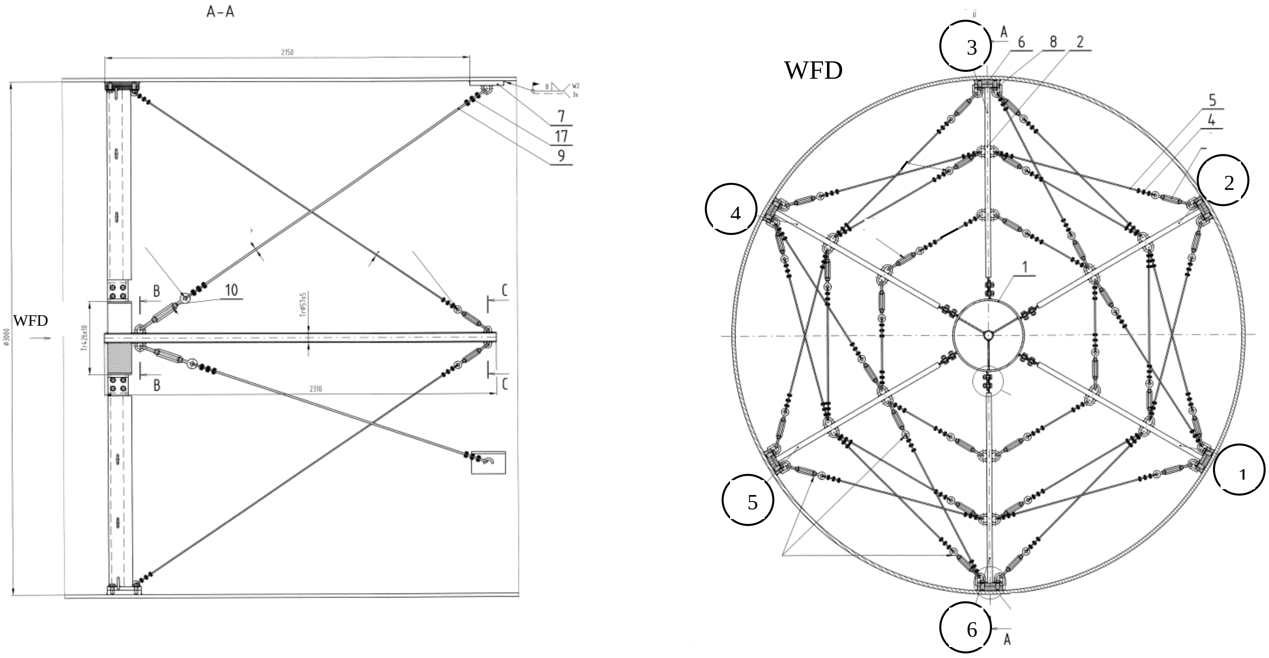

Figure 2: Supporting cross design

No. of radii	R_1 [m]	R_2 [m]	R_3 [m]	R_4 [m]	R_5 [m]	R [m]
1	0.623	0.884	1.075	1.249	1.393	1.500
2	0.622	0.889	1.089	1.255	1.397	1.510
3	0.641	0.900	1.100	1.266	1.415	1.523
4	0.654	0.906	1.105	1.276	1.419	1.540
5	0.625	0.885	1.087	1.254	1.400	1.518
6	0.635	0.894	1.103	1.260	1.408	1.526
Σ/6	**0.633**	**0.893**	**1.093**	**1.252**	**1.405**	**1.520**

Table 1: Measuring points distribution

2.1 Blockage effect correction

Presence of current meters and their support in a conduit, results in a reduction in the cross-section area and hence in a variation in the velocity distribution. The calculation of the flow rate in a conduit based on calibration data obtained in a channel, with a sufficient distance from the wall and free water level, generally leads to an overestimation of the local velocities. If the ratio *s* between frontal area of the supporting cross and the area of the measuring section is less than 6 % [4], then correction factor *k* shall be applied and measured flow rate shall be reduced. For our arrangement the $s=0.045$ and $k=0.0072$. Reduction of the measured flow rate *Q* is calculated according to (1)

$$Q_{corr} = (1-k)\cdot Q = 0.9928 \cdot Q \qquad (1)$$

2.2 Determination of the mean axial velocity by numerical integration

The mean axial fluid velocity *U* is based on numerical integration of velocity field function over the cross section of the flow area (2)

$$U = \frac{1}{\pi \cdot R^2}\int_0^{2\pi}\int_0^{R} v(r,\alpha)\, r\, dr\, d\alpha \qquad (2)$$

Taking into account that function of velocity field *v(r,α) is unknown* (only local averaged velocities at the measured points are known) it's necessary to approximate it another suitable way.
Usually at the defined points are measured local velocities and approximated by the smooth mathematical functions. Calculations are realized by *cubic spline function*.

This function is then integrated over flow area keeping the exponential velocity drop at peripheral zone and equal to (3) [4].

$$\left(\frac{m}{m+1}\right) u_p \left(1 - \frac{r_p^2}{R^2}\right) \quad (3)$$

Where, *m* is a boundary layer coefficient, depending on the wall roughness and Reynolds number in accordance with the method given in Annex E [4]. Generally, *m* is between 4 (rough wall at low Reynolds numbers) and 14 (smooth wall at high Reynolds numbers). In our calculations is *m=7.*

In order to illustrate the velocity field distribution in the penstock graphically (drawing of *IZOTACH)*, the calculations in polar coordinates with step of 3 degrees and 1/60 radius was used.

3. RESULTS OF THE FLOW RATE CALCULATIONS

The method of numerical integration is applicable when current meters are not located exactly on circumferences, owing to mounting errors and practical unfeasibility. Integration is carried out radius after radius by considering the actual position of each current meter (see Table 1) and then arithmetically averaging the elementary flow rates per radius.

The calibration curves of current meters are expressed with adequate accuracy by the straight lines whose equations are easily to calculate. The results of the current meters calibration is expressed in the form of two equations of the straight lines as the best fit for the calibration curves.

The program checks the number of revolutions per second *n* and applies adequate equation subsequently.

If some problem with current meter during measurement, due to mechanical reason, the number of revolutions are replaced by zero and program automatically apply smooth curve to interconnect adjacent points.

The procedure of flow rate calculation is depicted for optimum of the turbine efficiency.

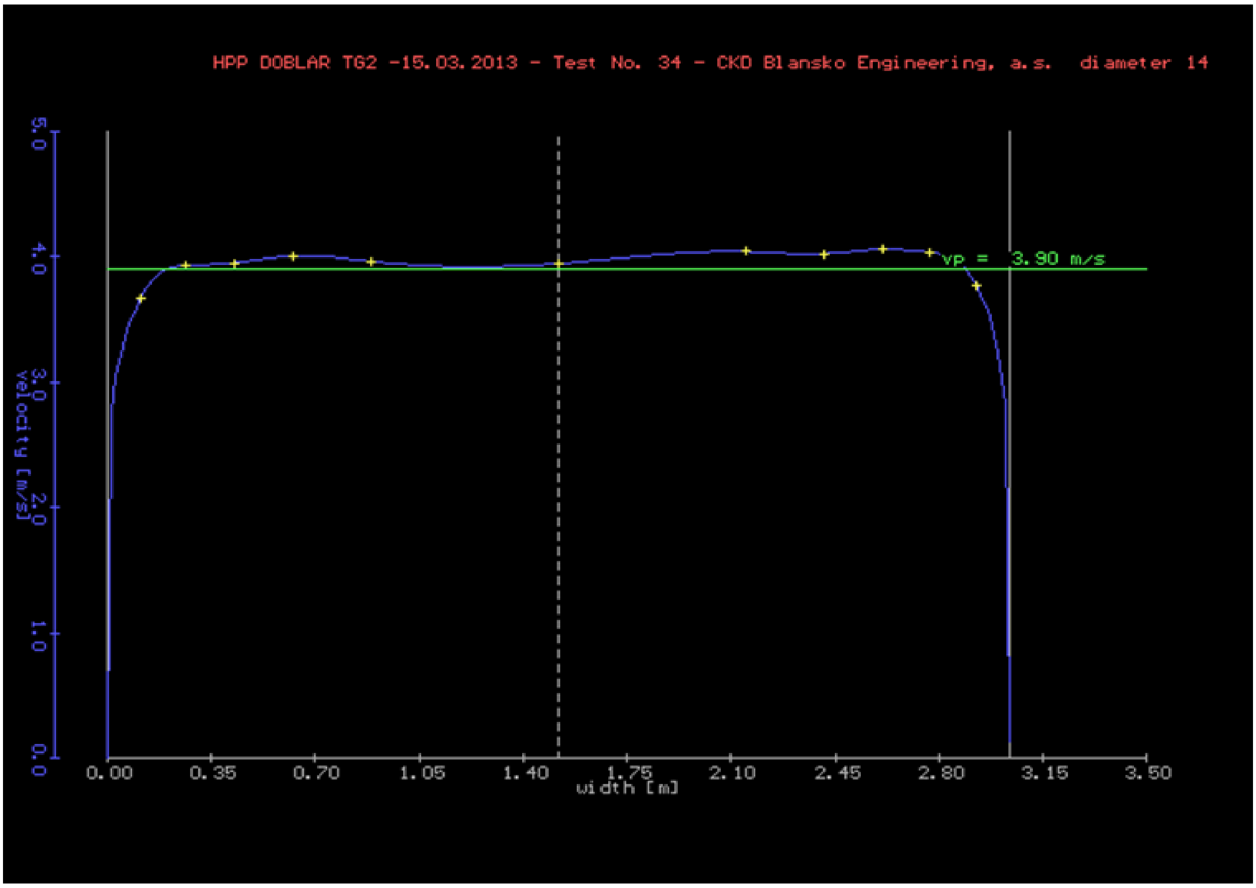

Figure 3: Velocity distribution along radii 1 & 4

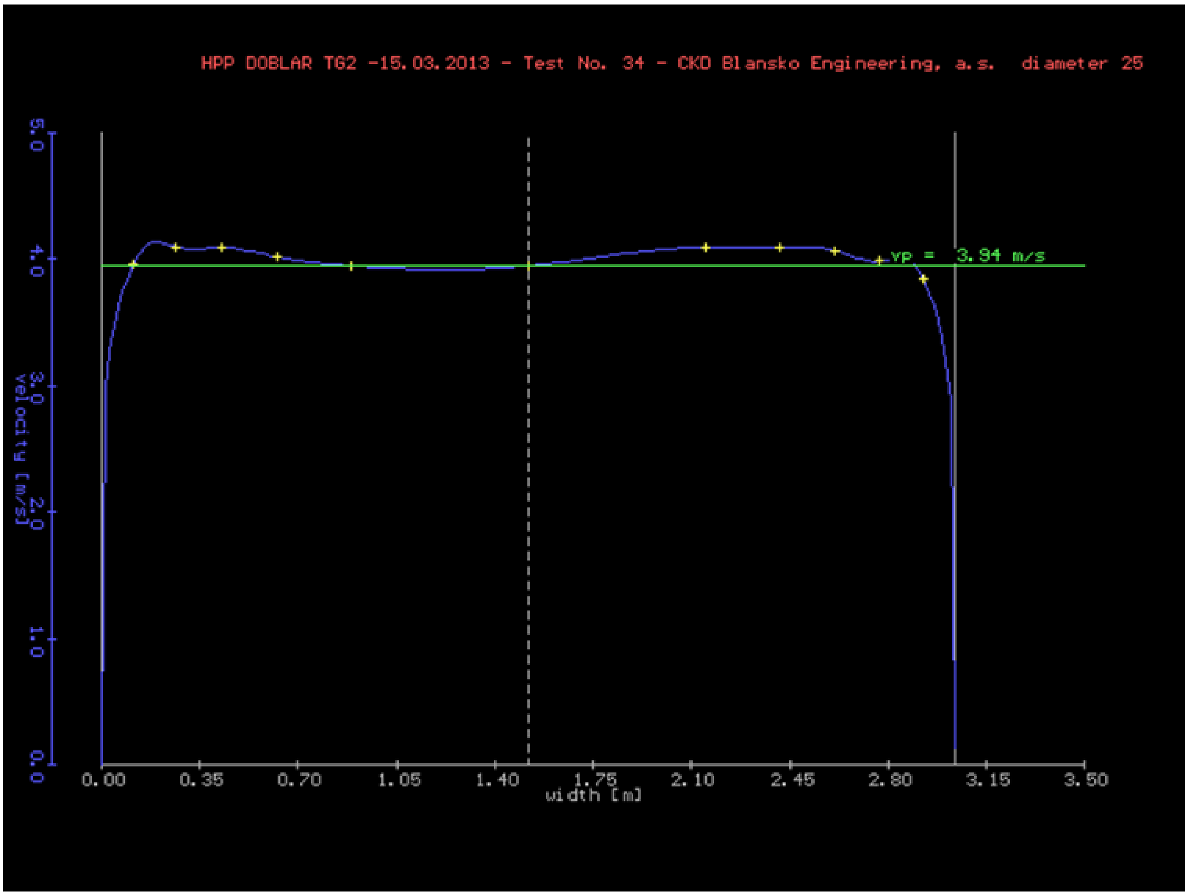

Figure 4: Velocity distribution along radii 2 &5

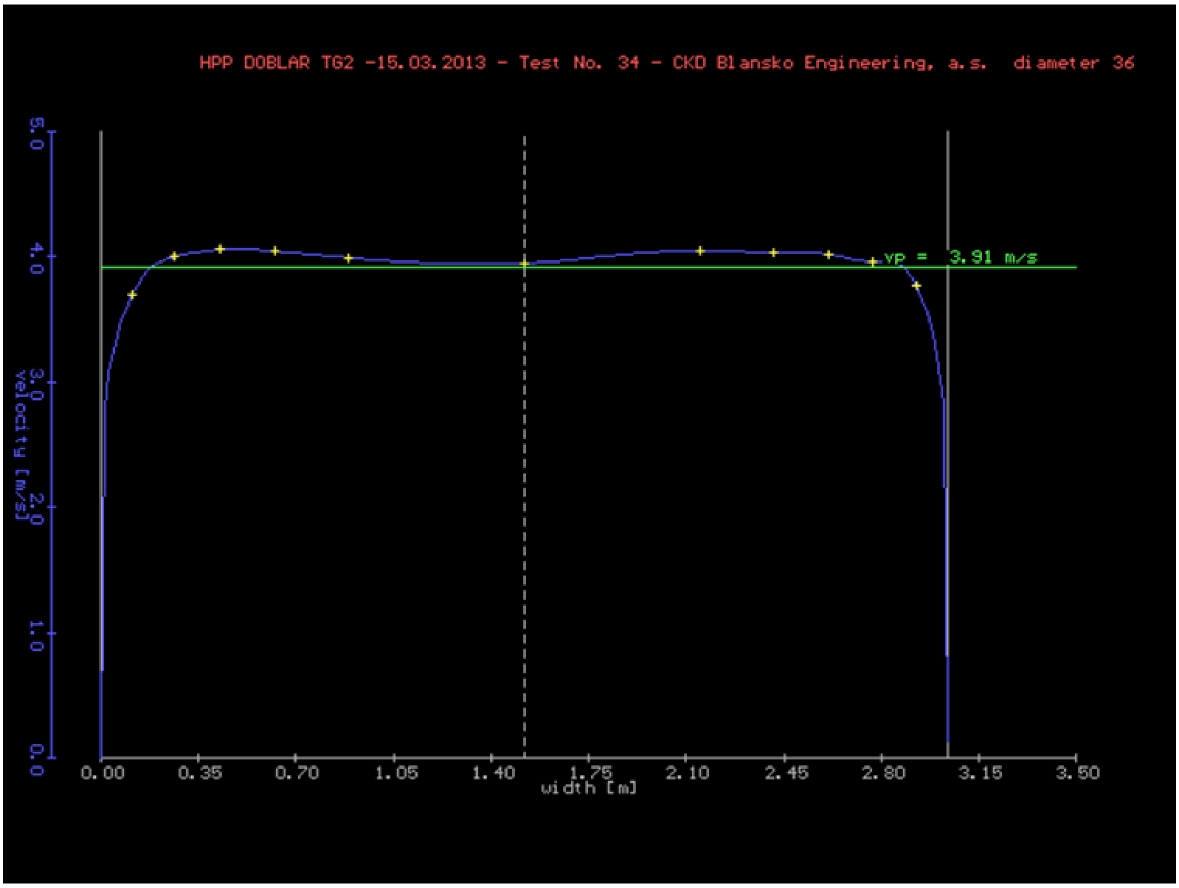

Figure 5: Velocity distribution along radii 3 & 6

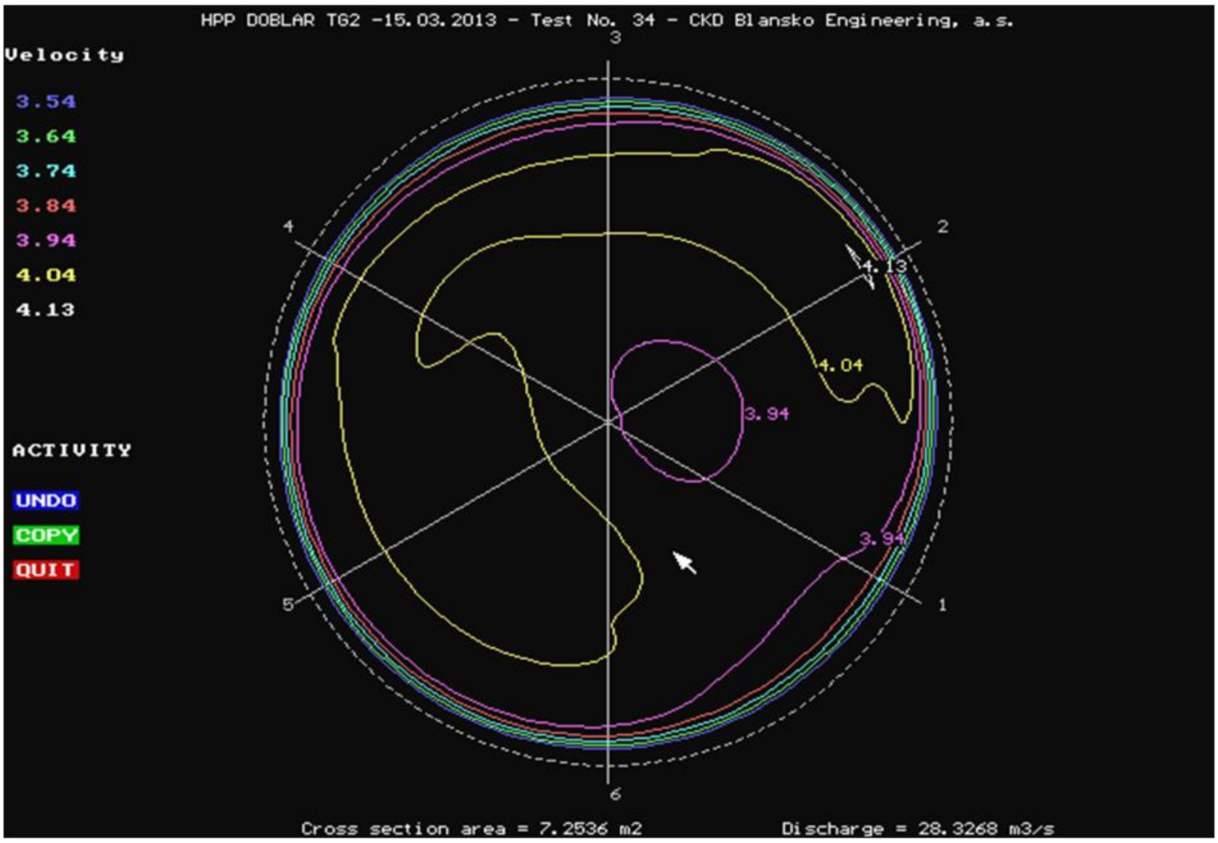

Figure 6: **Discharge calculation by the method of numerical integration**

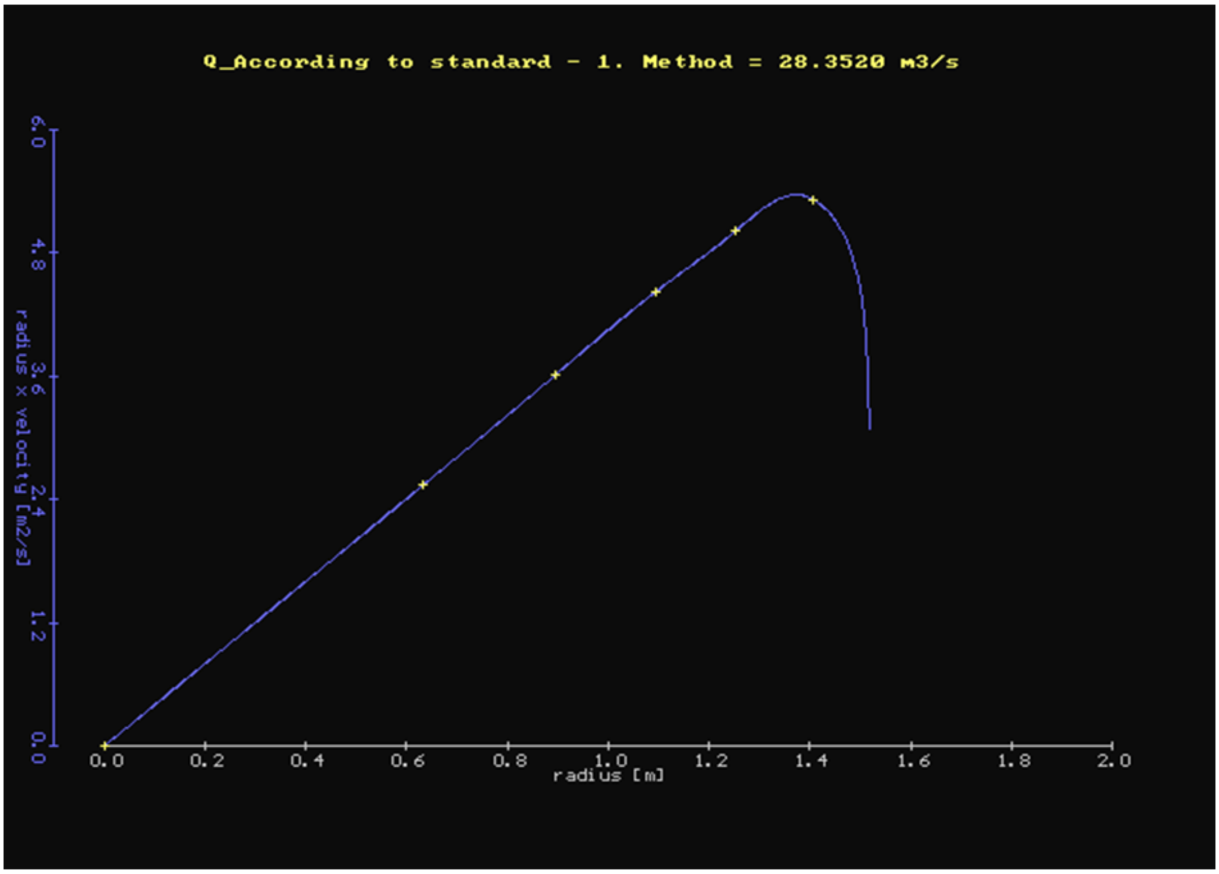

Figure 7: **Flow rate calculation by the 1. method *r.v=f(r)***

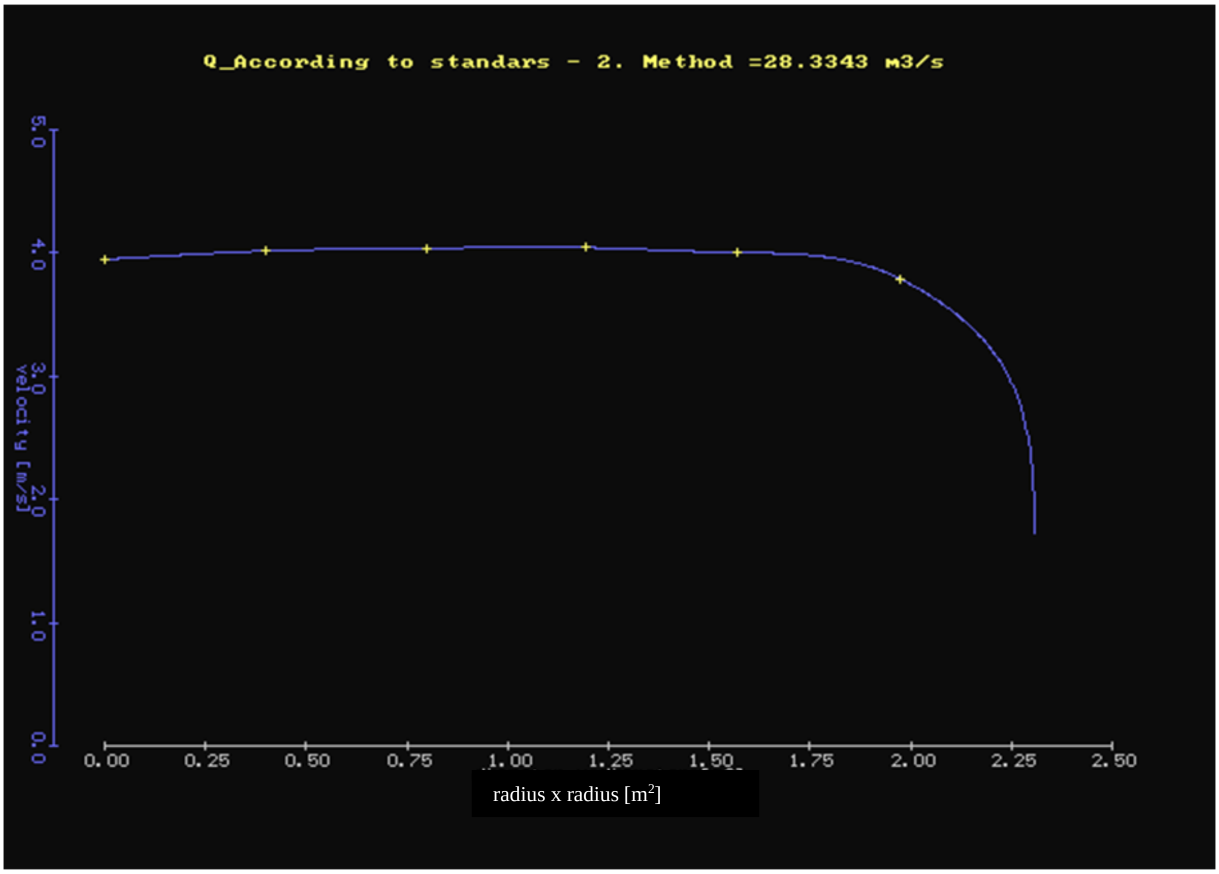

Figure 8: Flow rate calculation by the 2. method *v=f(r²)*

The difference from average value of flow rate is about ΔQ =0*.05* %. The flow asymmetry is *2.5 %*. Although systematic errors have been distinguished from random ones; the probability distribution of each systematic component is essentially Gaussian see Figure 11. In this case, the flow rate measurement shall be presented in the following form [4] *Q* ± *1.3 % [7]*.

4. INDEX METHOD

An index test may be used as part of a performance test to complement the primary method of the absolute discharge measurement, for any of the following purposes:

- To determine the shape of the performance characteristics and the relative efficiency of the turbine (shape control) alone, or the plant overall.
- To provide additional test data during a field expectance test, to extrapolate the range of data produced by the primary method. For instance, extrapolation towards higher velocities may be permitted up to 1.25 times the maximum current meters calibration velocity in the case when calibration cannot be achieved at those higher velocities [4].
- To make a cross check of the index discharge to any primary method.
- To obtain calibration data for permanent powerhouse flow monitoring.

The discharge is determined from the pressure difference measured by means of Winter-Kennedy piezometric taps, namely from the following equation:

$$Q_{W-K} = k_0(\Delta p_{W-K})^m \qquad (4)$$

Exponent *m* shall be in the range 0.48 to 0.52, which means that the variation of the discharge can differ by about ±2 % at 60 % of the flow related to the optimum.

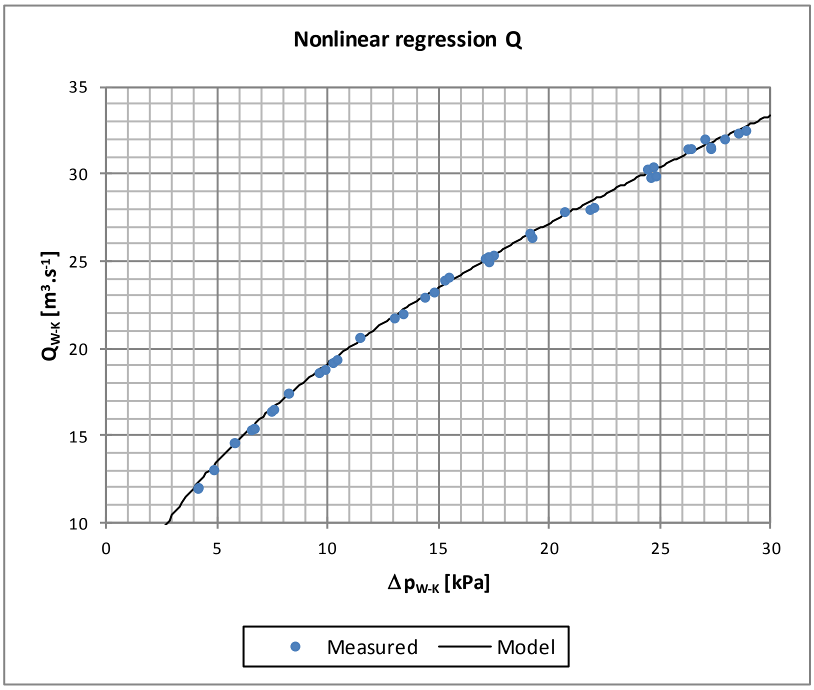

Figure 9: Evaluation of index method results by nonlinear regression

Equation of the model:

$$Q_{W\text{-}K} = 5.96396550402731*(\Delta p_{W\text{-}K}{}^{0.506212181216794}) \quad [m^3.s^{-1}; kPa] \qquad (5)$$

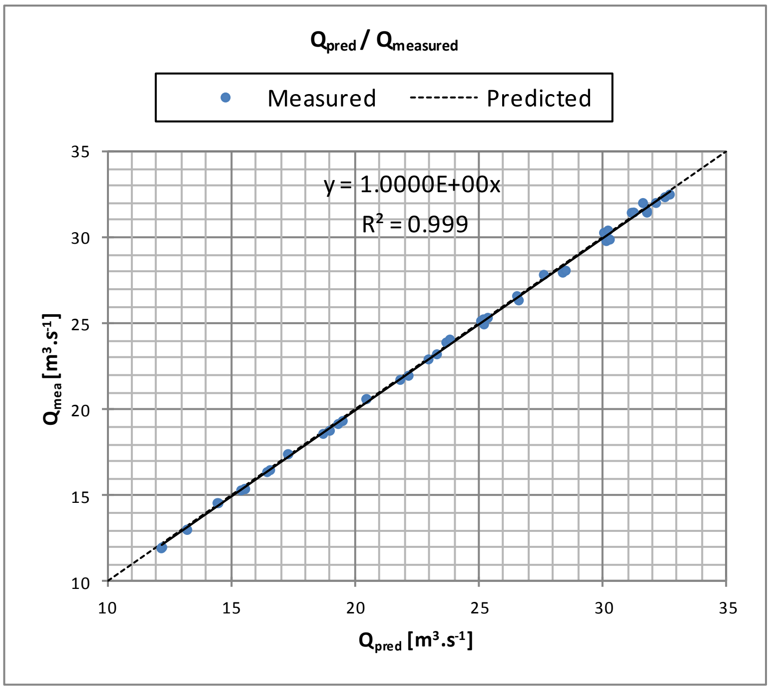

Figure 10: Correlation between measured and predicted flow rate (index method)

Jarque-Bera test (-8.67280061539901E-02):

JB (Observ	2.046
JB (Critica	5.991
DF	2
p-value	0.360
alpha	0.05

Test interpretation:

H0: The sample follows a Normal distribution.

Ha: The sample does not follow a Normal distribution.

As the computed p-value is greater than the significance level alpha=0.05, one should accept the null hypothesis H0.

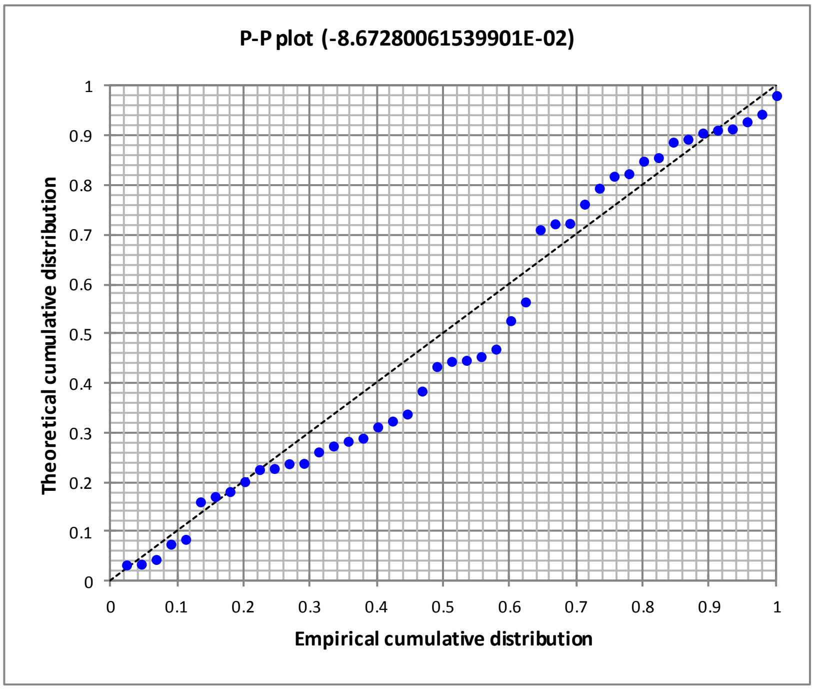

Figure 11: Test of normality of results

5. CONCLUSIONS

It is obvious that a curved penstock causes deformation of the uniform velocity field in its cross section, which subsequently causes aggravation of the velocity field method flow rate measurement. The uncertainty is reduced by increasing numbers of radii along with measurements are made to six and five points per radius in addition one point on the centre line.-see Figure 2. Flow rate was calculated, as a cross check, using three methods [4] with difference from average values less than *0.05 %* and it was compared to index method.

Figure 10 shows the discharge calculated by velocity area method and index method. The dotted line is the line of perfect agreement; the solid line is the least-squares regression of the current meters discharge on index method. The slope is *1.0000*, with correlation coefficient $R^2 = 0.999$. The least squares line represents overall agreement between the discharges, over the measurement range including extrapolation towards velocities above $4\ m.s^{-1}$ where calibration could not be achieved, to within *0.5 %*.

The improvement in a performance of the new runner could be measured, employing a described method, with acceptable accuracy. This method of the flow rate measurement for verification of the guaranteed efficiency was accepted by the plant owner.

REFERENCES

1. Cepa, Z., Report on FAT results of Unit #2 after rehabilitation. *In: CBE report no. MES-2013-0005b, July 2013.*
2. Spidla, J., HPP Doblar 1; Model turbine test final report. *In: Report of CBE no. 95-60-004-0867, June 2010.*
3. IBD1 6X/M11 HPP Doblar 1. Schedules of technical data of turbine, inlet valve and auxiliary mechanical equipment. Part 1: Guaranteed technical data.
4. ISO 3354 Third edition 2008-07-15. Measurement of clean water flow in closed conduits. Velocity-area method using current meters in full conduits and under regular flow conditions.
5. ISO 7194 Second edition 2008-07-15. Measurement of fluid flow in closed conduits. Velocity-area methods of flow measurement in swirling or asymmetric flow conditions in circular ducts by means of current-meters or Pitot static tubes.
6. IEC 41 Third edition 1991-11. Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines.
7. ISO 5168 October 2006. Measurement of fluid flow. Procedures for the evaluation of uncertainties.