

Experience with Kaplan turbine efficiency measurements - Current-meters and/or index test flow measurement

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Abstract

Some experience with discharge measurement with current-meters on the low head hydro power plants is presented in the paper. At each measurement a great number of current-meters were installed on the fixed profiled support. In all analyzed measurements the same current-meters, the same data acquisition system and the same data analyze procedures were used.

The flow in the measuring section and the influence of the flow condition on the Winter Kennedy (W-K) pressure difference are analyzed for several turbines. The results of optimization of guide vane and runner blade openings are presented for three turbines. For the estimation of measurement accuracy, the results of current-meters calibrations in two independent calibration laboratories, the repeatability of the discharge and efficiency measurement are analyzed. Collected data of measurements of 11 turbines, concerning failure of current-meters, are illustrated with the photos.

As a final conclusion concerning the discharge measurement with current-meters, which means absolute efficiency measurement at low head power plants, is that analyzed method is very reliable, stable and has considerable advantages despite its relatively high costs.

1. Introduction

The turbine discharge is the most difficult basic hydrodynamic parameter to be measured on a prototype turbine. The reasons for the discharge measurement are :

- turbine efficiency measurement for fulfilling the guarantees after commissioning,
- efficiency measurement for operating hill diagram,
- calibration of the W-K taps or any other discharge measurement device on the power plant for continuous discharge measurement,
- optimization of the guide vane and runner blade opening link.

There are several methods for turbine discharge measurement that are standardized in the IEC code as a result of various specialists' experiences during long term and numerous measurements. The difficulties with low head turbine discharge measurement are very well known and only few methods give reasonable results. According to our experience one of the best method for discharge measurement is the current-meter method with fixed installed current-meters. In that case the installation of current-meters fixed support is very expensive

and time consuming. The advantages of the approach are simultaneous velocity measurement in all measuring points (more than 100), stable and quick integration of measured velocities and simultaneous measurement of all values that define the turbine efficiency.

The W-K method for flow measurement through pressure difference between high and low pressure zone is cheaper and time for preparation is incomparably shorter than for current-meter method. Reasonable judgment which method should be used in particular case could be done considering the main aim of the measurement, the price, the consuming time and possible consequences of unsure results. With the analysis of our experience with low head power plants flow measurements we try to help the owners and test executors in their decision which method of flow measurement is the most suitable for particular case. All discussed results and conclusions are based on the tests of power plants which main characteristics are given in Table 1.

Table 1: Main data of measured and analyzed Kaplan turbines

Power plant		DJALE	FALA 9,10	FALA 8	MEDVODE	ZLATOLICJE	FORMIN
Country		Croatia	Slovenia	Slovenia	Slovenia	Slovenia	Slovenia
River		Cetina	Drava	Drava	Sava	Drava	Drava
No. of meas. units		2	2	1	2	2	2
Rated head	(m)	21.0	13.5	13.5	20	32.6	29
Max. discharge	(m ³ s ⁻¹)	110	175	155	60	225	225
Max. output	(MW)	20.4	21.4	18.3	9.5	66.6	60.0
Speed	(rpm)	166.7	100	125	214	125	125
Runner diameter	(m)	4.0	5.1	4.65	3.06	5.76	5.76
Cross section		rectang.	rectang.	rectang.	rectang.	rectang.	rectang.
Meas. section	(m)	2 x 7.5x5.25	2 x 6.5x7.	2 x 6x11	8.7x5.1	2 x 8.5x8.8	2 x 8.5x8.8
Meas. area	(m ²)	78.75	97.5	132	44.4	149.6	149.6
No. of curr. meters		2 x 90	2 X 90	2 x 96	112	2 x 110	2 x 110
Max. velocity	(ms ⁻¹)	1.52	2	1.44	1.8	1.94	1.94
Blockade factor	(%)	5.3	5.7	5.9	5.8	5.4	5.4

All mentioned Kaplan turbines are measured in recent years and the measurement are performed in accordance with the international standards in this field [1], [2], [3] and [4]. In some cases of discharge measurement, up to 220 current-meters were simultaneously used. Some of our experiences with current-meters, considered in this article, are described in [5] and [6]. An example of other experiences is article [7].

2. Index test measurement

The optimization of the turbine operating, of course when a hydro power plant and its equipment are correctly designed and realized, is reduced on setting of the optimal "on cam" link between runner and guide vane opening. The "on cam" link determined according to model measurement results is merely a good base to determine the link on the prototype. There are some examples where the optimal "on cam" link on site is quite different from that on the model. A reason for such cases is in the nonhomologuinity of the model and the prototype (especially at the turbine inlet) and the nonhomologuinity of the inlet flow. On a test rig, an irregular flow, caused with power plant inlet conditions, is normally not simulated. At prototype those inlet irregularities causes the difference in "on cam" link between the model and the prototype.

The prototype "on cam" link optimization is done regularly with the index test efficiency measurements. The discharge measurements that are the only "problematic measurement" are done with the measurement of pressure difference on the W-K taps. A key problem at the W-K method of discharge measurements is stability, regularity and predictability of the relation between pressure difference and discharge through the turbine. Unfortunately, on the base of our experience we establish, that pressure difference is often unstable, irregular and different from the predicted law. Other influences will be analyzed later on, now we would like to point out our experience with unpredictability of the dependence of the pressure difference and the discharge.

At regular inlet flow conditions and correct chosen position of the W-K taps the square root law of dependence between pressure difference and discharge is valid. At irregular inlet flow conditions the exponent of the W-K taps, due to our experience it is in the range of 0.475 to 0.524 (IEC code limits are 0.48 to 0.52). With calibration of the W-K taps, done by current meters, mentioned exponent is easy to determine. The problems arise in cases when the discharge constant is calculated only from the measured pressure difference and supposed optimum efficiency. The results of discharge measurements with current-meters for several Kaplan turbines and the W-K pressure difference are given in Fig. 1. The position of the W-K taps play important role on the value of pressure difference. From the measuring point of view, it is recommended to achieve as high as possible pressure difference on the prototype. Each curve in Fig. 1 was obtained on the basis of numerous measurement points. Example is the case e in Fig. 1. Numbers in parentheses represent different combination of the W-K taps.

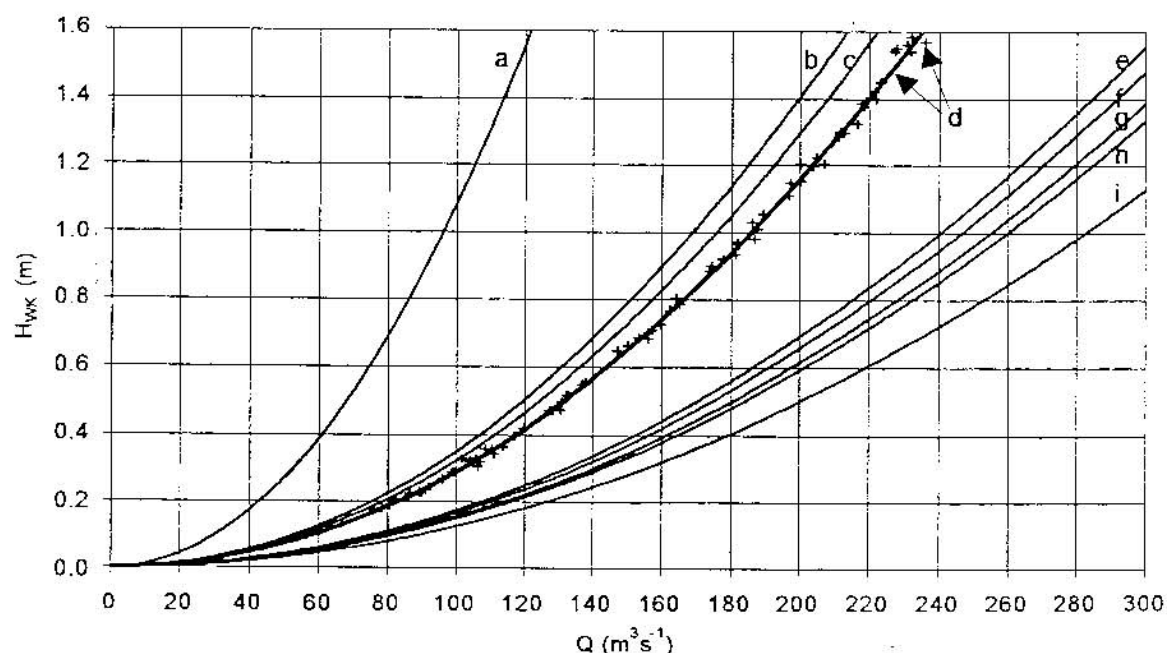


Fig. 1: Influence of different W-K taps on pressure difference: a) Medvode 1(3-4), b) Djale 1, c) Medvode 1 (1-2), d) Zlatoličje 2 (2-3), e) Formin 2 (1-3), f) Zlatoličje 2 (1-2), g) Formin 2 (1-2), h) Fala 10, i) Fala 8

The results of efficiency testing of Kaplan turbine at Fala 8 HPP at approximately constant head are given in Fig. 2. With bold lines the results obtained by current-meters are presented. From the measured pressure differences on the W-K taps, turbine characteristics with exponent values 0.48, 0.50 and 0.52 are computed and presented on

the diagram. Various exponent values rotate efficiency curve around chosen optimal point. From the diagram it can be seen that the influence of exponent value increase with digression from optimum and is especially important at full loads. The influence of exponent value is evidently shown: on the optimum position considering optimum discharge (optimum efficiency value is input parameter and therefore it is constant), on the flatness of efficiency curve and on the efficiency value at the full load, respectively. The difference in efficiency at full load is in the range of $\pm 2\%$.

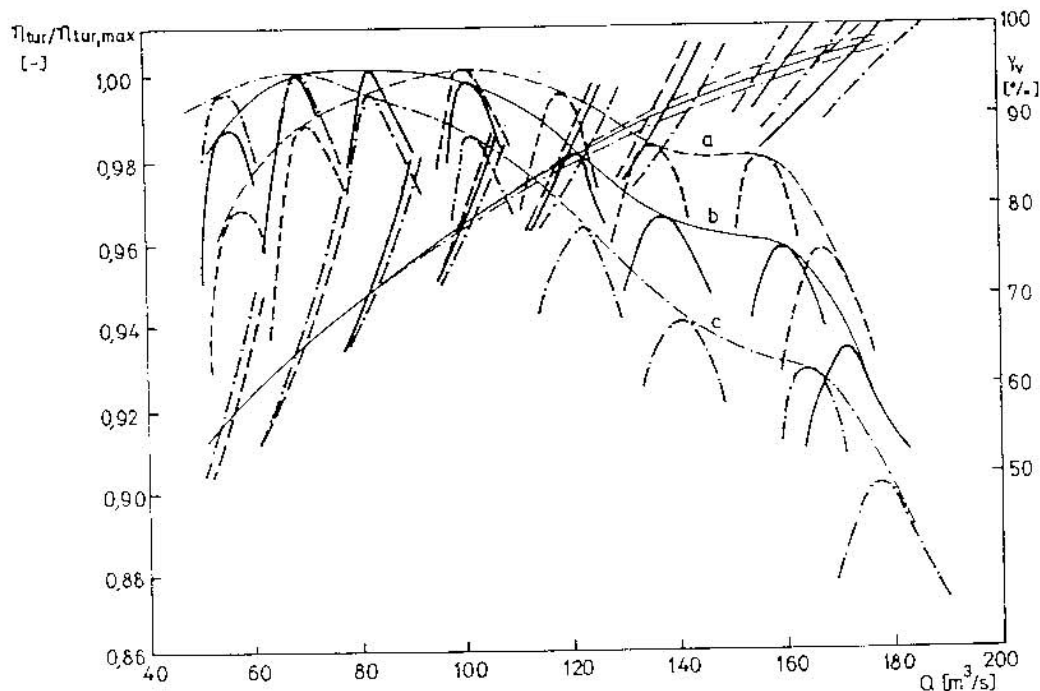


Fig. 2: Influence of pressure difference exponent value on efficiency characteristics:
a) $Q = 269.74 \cdot H_{WK}^{0.48}$, b) $Q = 282.00 \cdot H_{WK}^{0.50}$, c) $Q = 298.08 \cdot H_{WK}^{0.52}$

The conclusions concerning the W-K method of efficiency measurement, on the base of our experience, are:

- for "on-cam" link optimization the W-K method is enough stable and reliable because, the guide vane and runner blade opening link determined with the W-K pressure difference is the same, regardless of the used exponent value,
- above conclusion is not valid only in limited cases when the inlet flow conditions cause strong disturbances in the spiral case and therefore disturb the measured pressure difference,
- for guaranteed efficiency measurement, the W-K method is unacceptable in any case and under any circumstances.

3. Current-meters measurement

3.1. Current-meters installation - experiences and difficulties

Installation of current-meters in a measuring plane in the spiral case is one of the hardest tasks in the preparation of the discharge measurement in low head hydro power plants. The assembling of large current-meters support is done in unpleasant and even dangerous conditions (moisture, low air temperatures, slippery ground, work on heights up to 10 m).

Especially important is connecting each current-meter with measuring system. The cable connections should be strictly tested before filling the turbine tract with water. Time necessary for all these preparations is approximately one week with very skilled team. Turboinstitute's largest current-meters installation is in Fig. 3 (see also Table 1). Often trouble happening during the discharge measurements is dirt on the current-meters (Fig. 4). Concerning our experience with the malfunction of current meters at the end of turbine tests (which usually consume 2-3 days) for 10 measured turbines is that in average 1.5 % current meters failed at the end of the test. Only during one turbine test at the end 6 % of current meters failed due to extremely dirty water with great content of grass in the water.

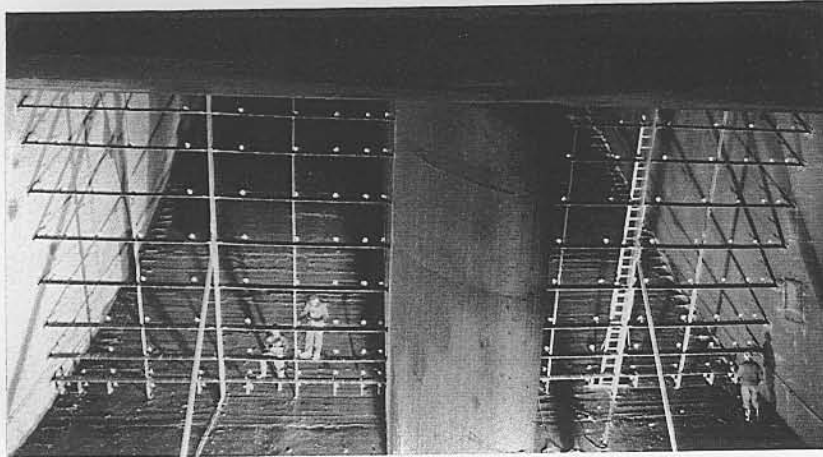


Fig. 3: View to the installed current-meters at Formin HPP

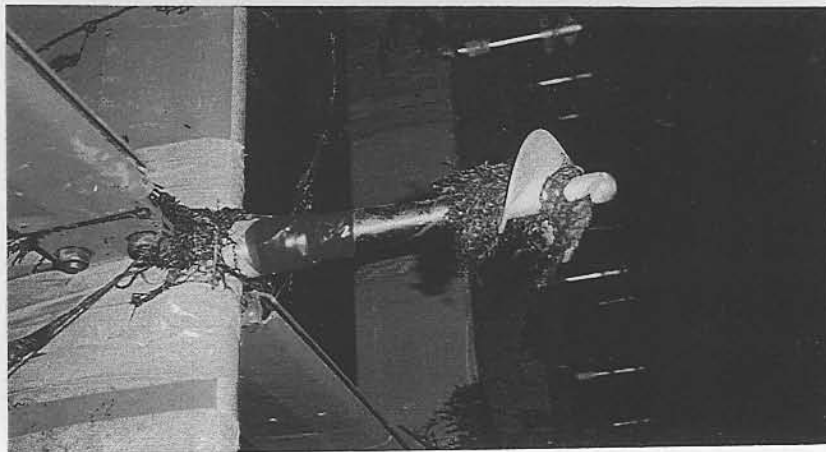


Fig. 4: Grass on a current-meter at the end of the tests

3.2. Current-meters calibration

We calibrate current-meters in the towing tank of the Brodarski institut, Zagreb, Croatia [8], since 1988. Four current-meters were calibrated for comparison also in the Calibration Laboratory of Swiss National Hydrological and Geological Survey, Bern, Switzerland in March 1995.

At the Brodarski institut, the large towing tank: length 276.3 m, width 12.5 m, depth 6.0 m, speed range 0.014 to 14 ms^{-1} , max. acceleration 1 ms^{-2} is used for current-meters calibration.

The calibrations are performed with the same hardware and software as on site measurements. Each current meter has a permanent magnet on the axis which switches a reed relay on and off two times during one revolution of the propeller. Signals from current-meters are fed through an optical isolating device in a 240 channel

digital I/O interface board Burr-Brown PCI-20378W-1 which is installed in the PC Pentium-133 computer. The software is written in Turbo Pascal by the Turboinstitute. The status of reed relay in each current-meter during calibration is checked at least 400 times during one revolution of the propeller. So accurate counting of the propeller revolutions in chosen time can be performed. Time is measured with the computer's on board clock.

The velocity of the carriage is measured with the wheel which has circumference of 1.00000 m, and it triggers counter 10000 times in one revolution. Instability of carriage's velocity has maximum standard deviation 0.002 ms^{-1} and typical 0.001 ms^{-1} .

Our experience shows that 32 current-meters on four vertical supports (horizontally spaced approx. 0.8 m) can be successfully calibrated simultaneously (Fig. 5). This way of calibrations is shorter and cheaper. We have repeated results of calibration of four current-meters on one vertical support.

After each calibration run, the carriage is driven back to its initial position with velocity 0.2 ms^{-1} to minimize additional disturbance of water. The settling time of tank's water to the next run was 15 min for velocities up to 0.6 ms^{-1} and 20 to 40 min. for velocities above 0.6 ms^{-1} . For these conditions most of the measured calibration points are within the band of $\pm 0.2 \%$ around the calibration lines computed with linear regression. Shorter settling time may extend this band more than $\pm 1 \%$.

As it can be seen in Fig. 6, the repeated calibration of the current-meters in Zagreb and Bern gave results with very small differences. These current-meters were calibrated with velocities up to 6 ms^{-1} (designed are for measuring velocities up to 8 m/s). Most calibration points deviates from the computed values (constants obtained in Bern calibration) within $\pm 0.2 \%$. In both cases the same current-meter support shape a) (for Francis and Pelton turbine measurements, Fig. 5) was used.

Repeated calibrations of the same current-meters (only with velocities up to 2 ms^{-1}) mounted on support shape b) (Fig. 5), which is designed for axial turbine measurements, gives the differences of -0.5 to -1.2% in comparison with the constants obtained in Bern calibration. From these results we conclude that accurate current-meter calibration and use could be achieved only in case when the same support is used during the calibration and site measurements.

3.3. Measurement repeatability

Measurement repeatability is a "dream" of any measurement specialist and also a "nightmare" of many of them. The repeatability of measurement results is very important for the reliability of turbine characteristics, especially for researching the influence of different conditions although the results are not absolutely accurate. The repeatability of discharge and efficiency measurement is checked on each site test and some results, which are proven in the later tests, are given in [6].

On the basis of current-meters discharge measurement on more than 25 turbines of various types we conclude that measurement repeatability of discharge is between 0.15 in well defined condition and 0.35 % in other cases. Bigger differences are

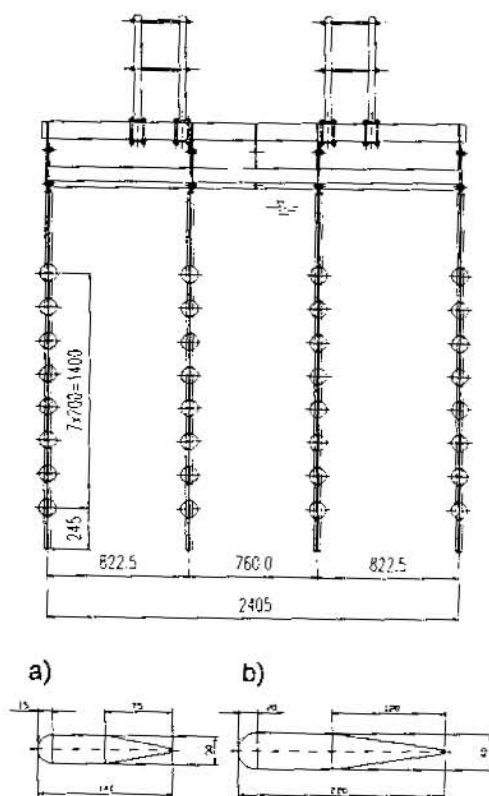


Fig. 5: Current-meter support

the consequences of malfunction of current-meters (rarely due to great number of current-meters) or unsteady flow conditions in the measuring cross section due to unsteady inlet conditions (only on the low head turbines).

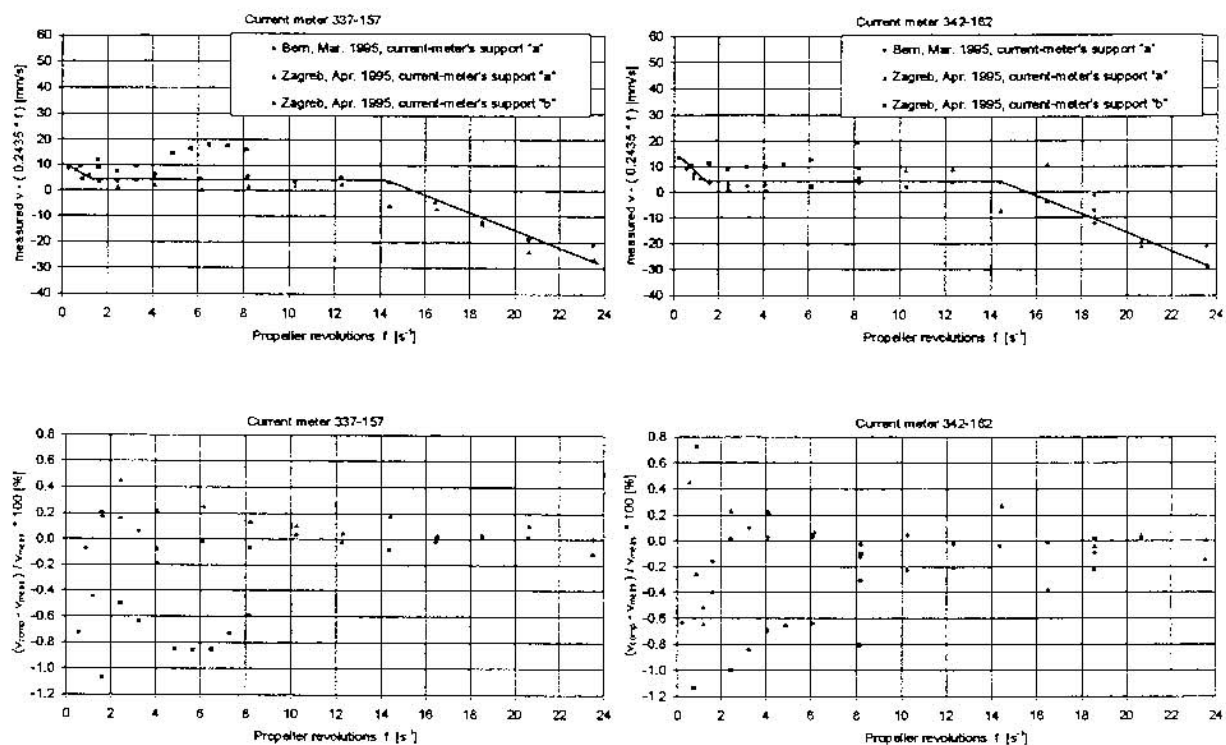


Fig. 6: Comparison of two current-meter calibrations

With so high repeatability, discharge measurements with current-meters are very reliable in the site tests of various influences on the turbine characteristics. The accuracy of discharge and efficiency measurement on low head turbines and the results of comparison between scaled model and measured prototype characteristics will be discussed in another paper.

4. Case studies and results

4.1. Influence of water intake on turbine characteristics

At low head water turbines the intake geometry and inflow conditions play important role in affecting the turbine characteristics. During the last several years, Kaplan turbine models were tested with the intakes geometrical completely similar to the prototype. Of course on the test rig the intake flow is caused by the flow conditions in the pressure vessel in front of the model. Design of power plant as well as operating conditions of turbine itself caused the intake flow conditions on the measured prototype. According to our experience, intake flow conditions vary from case to case and cause the unstability of the W-K measurement, the decrease of measurement repeatability and the increase of errors, respectively.

The ratio between the flow in the right and left part of spiral case (there are inlet piers in all analyzed turbines) at 5 turbines and various operating regimes is plotted in Fig. 7. In case of very stable inflow conditions, the operating head and discharge have small influence on the afore mentioned ratio (case c). In case of low operating head the strong vertical axis vortex appears in front of the turbine intake due to power plant design and river flow conditions. Mentioned vortices at low head completely change the flow conditions in the

spiral case and consequently the W-K pressure difference is not a measure of the total turbine flow. The efficiency obtained with so measured pressure difference is unrealistic and unusable.

In case b) the operating head has important influence on measured pressure difference although the strong vortex on the lake surface did not appear. The pressure difference is stable in contrary with the case a). The computed results for low head considering the same law as for high operating head are unrealistic and, without carefully judgment, unusable.

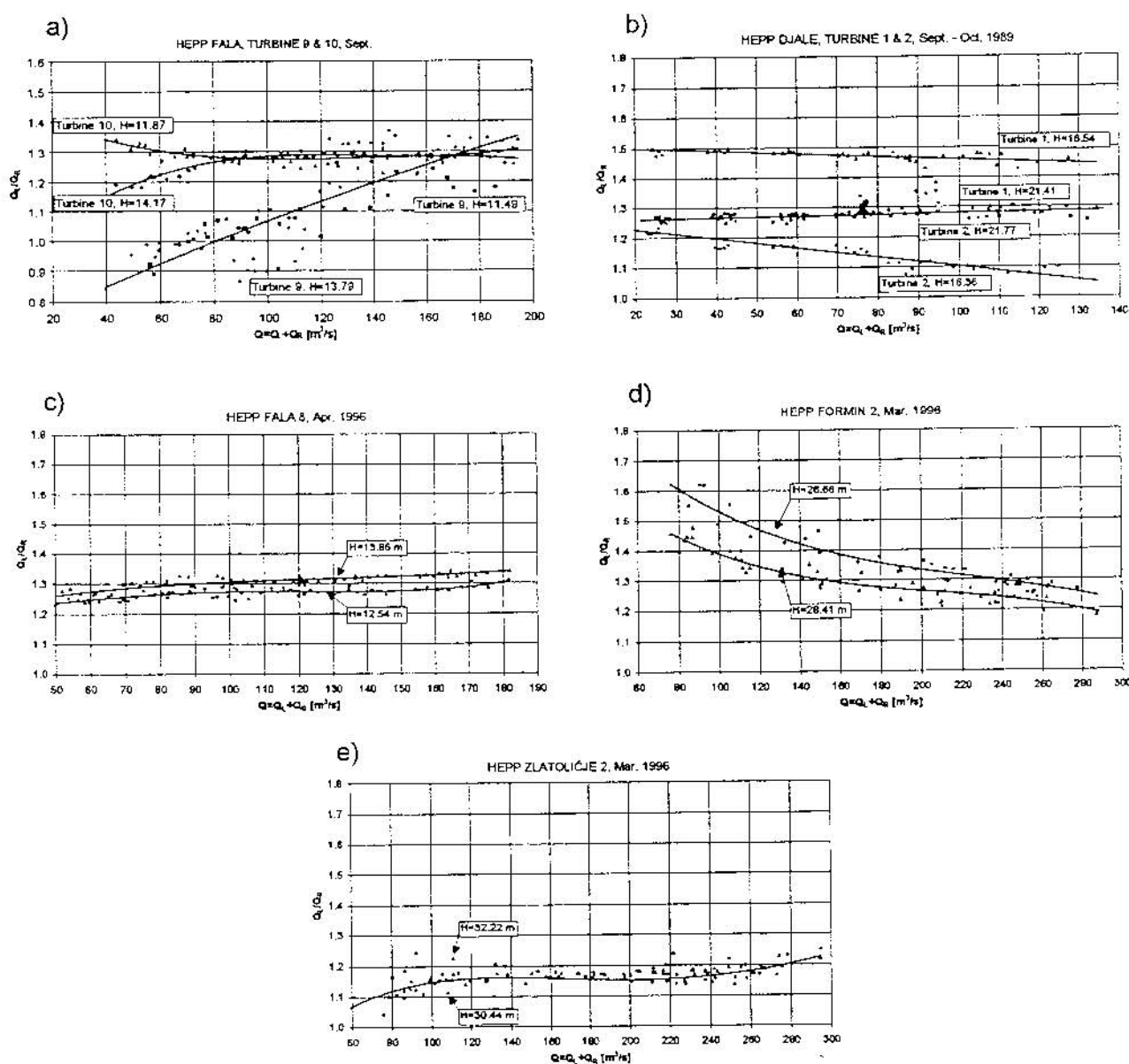


Fig. 7: Ratio between discharge through the left and right part of the spiral case

Cases d) and e) are typical for well-defined inlet conditions which cause stable and repeatable characteristics with more or less turbine head influence. If turbine head is more influenced at small discharges, weighted average constant and exponent value of the W-K taps is proper solution. Therefore, instead of big influence of head, the constant is stable and the results concerning repeatability are very reliable. The other story is influence of flow

conditions on the reality of measured efficiency. From our experience with calibration of the W-K taps during the model measurement it could be concluded that the testing head has no influence on the values of the constant and exponent. This is reasonable, due to the fact that on model testing a lot of efforts is invest to achieve as well as possible flow conditions (uniform and without vortices) on the turbine model inlet.

4.2. Optimization of power plants chain

The proper adjustment of the guide vane and runner blade opening "on cam" links is the first condition towards the maximal hydro power plant energy production. The openings link on the prototype is set by the turbine producer on the base of model or site tests. Only in the case of well-defined inlet flow conditions "on cam" determined on the model is suitable on the prototype. In other cases the discrepancies appear and proper "on cam" on prototype could be set only on the basis of site measurements. As it is mentioned before for the guide vane and runner blades opening link, index test measurements are normally enough except in the cases when very strong disturbances at the turbine inlet exist.

Three examples of turbine efficiency measurements with current meters are presented in Figs. 8 to 10. The "on cam" setting is well done at turbine in Fig. 8. The setting at turbine in Fig. 9 is failed on the right side of the "on cam" curve, at large discharge values and large turbine power rates. Because of this, guaranteed maximum power rate cannot be reached. On the other hand the runner is less exposed to cavitation and its negative effects, but this fact cannot satisfy the owner at all. The case in Fig. 10 is completely failed "on cam" curve and it's adjustment should be done immediately.

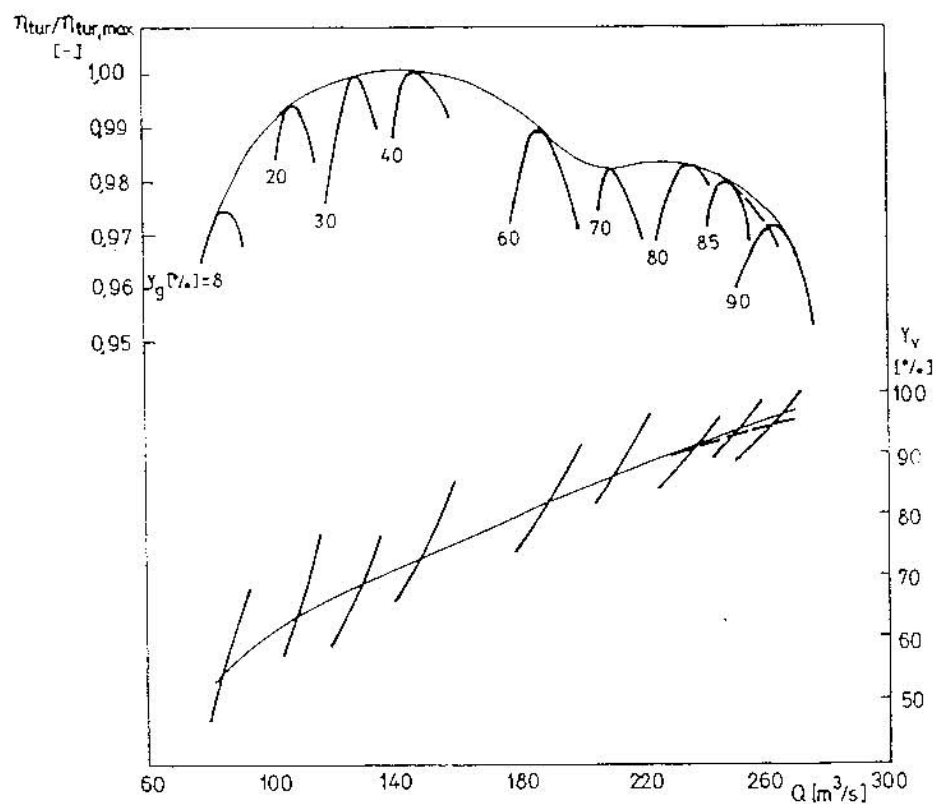


Fig. 8: Existent (dashed line) and optimized "on cam" curve setting at Formin HPP

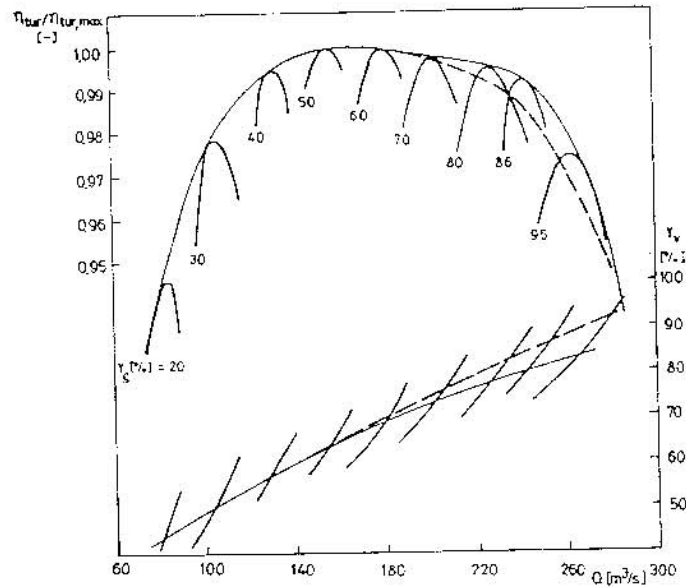


Fig. 9: Existent (dashed line) and optimized "on cam" curve setting at Zlatoličje HPP

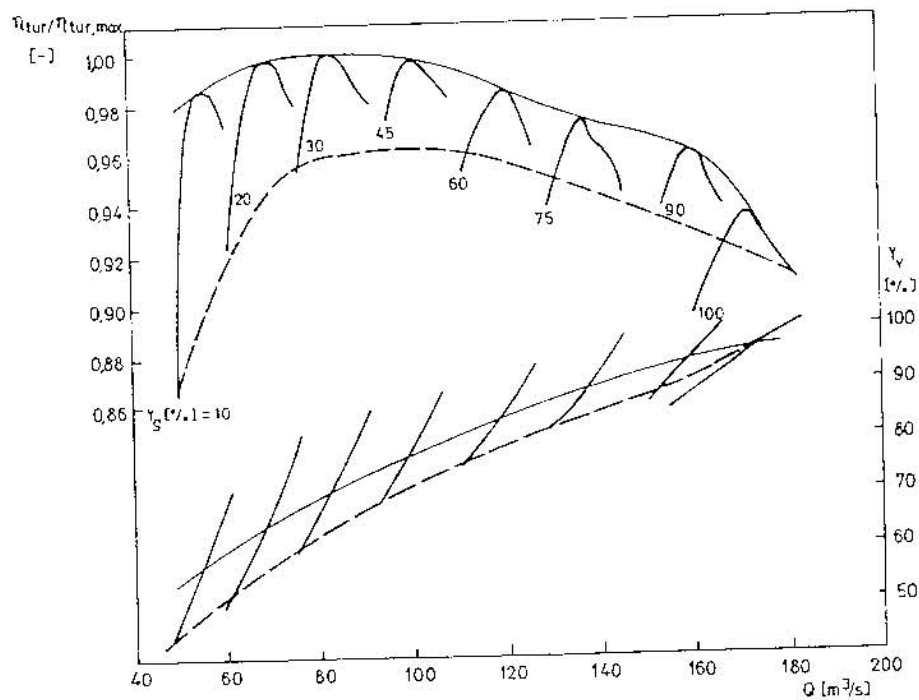


Fig. 10: Existent (dashed line) and optimized "on cam" curve setting at Fala 8 HPP

Conclusion

According to our experience with the efficiency tests at low head hydro power plants we established great advantages of current-meter's method due to its stability, reliability, repeatability and accuracy. Consuming time and higher price are its main disadvantages and therefore in each case of its use the client should reasonably judge the price/performance ratio of the method due to its requirements.

With uniform intake conditions and proper positions of pressure taps the square root law between pressure difference and discharge is valid. In case of the "on cam" optimization, index test method is sufficient and gives very reasonable results. Site optimization, even in cases of known model test results, is deeply recommended.

Great number of current-meters installed on the fixed support allow well defined velocity profile measured simultaneously with other values that determine the turbine efficiency. Therefore, the high repeatability of the efficiency measurement (range of 0.2 %) is achieved. With skilled staff and prescribed procedure of current-meter's calibration, maintenance and erection high reliability of their use are achieved.

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Nomenclature

H	(m)	height of water column	g	runner
Q	(m ³ s ⁻¹)	discharge	L	left
Y	(%)	opening position	R	right
η	(-)	turbine efficiency	tur	turbine
			v	guide vane apparatus
			W-K	Winter-Kennedy

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