Validation of Numerical Results with In-situ Measurements for Kaplan Turbine

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Abstract

Turbine discharge determination is an important and a difficult problem. Index tests methods generally offer orientative values and absolute methods are difficult to perform. Consequently, a numerical method that helps evaluating the discharge values is welcome. The paper presents numerical simulation of the flow considering a 3D steady, inviscid and incompressible flow in order to determine discharge of Kaplan turbines. In fact, by numerical simulation it is determined the Winter-Kennedy pressure drop for a number of operating points and discharge evaluation using Winter-Kennedy formula. Two experimental methods are employed to validate computed discharge values. Numerical results are in good agreement with experimental data, and thus the first method can be successfully applied.

Introduction

The measurement of the discharge in a hydroelectric power plant is required for acceptance test, or to evaluate the performance in operation. The choice of measurement method is imposed by some limitations, such as hydroelectric plant design, plant operation conditions, installation and special equipment costs and desired accuracy.

Most of hydropower plants are equipped with pressure taps in spiral casing for discharge measurement using the Winter – Kennedy method. However, for various reasons either the calibration was not performed, or the pressure taps are not in the best locations or are temporary out of service. As a result, difficulties are encountered when attempting discharge measurement. The major problems with the Winter – Kennedy method are stability and predictibility of the relation between pressure drop and turbine discharge within the whole operating range.

From the design and operating practice of low head hydraulic turbines it is well known the major influence of intake and spiral casing inlet geometry on operations characteristics. Therefore, plant designing and operation conditions can induce major perturbations even in discharge measurement. Permanent modifications of inlet conditions caused instability in discharge measuring process by Winter – Kennedy method, low repeatability and low accuracy, [2]. When inlet conditions are steady, discharge measurements using Winter – Kennedy method leads to high precision determinations and a very good repeatability, [2].

Present paper deals with the calibration of Winter - Kennedy method using numerical simulation. Practical application on a low head Kaplan turbine is considered. The computed pressure distribution allowed to establish correct position of the pressure taps in spiral casing and the relation between pressure drop and discharge value. In order to verify numerical results, experimental studies were made in situ, using thermodynamic method and Winter – Kennedy method.

Computational domain. Equations and boundary conditions.

Figure 1 presents the cross section through the Kaplan turbine as well as the computational domain considered in the present study. The inlet section of computational domain corresponds to the power plant inlet section.

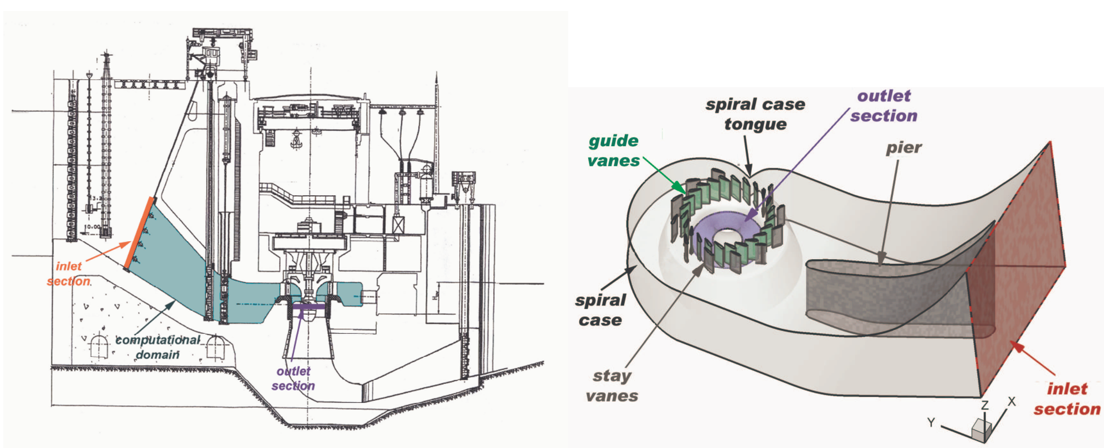

Figure 1. Three-dimensional computational domain extended from the power plant inlet to the runner reference plane.

The outlet section is conventionally chosen in the runner reference plane. Normally, one would consider a computational procedure that couples the steady absolute flow in spiral case/distributor domain with the relative flow in the runner [9].

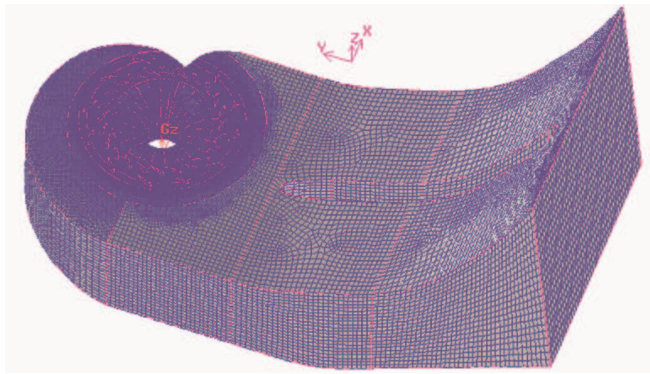

Figure 2. 3D structured mesh with 2 millions hexahedral cells.

A structured 3D mesh is generated. In the inflow region we consider a relatively coarse mesh, and the mesh is further refined downstream as the flow accelerates. A particular attention is paid to the discretization near the stay/guide vanes, to correctly represent the local large velocity gradients. The mesh has approximately 2 million computational cells.

A 3D steady, inviscid and incompressible flow is considered, thus we solve the steady Euler equations:

$$\nabla \cdot \boldsymbol{V} = 0 \tag{1}$$

$$\rho(\boldsymbol{V} \cdot \nabla)\boldsymbol{V} = -\nabla p \tag{2}$$

On the inlet section we prescribe a constant total pressure. The value of the total pressure is adjusted to obtain the maximum operating flow rate for the Kaplan turbine under consideration. On the outlet section, the swirling flow structure is compatible with the so-called pressure radial equilibrium. This condition is derived from the radial component of the Euler equation,

$$V_r \frac{\partial V_r}{\partial r} + \frac{V_u}{r}\frac{\partial V_r}{\partial \theta} + V_z \frac{\partial V_r}{\partial z} - \frac{V_u^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r}\,. \tag{3}$$

If the radial velocity component is negligible, $V_r \approx 0$, one obtains the pressure radial equilibrium condition,

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{V_u^2}{r}\,. \tag{4}$$

This condition has been successfully employed on the draft tube inlet section when computing the runner flow [7], and it has been validated experimentally [8]. A reference pressure is conventionally set to zero at the hub on the outlet section, since condition (4) defines the pressure only up to an additive constant.

Computations are performed in twenty-one operating points, see Figure 3. The parameters of the operating points investigated are presented in Table 1.

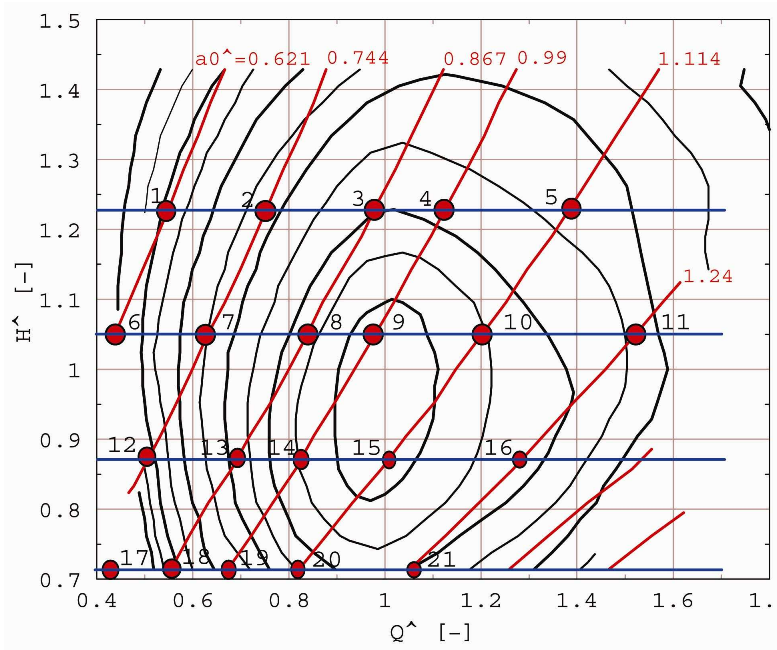

Figure 3. Kaplan turbine hill chart and the operating points investigated.

Table 1 Parameters for the operating points investigated.

OP No.	$a_{0^\wedge}$ [-]	$Q^\wedge$ [-]	$H^\wedge$ [-]	OP No.	$a_{0^\wedge}$ [-]	$Q^\wedge$ [-]	$H^\wedge$[-]
1	0.621	0.601					
2	0.744	0.816		12	0.744	0.564	
3	0.867	1.046	1.234	13	0.867	0.740	0.875
4	0.990	1.191		14	0.990	0.886	
5	1.114	1.492		15	1.114	1.102	
				16	1.240	1.402	
6	0.621	0.475					
7	0.744	0.691		17	0.744	0.418	
8	0.867	0.894	1.05	18	0.867	0.635	0.7
9	0.990	1.049		19	0.990	0.724	
10	1.114	1.299		20	1.114	0.886	
11	1.240	1.645		21	1.240	1.139	

Discharge evaluation through Kaplan turbine

The Kaplan turbine is equipped with two pairs of Winter-Kennedy taps. Each Winter-Kennedy pair contains two pressure taps. In our case, the first pair (includes taps no. 1 and no.

2, see Figure 4) is displaced at 150° relative to the spiral casing tongue while the second one (contains taps no. 3 and no. 4) at 100°. One pressure tap from each pair is displaced on the spiral case ceiling (taps no. 1 and no. 4) whilst the second one on the side surface (taps no. 2 and no. 3), see Figure 4(right).

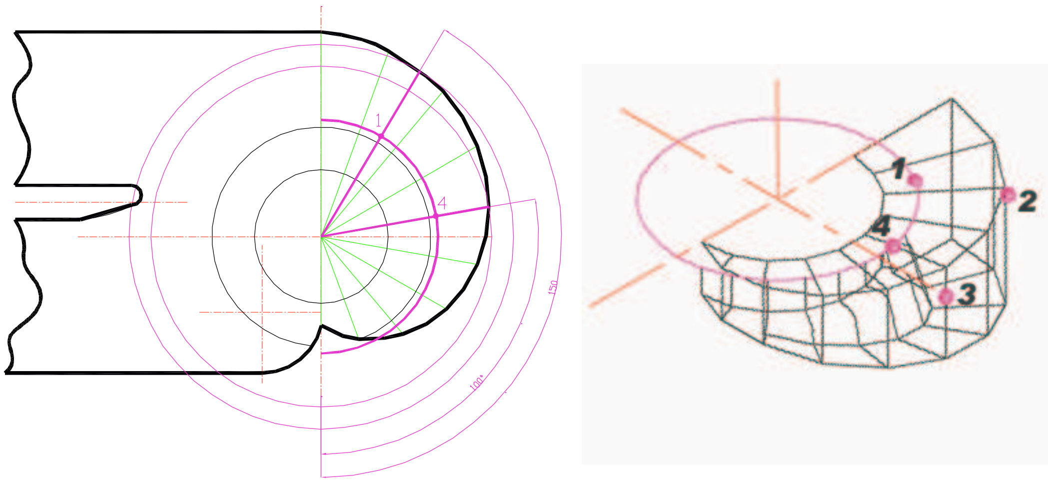

Figure 4. Position of Winter-Kennedy taps on Kaplan turbine spiral casing: (left) top view and (right) axonometric view.

Using numerical simulation performed on Kaplan turbine the Winter-Kennedy pressure drop is computed from pressure field in all twenty-one operating points. Applying a non-linear least square procedure on numerical pressure drop both multiplier k and exponent n from equation (5) are computed, see Table 2.

$$Q = k \cdot \Delta p^{n} \tag{5}$$

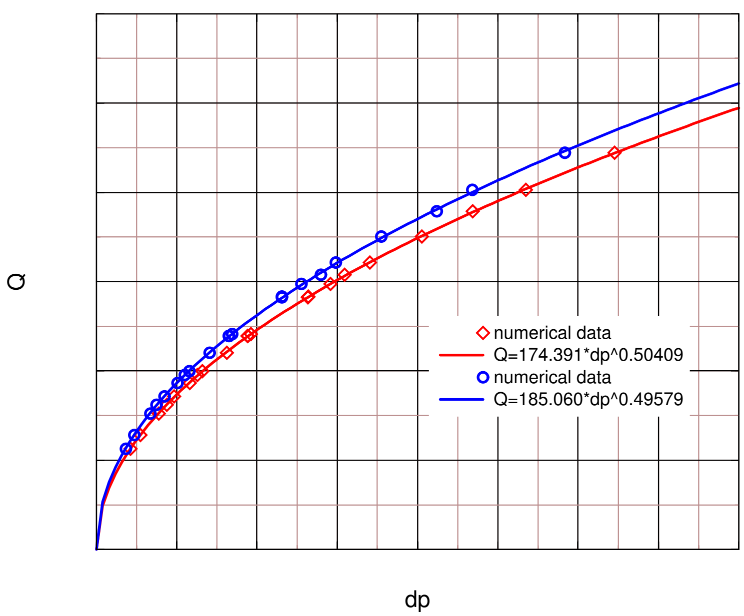

Figure 5. Numerical results and non-linear curve fitting for both pair taps.

Table 2 Winter-Kennedy parameters (k, n) computed using non-linear least square procedure.

	k	n
First pair (taps no. 1 and no. 2)	174.391	0.50409
Second pair (taps no. 3 and no. 4)	185.060	0.49579

According to the IEC 41 recommendations, the best choice for exponent value is 0.5. In our case, choosing the recommended exponent value lead to ±0.82% and ±0.85% uncertainties in discharge values, respectively. Based on pressure drop measured in situ on second pair (taps no. 3 and no. 4) the following values are obtained: k=186.8 and n=0.5. Unfortunately, the experimental data on the first pair (taps no. 1 and no. 2) cannot be measured since one tap was clogged.

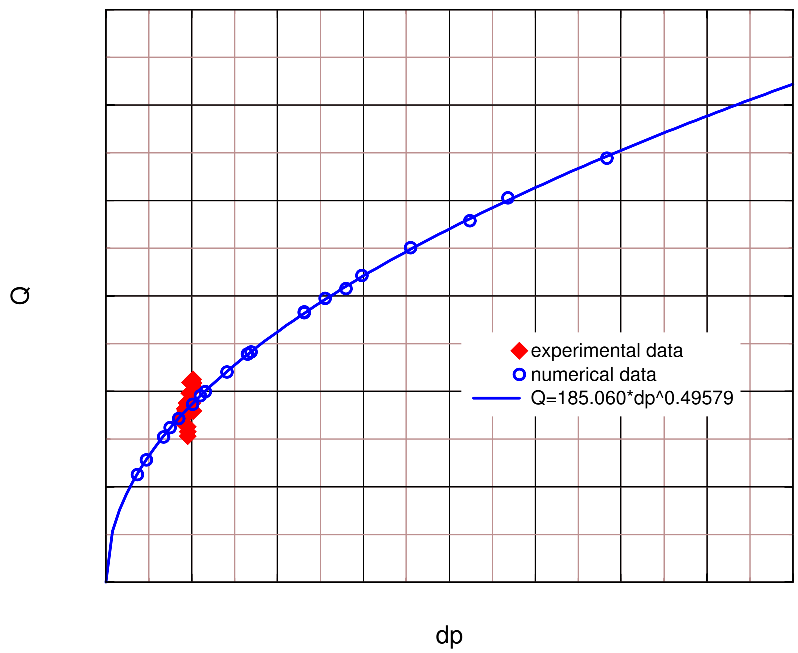

Figure 6. Comparison between numerical results and experimental data.

The ratio between the flow in the right and left part of spiral case (there is an inlet pier) is analyzed. On the inlet section constant total pressure is imposed. Although in numerical investigation the discharge changes from 0.418$Q_{\wedge}$ to 1.615 $Q_{\wedge}$ and head from 0.7$H_{\wedge}$ to 1.234$H_{\wedge}$ respectively. In our case, the ratio between the flow in the right and left part of spiral case (there is an inlet pier) is 44.5%±0.5 and 55.5%±0.5, see Figure 4.Thanks to a very stable inflow condition considered here, the operating head and discharge have a negligible influence on the above-mentioned ratio.

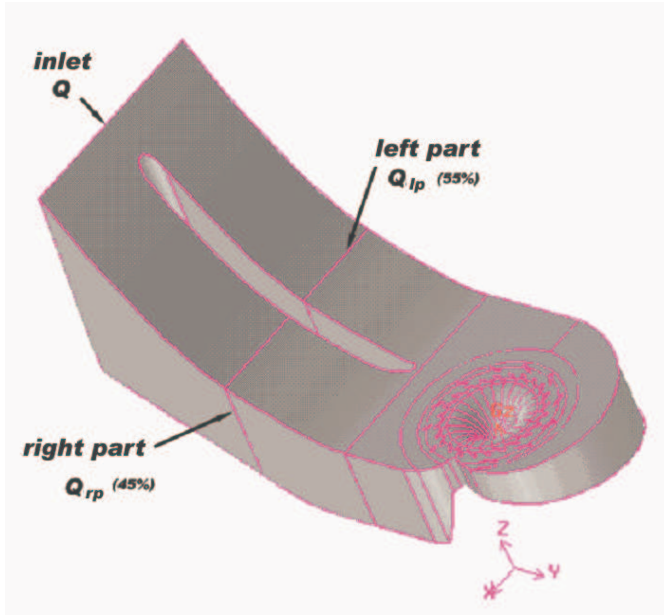

Figure 7. Position of the control sections on Kaplan spiral case in order to compute the ratio between the flow in the right and left part.

Validation the numerical results against experimental data

In Figure 8 are presented discharge dependencies of distributor opening considering 4 values of turbine's head, extended on all operation regimes. Selected points for numerical simulation are represented such as: □ $H_{^min}$=0.7; □ $H_{^}$=0.875; □ $H_{^n}$=1.05; □ $H_{^max}$=1.234. In order to evaluate turbine behavior in all head range $H_{\wedge} \in [0.7, 1.234]$ and for all range of guide vane opening have been determined polynomial coefficients for every head value, like as:

$$Q = c_0 + c_1 \cdot (a_0) + c_2 \cdot (a_0)^2$$

Coefficients' values c_0, c_1, c_2 for upper mentioned heads are presented in Table 3.

Table 3. Coefficients values for parabolic fit at four heads investigated.

Nr. Crt.	H^ [-]	c_0	c_1	c_2
1	*0.700*	*0.006441*	*0.04962*	*0.0006674*
2	*0.875*	*0.325000*	*0.06953*	*0.0007981*
3	*1.050*	*0.529800*	*0.10490*	*0.0008853*
4	*1.234*	*0.718200*	*0.15990*	*0.0009145*

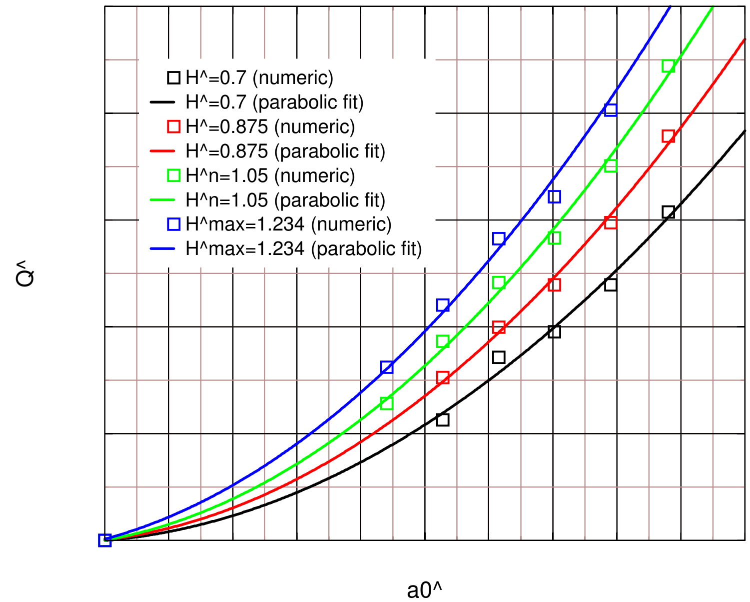

Figure 8. Discharge (*Q*) versus guide vane opening (a_0) evaluated by numerical simulation.
(▬$H^{\wedge}_{min}$=0.7; ▬ H^=0.875; ▬ $H^{\wedge}_{n}$=1.05; ▬ $H^{\wedge}_{max}$=1.234)

It can be mentioned that guide vane opening was considerate independent of runner blades position, mainly not "on cam" condition. In order to validate numerical simulation results two experimental methods were used:

1. **Thermodynamic method (MT)** used during operation on cam, at head H^=1.04;
2. **Index test measurements (MOR)**, used for 3 operating off-cam regimes, for H^=1.01

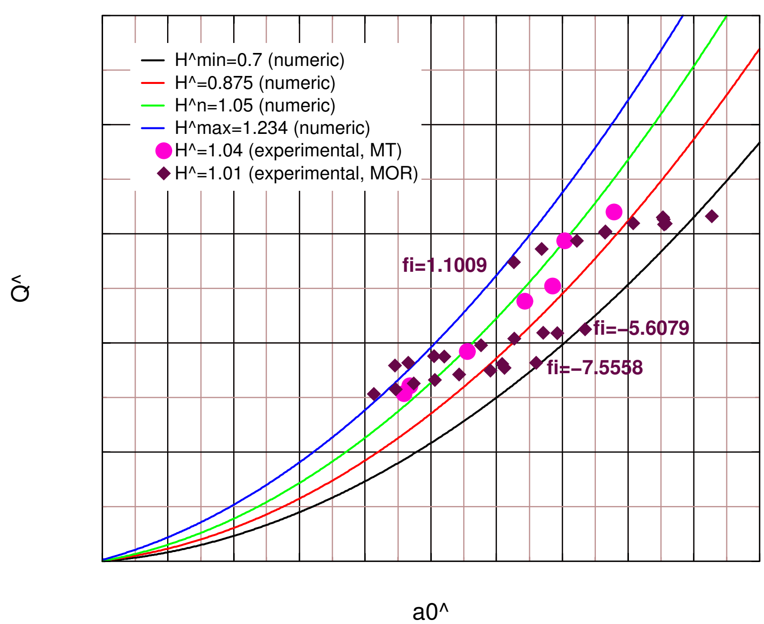

Figure 9. Comparison between numerical results and experimental data

Figure 9 presents o good agreement between numerical results and experimental data of thermodynamic method. Experimental data from MOR method for three propeller regimes (off cam operating Kaplan turbine) are also presented. Large magenta circles from Figure 9 indicate operation on cam. A good agreement with numerical results is obtained.

Conclusions

The paper presents a methodology for calibrating the Winter-Kennedy method using numerical simulation. First, the full three-dimensional flow upstream the Kaplan turbine runner is computed. We have developed a methodology for accurately describing the complex 3D geometry, as well as for building a suitable structured 3D mesh. A significant step forward has been made to reduce the time devoted to the problem definition (geometry and mesh), in order to be able to apply the present approach to design improvement and optimization.

With calibration of the Winter-Kennedy taps, done by numerical simulation, the parameters (multiplicative constant k and exponent n) are easily determined. In our case, a non-linear function fitting is used to evaluate both multiplier and exponent for calibration the Winter-Kennedy method. The position of the Winter-Kennedy taps plays an important role on the value of pressure drop. From the measuring point of view, it is recommended to achieve as large as possible pressure drop on the prototype.

The two experimental methods validated numerical method of determining discharge values of a low head of a Kaplan turbine, so that computed method can be successfully applied. A good agreement between numerical results and experimental data is obtained. The Winter-Kennedy method for discharge measurement using pressure drop between high and low pressure zone is cheaper and time for preparation in incomparably shorter than for other methods. Determination on which method should be used for a particular situation could be done considering the main aim of the measurement, the price, the consuming time and possible consequences of result uncertainties.

Acknowledgments
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References

[1] ***, International code for field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump turbines, Publication 41, 3rd edition, 1991

[2] Kercan V, Djelic V., Rus T., Vujanic V, “Experience with Kaplan turbine efficiency measurements – current-meter anr/or index test flow measurements”, Proceeding of the 1st International Group for Hydraulic Efficiency Measurements (IGHEM1996), Montreal, Canada, 1996.

[3] Lemon D., Bell P.W., “Measuring hydraulic turbine discharge with acoustic scintillation flow meter”, Proceedings of the 1st International Group for Hydraulic Efficiency Measurements (IGHEM1996), Montreal, Canada, 1996..

[4] Muciaccia F.F., Walter R.B., “Evaluation of the benefits of turbine refurbishment by means of Index Test Method Reliability of results and Problems in Applications”, Proceedings of the 3rd International Group for Hydraulic Efficiency Measurement (IGHEM2000), Kempten, UK, 2000.

[5] Rus T, Djelic V., “Absolute flow measurements on HPP Ozbalt using 320 current-meters simultaneously”, Proceeding of the 3rd International Group for Hydraulic Efficiency Measurements (IGHEM2000), Kempten, UK, 2000.

[6] Karlicek R.F., ”Test Equipment and Results from 25 Hydraulic Turbine Tests using Thermodynamic Method”, Proceedings of the 1st International Group for Hydraulic Efficiency Measurement (IGHEM1996), Montreal, Canada, 1996.

[7] Muntean S., Balint D., Susan-Resiga R., Anton I., Darzan C., 3D Flow Analysis in the Spiral Case and Distributor of a Kaplan Turbine, Proceedings of the 22nd IAHR Symposium, June 29 – July 2, 2004, Stockholm, Sweden, PaperA10-2, 2004.

[8] Dahlhaug O.G., A study of swirling flow in draft tube, PhD Thesis Norwegian University of Science and Technology, Trondheim, Norway, 1997.

[9] Balint D., Muntean S., Susan-Resiga R., Accurate evaluation of Kaplan turbine efficiency by improving the subdomain numerical coupling approach, Proceedings of International Conference “Energy and Environment”, Bucharest, Romania, 2005. (on CD-ROM)

[10] ***, (2001), FLUENT 6. User’s Guide, Fluent Inc.

[11] ***, (2001), Gambit 2. User’s Guide, Fluent Inc.