The Calculation of the Pelton and Francis Turbine Hill Chart Using the HydroHillChart Software

Prof. **Dorian NEDELCU** PhD[1], St. PhD Eng. **Adelina GHICAN (BOSTAN)**[1]

[1] "Eftimie Murgu" University of Reşiţa, Romania, d.nedelcu@uem.ro

Abstract: *The paper presents the HydroHillChart software, which is designed to calculate the hill chart for hydraulic turbines (Pelton, Francis and Kaplan) and the operation diagram, based on the energetic primary data that is obtained through turbine model measurements performed on the test rig. The HydroHillChart software is made up of the following four modules: the Pelton, Francis and Kaplan modules – which are used to calculate the turbine model hill chart and the DEX module – which is used to calculate the operation diagram for the industrial turbine prototype. The results of the software consist of graphical curves and numerical results which can be viewed in HydroHillChart and exported as Excel files with a template structure and also as PDF and Word files. The lack of paper space will limit the presentation to the Pelton and Francis modules only.*

Keywords: *model, turbine, Pelton, Francis, Kaplan, hill chart, software, Python*

1. Introduction

The design of hydraulic turbines is based on energetic and cavitation characteristics, obtained by measuring the turbine models in the test rig. The efficiency hill chart can be obtained through graphical packages, like general graphic processing and by computer-aided design programs, or through specialized programs like [1]. The HydroHillChart software was created using Python – a high-level object-oriented language and related modules: wxPython - a graphical user interface toolkit for the Python language, matplotlib - a python 2D plotting library which produces publication quality figures, SQLite – a database engine, SciPy - a Python-based ecosystem of open-source softwares for mathematics, science, and engineering. The HydroHillChart software, presented at http://www.cchapt.ro/HydroHillChart.htm, is a continuation of the Preldate software, which was originally conceived to compute the characteristics of hydraulic turbines [2], [3] and is the result of a PhD thesis [4], using tools similar with those from [5].

2. The HydroHillChart main interface

The HydroHillChart software is equipped with instruments for zooming (fit, pan, zoom in, zoom out), for spline curves interpolations, for graph intersections with constant X or Y values, for saving the graph as an image file and for the modification of the general/graph setting. For each graph generated by the HydroHillChart software, a toolbar with command buttons that are marked with specific icons appears at the bottom of the window. It performs the following functions:

Home	- Return to initial view;	**Pan**	- Left click & hold to zoom, zoom in/out with the right mouse button pressed;
Back	- Back to previous view;	
Forward	- Forward to the next view;	**Save**	- Save chart format: EPS; JPG, PGF, PDF; PNG, PS; RAW, SVG, TIF;
Zoom	- Enlarge selected area;	**Subplots**	- Chart configuration.

Fig. 1 shows the main menu of the HydroHillChart software. From the "File" menu, one can select the type of turbine for which the hill chart will be calculated (Pelton, Francis or Kaplan turbine) or the DEX option for which the operation diagram can be calculated. Based on the measured data of the turbine model, the software generates the hill chart for turbine models and the operation diagram for the industrial turbine prototype, providing the necessary tools for designing a turbine:

graphic visualization of functional dependencies, intersections in the hill chart and in the operation diagram, the generation of numerical results and their export in the usual programs: Excel, Word, PDF. The 2D curve interpolations are calculated by using the cubic spline functions. The constant efficiency curves are numerically and graphically generated using the mplot3d toolkit, which is included in the matplotlib library [6].
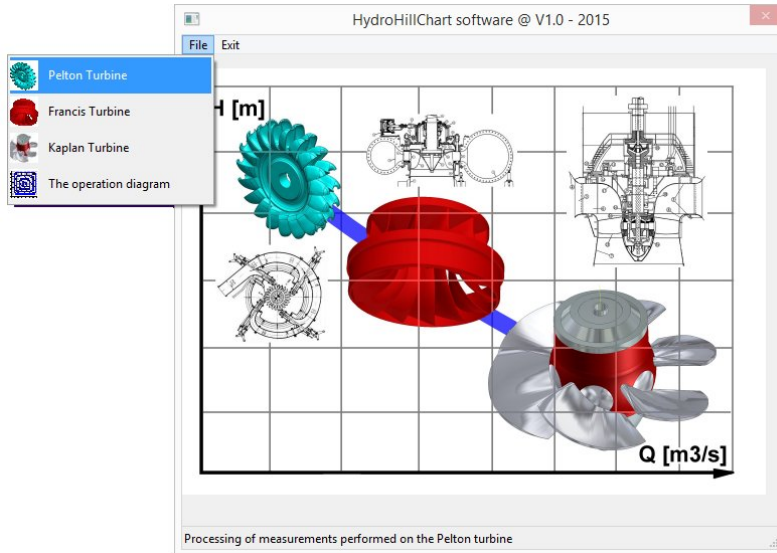

Fig. 1. The HydroHillChart main menu

3. HydroHillChart – Pelton module

The Pelton module [7], [8] can be selected from the "Pelton Turbine" option of the main menu and it displays a window with a specific interface, Fig. 2, composed of: a toolbar, a measured data table, called "Measured Points", which stores measured data for a model runner and a table called "Intersection with efficiency constant values", where the application stores values arising from the intersection of primary curves with constant efficiency values.
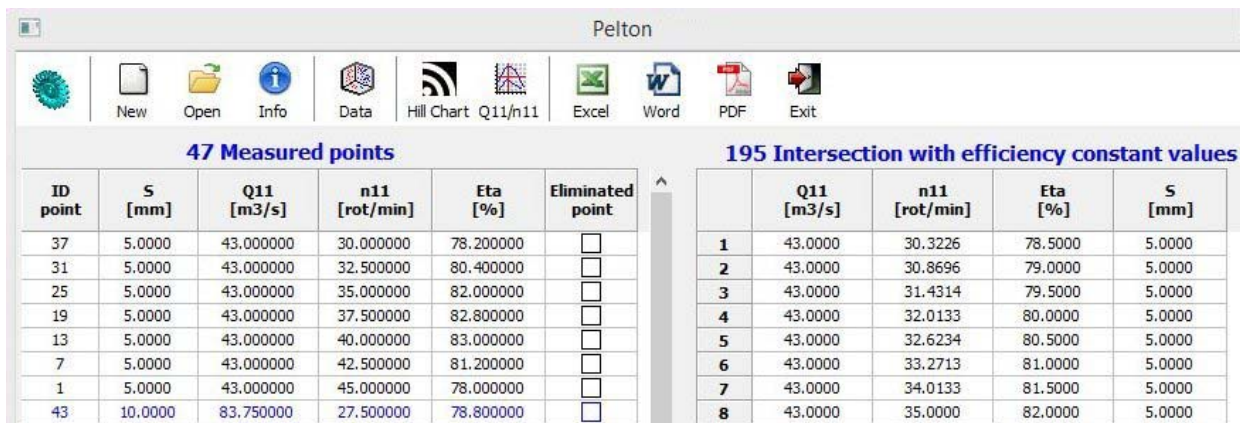

47 Measured points

ID point	S [mm]	Q11 [m3/s]	n11 [rot/min]	Eta [%]	Eliminated point
37	5.0000	43.000000	30.000000	78.200000	☐
31	5.0000	43.000000	32.500000	80.400000	☐
25	5.0000	43.000000	35.000000	82.000000	☐
19	5.0000	43.000000	37.500000	82.800000	☐
13	5.0000	43.000000	40.000000	83.000000	☐
7	5.0000	43.000000	42.500000	81.200000	☐
1	5.0000	43.000000	45.000000	78.000000	☐
43	10.0000	83.750000	27.500000	78.800000	☐

195 Intersection with efficiency constant values

	Q11 [m3/s]	n11 [rot/min]	Eta [%]	S [mm]
1	43.0000	30.3226	78.5000	5.0000
2	43.0000	30.8696	79.0000	5.0000
3	43.0000	31.4314	79.5000	5.0000
4	43.0000	32.0133	80.0000	5.0000
5	43.0000	32.6234	80.5000	5.0000
6	43.0000	33.2713	81.0000	5.0000
7	43.0000	34.0133	81.5000	5.0000
8	43.0000	35.0000	82.0000	5.0000

Fig. 2. The HydroHillChart interface for the Pelton module

The primary data is taken from Excel and stored in the table called "Puncte măsurate - Measured Points" by completing the following fields:
- **ID Point** - represents the current number for the measured point;
- **S** [mm] - represents the nozzle spear opening of a Pelton model;
- Q_{11} [m^3/s] - represents the unit discharge;
- n_{11} [rot/min] - represents the unit speed;
- η [%] - represents the efficiency;

- **Eliminated point** – allows the removal of a measured point, by selecting a **Check Box** control.

The Pelton module toolbar is located at the top of the window and includes control buttons marked with specific icons, figure 2, which fulfill the following functions:

- informative icon for the Pelton runner, without a related function;

New   - create a new database for Pelton runners;

Open   - open and load an existing database for Pelton runners;

Info   - provides information about the current database;

Data   - primary data visualization in graphic form: 3D curves and $\eta = f(n_{11}, Q_{11}, S)$ 3D surface, respectively $\eta = f(n_{11})$ 2D curves at S parameter and S = f (Q$_{11}$);

Hill Chart - calculating and plotting of the hill chart for a number of specified efficiencies values;

n$_{11}$ - imposing a double unit speed n$_{11}$ to calculate the characteristics' intersection $\eta = f(n_{11}, Q_{11})$ in order to determine the curve $\eta = f(Q_{11})$ respectively $\eta = f(S)$;

Q$_{11}$-n$_{11}$ - imposing a double unit speed n11 and unit discharge Q11, followed by a hill chart intersection $\eta = f(n_{11}, Q_{11})$ in order to calculate the efficiency point (Q$_{11}$, n$_{11}$);

Excel   - export results in an Excel file: input data and the numerical and graphical processing carried out;

Word   - graphics export in a Word file;

PDF   - graphics export in a PDF file;

Exit   - return to the main window of the HydroHillChart software.

The HydroHillChart - Pelton module software will be verified through calculation and a hill chart comparison for the following Pelton models which was taken from literature:

- K560 runner with a diameter D = 375 mm, 24 buckets and 6 nozzle spears with a diameter of Ø42mm; the primary data was taken from measurements performed on the [11] model, page 98; from the hill chart of Fig. 3, a matrix point was extracted for the following nozzle spear openings S=5, 10, 15, 20, 25, 30, 40 mm and imported as primary data to the HydroHillChart – Pelton module software;

- K600/461 runner with a diameter D = 450 mm, 20 buckets and 6 nozzle spears with Ø47.25 mm in diameter [12], page 31; from the hill chart of Fig. 4, a matrix point was extracted for the following nozzle spear openings S=7.5, 10, 12.5, 15, 20, 40 mm and imported as primary data to the HydroHillChart – Pelton module software;

Fig. 5, 6 and 7 show the $\eta = f(n_{11}, Q_{11})$ 3D surface, the 3D intersection curves with constant efficiency values and the hill chart for the Pelton K560 runner, generated by the HydroHillChart – Pelton module software. Fig. 11 shows the HydroHillChart comparison for the Pelton K560 runner.

Fig. 8, 9 and 10 show the $\eta = f(n_{11}, Q_{11})$ 3D surface, the 3D intersection curves with constant efficiency values and the hill chart for the Pelton K600/461 runner, generated by the HydroHillChart – Pelton module software. Fig. 12 shows the HydroHillChart comparison for the Pelton K600/461 runner.
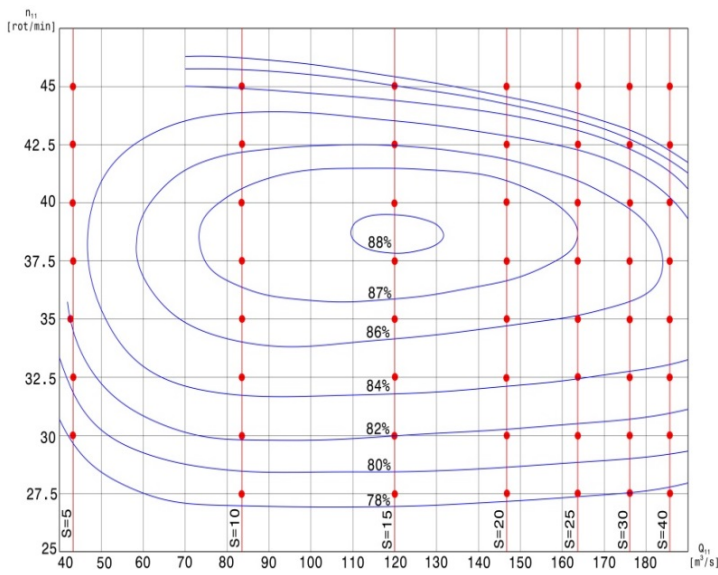
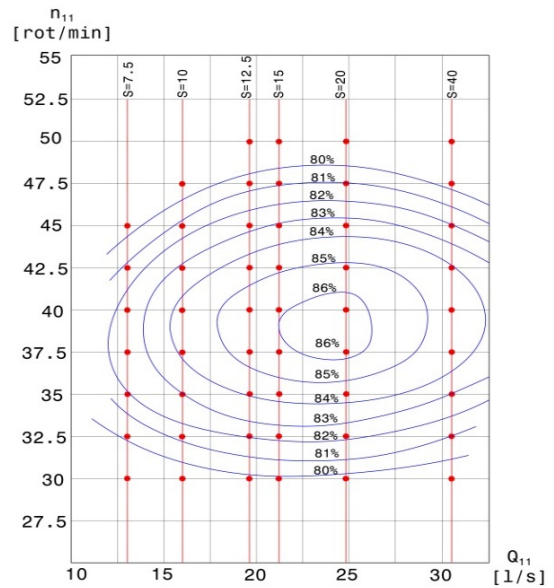**Fig. 3.** The hill chart for the Pelton K560 runner and the matrix points

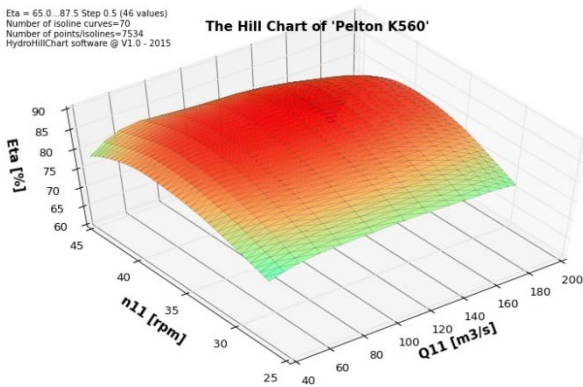**Fig. 4.** The hill chart for the Pelton K600/461 runner and the matrix points

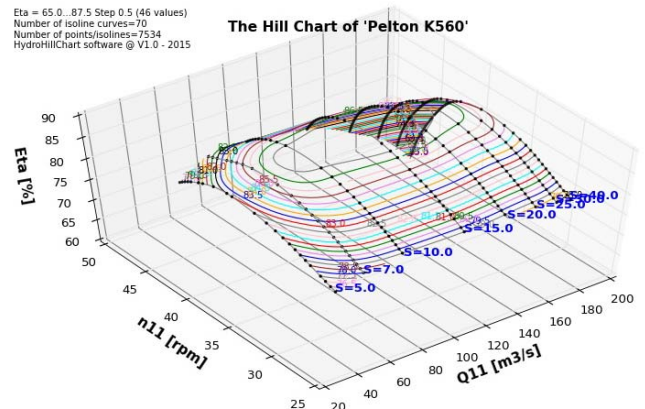**Fig. 5.** The $\eta = f(n_{11}, Q_{11})$ 3D surface for the Pelton K560 runner

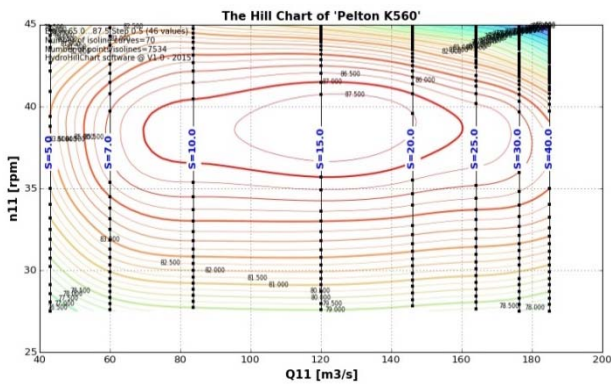**Fig. 6.** The 3D intersection curves with constant efficiency values for the Pelton K560 runner

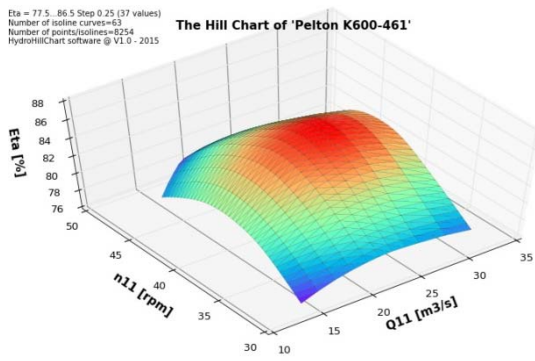**Fig. 7.** The 2D hill chart for the Pelton K560 runner calculated by using HydroHillChart

Fig. 8. The $\eta = f(n_{11}, Q_{11})$ 3D surface
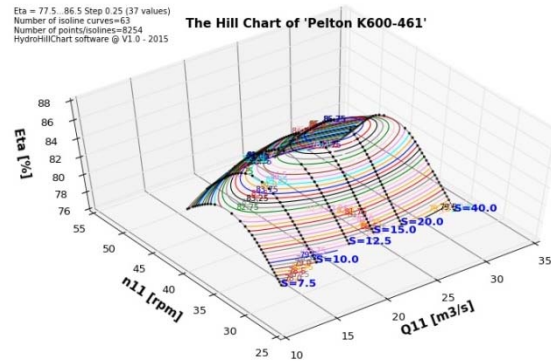
For the Pelton K600/461 runner

Fig. 9. The 3D intersection curves with constant efficiency values for the Pelton K600/461 runner
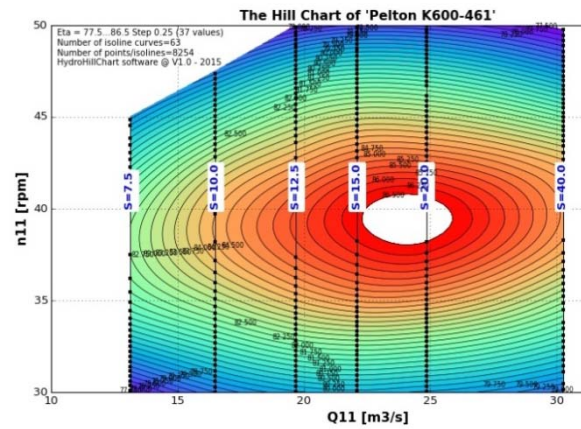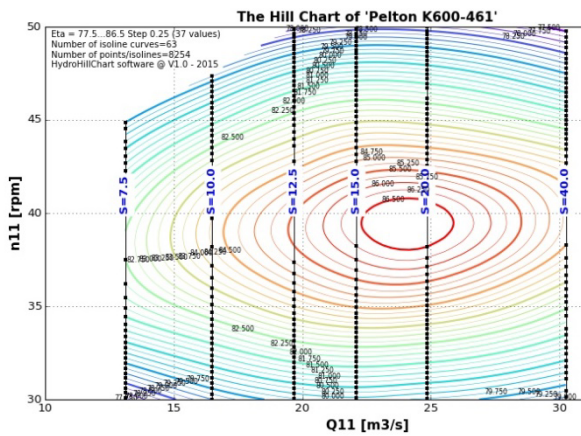

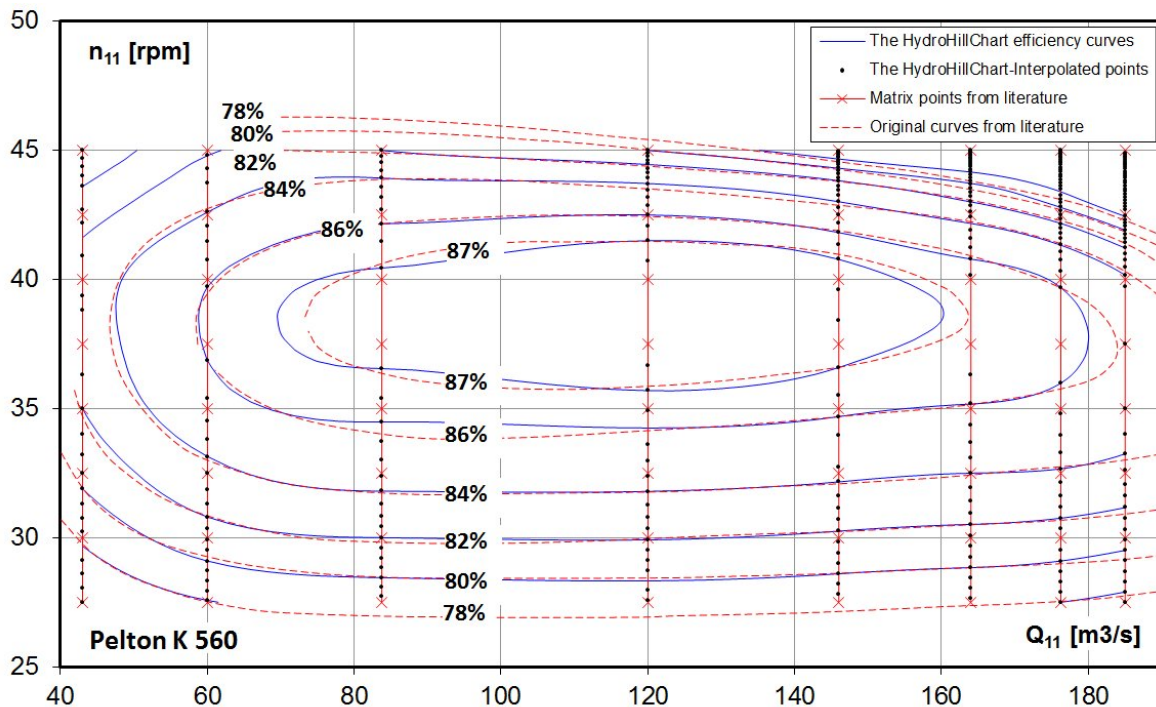**Fig. 10.** The 2D hill chart for the Pelton K600/461 runner calculated by using HydroHillChart

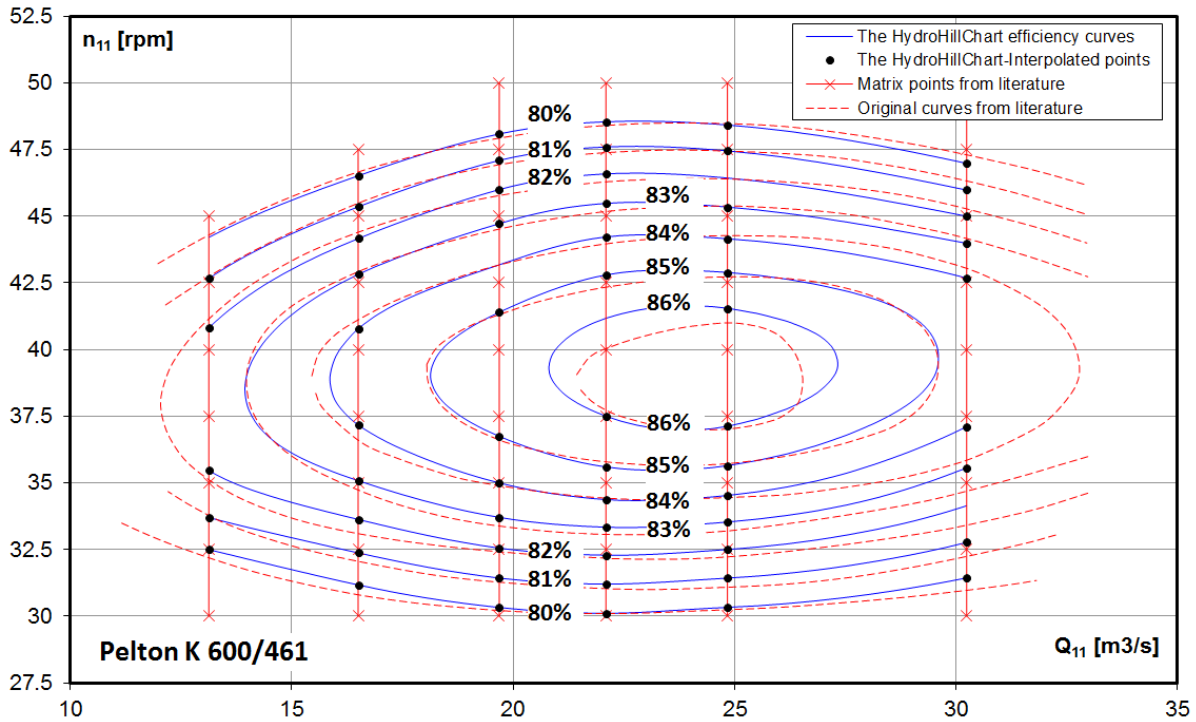**Fig. 11.** The 2D hill chart comparison for the Pelton K560 runner

Fig. 12. The 2D hill chart comparison for the Pelton K600/461 runner

4. HydroHillChart – Francis module

The Francis module [9], [10] can be selected from the "Francis Turbine" option of the main menu and it displays a window with a specific interface, Fig. 13, composed of: a toolbar, a measured data table, called "Measured Points", which stores measured data for a model runner and a table called "Intersection with efficiency constant values", where the application stores values arising from the intersection of primary curves with constant efficiency values.
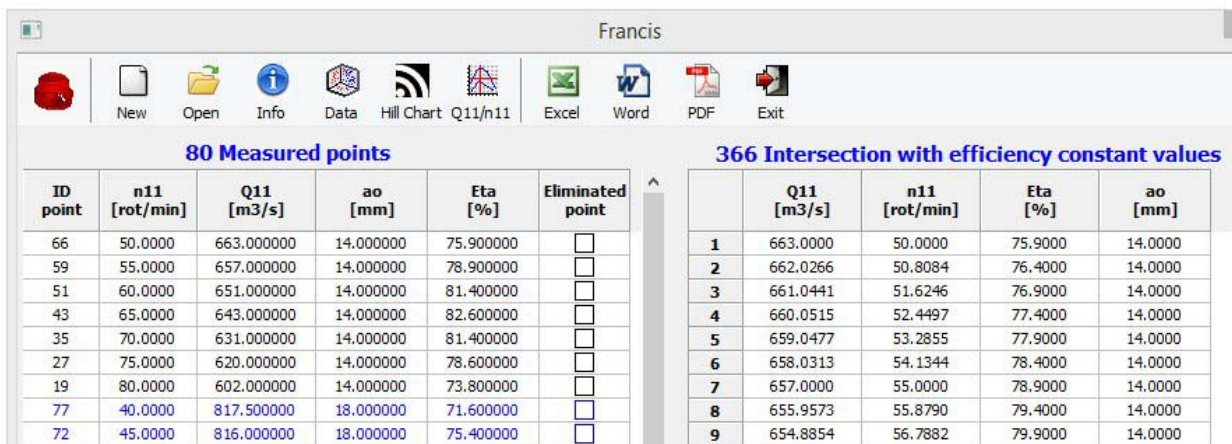

Fig. 13. The HydroHillChart interface for the Francis module

The Francis module toolbar is located at the top of the window and includes control buttons marked with specific icons, which fulfill functions similar to those of the Pelton module. The primary data is similar to the Pelton module, with the exception of ao [mm], which represents the wicked gate opening and replaces the S parameter. For a Francis turbine model, measurements can be performed by using the following parameters a_o=const., wicked gate opening, or n_{11}=const., unit speed. Although the input data fields are identical, for all measurement scenarios, graphic representation and calculation algorithms differ for the two scenarios. The resulting curves are

different, but if the interpolations are precise enough, the hill chart should coincide. Thereby, for a data set where the matrix point (n_{11}, Q_{11}, a_o, η) is at the intersection of a a_o=const. range of values with a n_{11}=const. range of values, the hill chart, which arises from the primary data considered to be measured at a_o=const., should overlap with the one which arises from the primary data considered to be measured at n_{11}=const. An example of the comparison is presented in Fig. 14. As shown in the figure, the difference between the isolines is insignificant and that validates the interpolation algorithms used to calculate the hill chart with the HydroHillChart software.
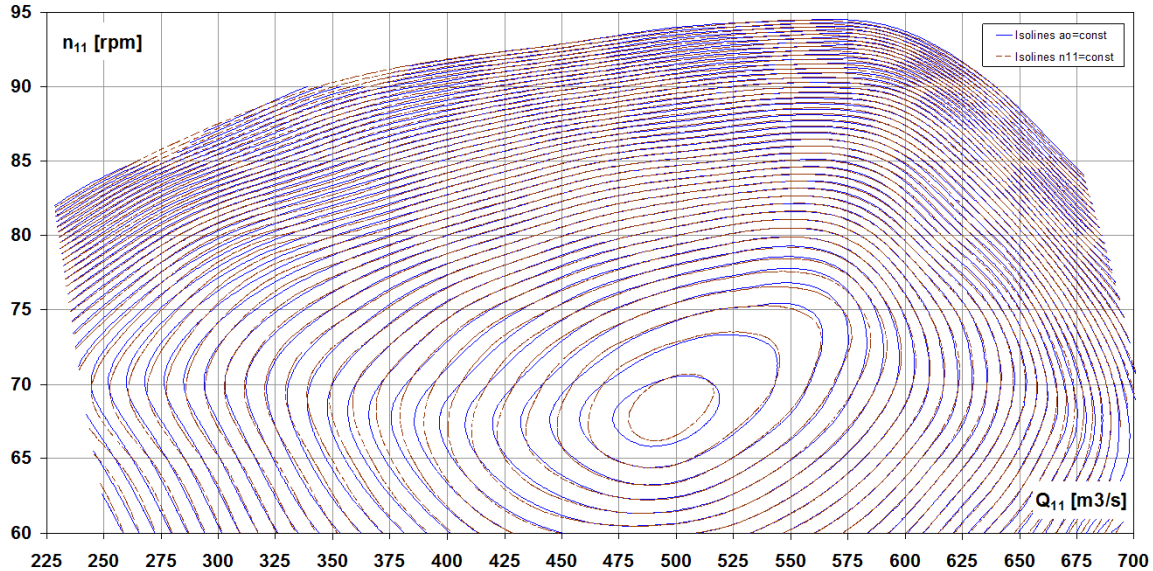

Fig. 14. The 2D hill chart comparison for a_o / n_{11}=const. scenarios

The HydroHillChart - Francis module software will be verified through calculation and a hill chart comparison for the following Francis models which was taken from literature:

- F316.5 runner with a diameter D = 460 mm and 14 runner blades; the primary data was taken from measurements performed on the [13] model, page 68; from the hill chart of Fig. 15, a matrix point was extracted for the following wicked gate openings: a_o=14, 18, 22, 26, 30, 34, 38, 42, 46, 50 mm and imported as primary data to the HydroHillChart – Francis module software;

- RO 115 runner with a diameter D = 460 mm and 13 runner blades; the primary data was taken from measurements performed on the [12] model, page 69; from the hill chart of Fig. 16, a matrix point was extracted for the following wicked gate openings : a_o=14, 18, 22, 26, 30, 34, 38, 42 mm and imported as primary data to the HydroHillChart – Francis module software;
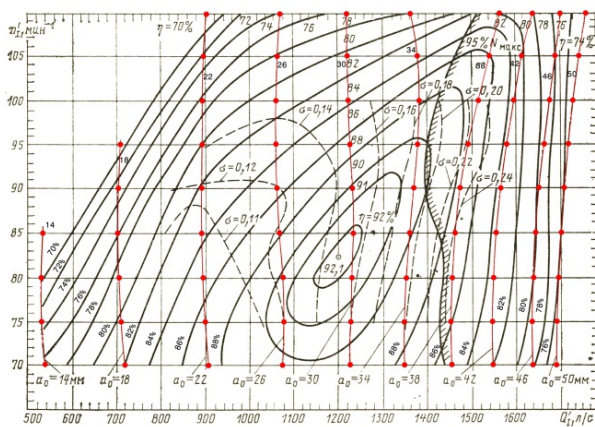
Fig. 15. The hill chart for the Francis F316.5 runner and the matrix points
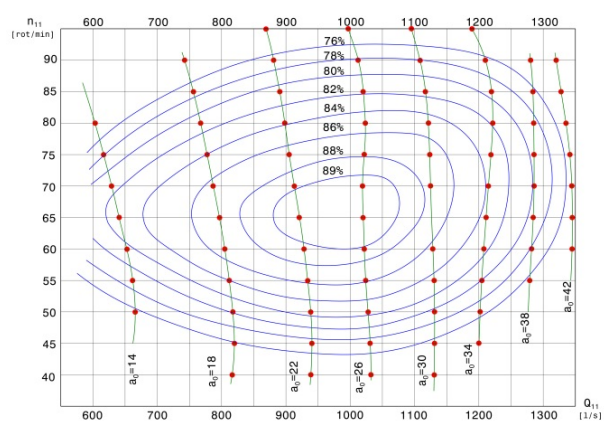
Fig. 16. The hill chart for the Francis RO 115 runner and the matrix points

Fig. 17, 18 and 19 show the $\eta = f(n_{11}, Q_{11})$ 3D surface, the 3D intersection curves with constant efficiency values and the hill chart for the Francis F316.5 runner, generated by the HydroHillChart –Francis module software. Fig. 23 shows the HydroHillChart comparison for the Francis F316.5 runner.

Fig. 20, 21 and 22 show the $\eta = f(n_{11}, Q_{11})$ 3D surface, the 3D intersection curves with constant efficiency values and the hill chart for the Francis RO 115 runner, generated by the HydroHillChart –Francis module software. Fig. 24 shows the HydroHillChart comparison for the Francis RO 115 runner.
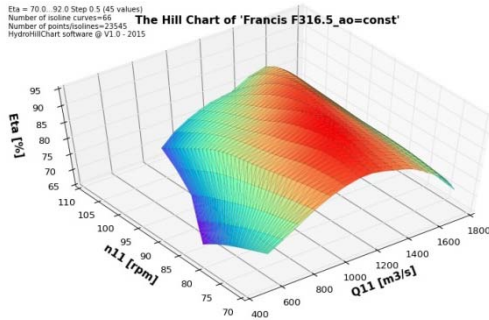

Fig. 17. The $\eta = f(n_{11}, Q_{11})$ 3D surface
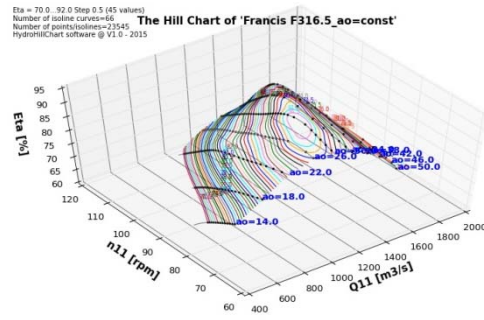
For the Francis F316.5 runner

Fig. 18. The 3D intersection curves with constant

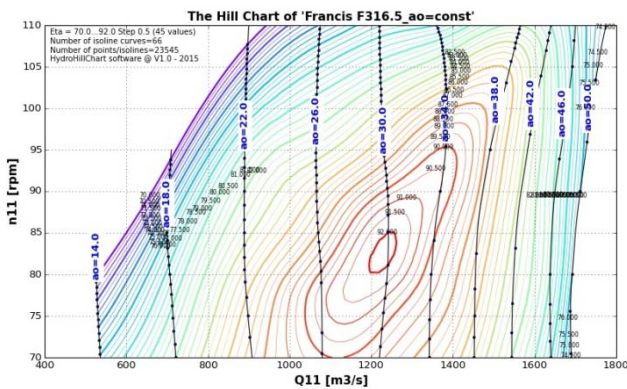efficiency values for the Francis F316.5 runner

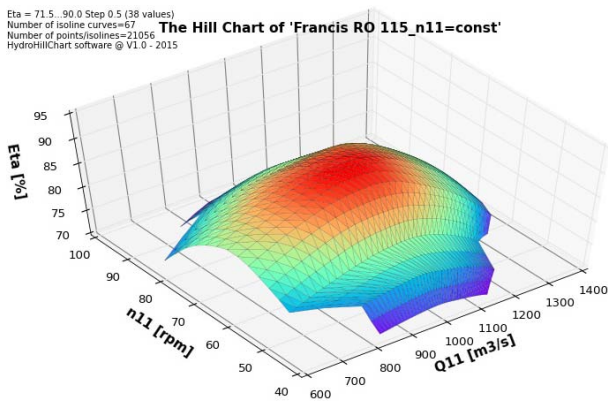**Fig. 19.** The 2D hill chart for the Francis F316.5 runner calculated by using HydroHillChart

Fig. 20. The $\eta = f(n_{11}, Q_{11})$ 3D surface

for the Francis RO 115 runner

Fig. 21. The 3D intersection curves with constant

efficiency values for the Francis RO 115 runner

Fig. 22. The 2D hill chart for the Francis RO 115 runner calculated by using HydroHillChart
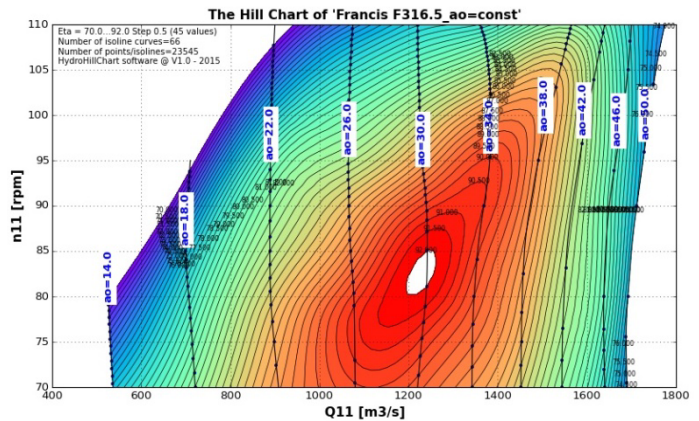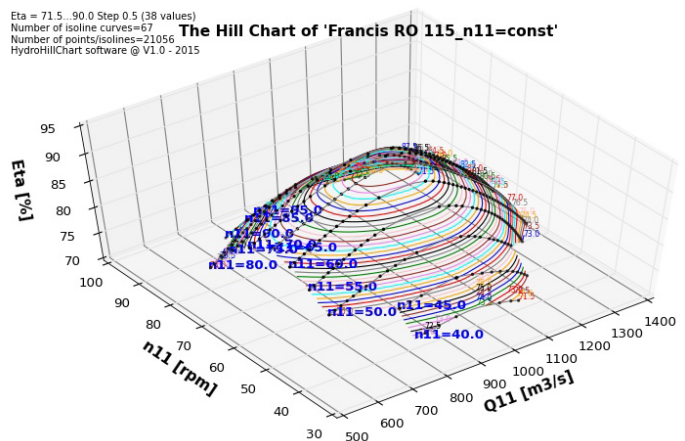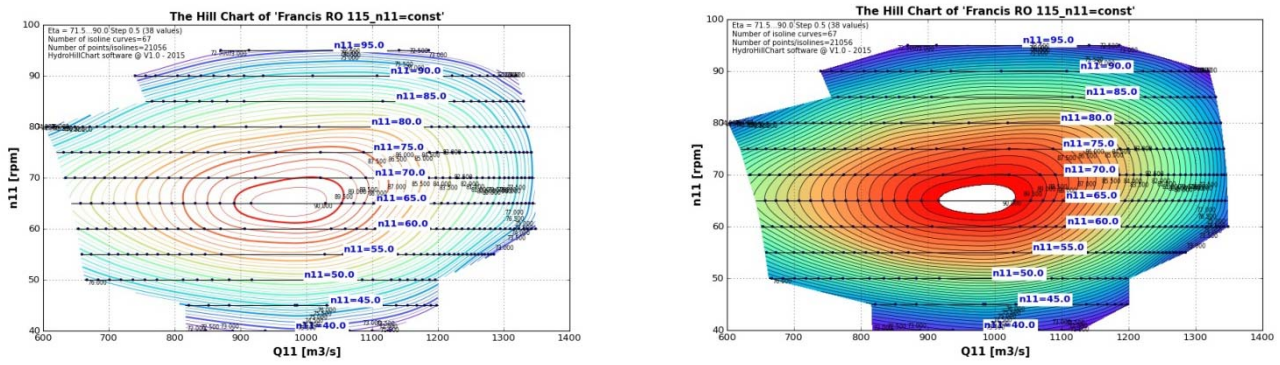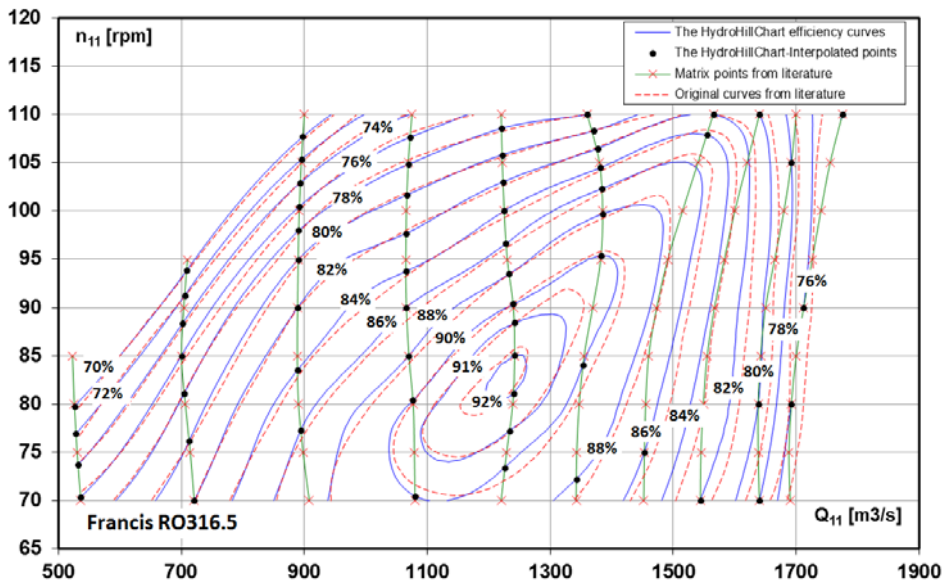

Fig. 23. The 2D hill chart comparison for the Francis F316.5 runner
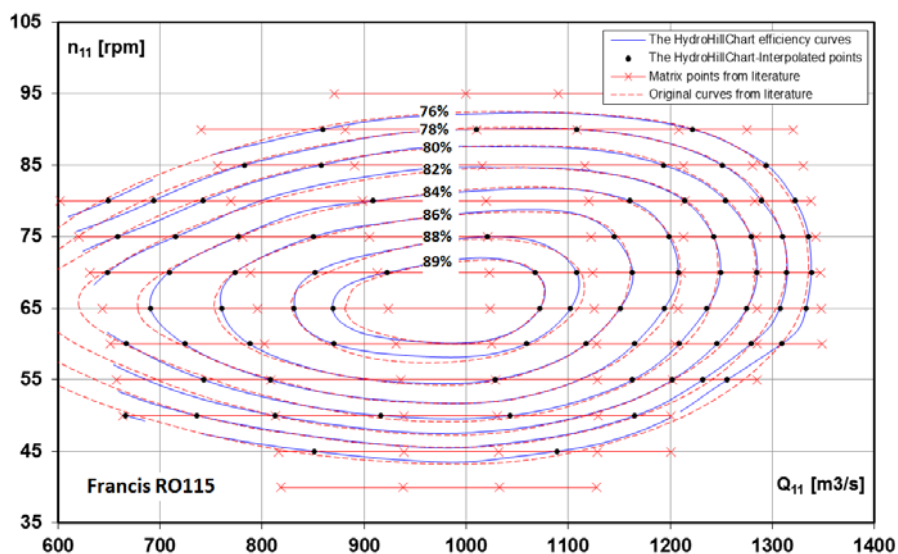

Fig. 24. The 2D hill chart comparison for the Francis RO 115 runner

5. Conclusions

Small differences between the original efficiency curves which were taken from literature and the HydroHillChart calculated curves can be observed in Fig. 11, Fig. 12, Fig. 23, Fig. 24, but the shapes are similar and the curves overlap on their longest length. Those hill charts were calculated by using different mathematical interpolation tools and by starting from different primary data: *the original efficiency curves taken from literature* were calculated by starting from the points that were measured on the turbine model; *the HydroHillChart curves* were calculated by starting from the matrix points that were extracted from the literature hill chart, Fig. 3, Fig. 4, Fig. 15, Fig. 16, which also lead to these differences. The differences can be reduced by increasing the number of matrix points extracted from the literature hill chart. HydroHillChart is a powerful software, equipped with all the necessary instruments to calculate, generate and explore the hill chart, based on the turbine model measurements, offering 2D/3D graphical and numerical results. The comparison of characteristics that were taken from literature with those calculated using the HydroHillChart software confirms the correctness of the interpolation algorithms that were used. In the future, the software will focus on the characteristics of the cavitation turbines [14].

References

[1] G. A. Aggidis*, A. Zidonis, "Hydro turbine prototype testing and generation of performance curves: Fully automated approach", Renewable Energy, 71, 2014, pp 433-441;

[2] D. Nedelcu, C.V. Campian, "Software for Computing of the Hydraulic Turbines Characteristics", The 6th International Conference on Hydraulic Machinery and Hydrodynamics, Timisoara, Romania, October 21 - 22, 2004, pp 137-142;

[3] D. Nedelcu, "Numerical Methodology for Computing the Hydraulic Turbine Hill Chart", Proceedings of the Workshop on Numerical Methods in Fluid Mechanics and Fluent Applications, Timişoara, May 22-23, 2003, pp. 179-186;

[4] A. Ghican (Bostan),"Contributions regarding the improving of experimental measurement methods and processing the results on the test rig for hydraulic turbine models", PhD Thesis, PhD Supervisor Prof. D. Nedelcu, "Eftimie Murgu" University of Reşiţa, 2015;

[5] D. Nedelcu, "Voice commands of a 2D graph", SISOM 2010 and Session of the Commission of Acoustics, Bucharest, May 27-28, 2010;

[6] J. D. Hunter, "Matplotlib. A 2D graphics environment", Computing In Science & Engineering, Vol. 9, No. 3, pp. 90-954, Publisher IEEE COMPUTER SOC., 2007.

[7] D. Nedelcu, A. Ghican (Bostan), F. Periş-Bendu, "HydroHillChart - Pelton module. Software for calculating universal characteristic of Pelton hydraulic turbines", "Eftimie Murgu" University Annals, Year XXI, No. 1, ISSN 1453 - 7397, Reşiţa, 2015;

[8] A. Ghican (Bostan), D., Nedelcu, F. Periş-Bendu, "Calculation of universal characteristics for Pelton runner models using the HydroHillChart - Pelton module software","Eftimie Murgu" University Annals", Year XXI, No. 1, ISSN 1453 - 7397, Reşiţa, 2015;

[9] D., Nedelcu, A. Ghican (Bostan), F. Periş-Bendu, "HydroHillChart – Francis module. Software for calculating universal characteristic of Francis hydraulic turbines","Eftimie Murgu" University Annals, Year XXI, No. 1, ISSN 1453 - 7397, Reşiţa, 2015;

[10] A. Ghican (Bostan), D., Nedelcu, F. Periş-Bendu, "Calculation of universal characteristics for Francis runner models using the HydroHillChart - Francis module software"Eftimie Murgu" University Annals, Year XXI, No. 1, ISSN 1453 - 7397, Reşiţa, 2015;

[11] Iu.U. Edel, "Turbine hidraulice Pelton. Teorie, cercetare, calcule" (Russian translation), Masghiz Publisher, Moscova, 1963;

[12] N. N. Kovalev, "Turbine hidraulice. Construcţii şi probleme de proiectare", (Russian translation), Maşinostroienie Publisher, Leningrad, 1971;

[13] D.S. Shavelev, "Echipament hidroenergetic şi auxiliar de la centralele hidroelectrice", (Russian translation), Vol. 1, Energoizdat Publisher, Moscova, 1988;

[14] I. Bordeiaşu, M.O. Popoviciu, "Cavitation erosion resistance for a set of stainless steels having 10% Nickel and variable Chromium concentrations", Revista Hidraulica, no. 1/ 2013, pp. 79-85.