

The Calculation of the Kaplan Turbine Hill Chart Using the HydroHillChart Software

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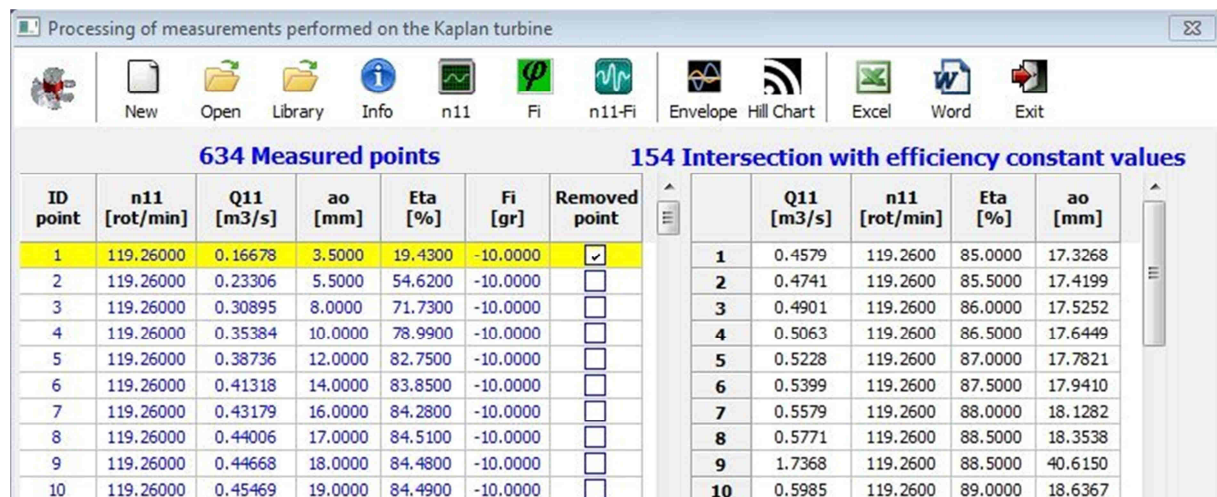
Abstract. The HydroHillChart software is a complex one used to calculate and plot the hill chart for Pelton [1], [2] Francis [3], [4] and Kaplan turbines [5]. The application was developed in the Python programming language, while the mathematical tool used for interpolation is the cubic spline type function. The paper presents the Hydro Hill Chart - Kaplan module application, used to calculate the hill chart of the Kaplan hydraulic turbine models, by processing the data measured on the test rig. The hill chart expresses graphically the functional dependence of the Kaplan turbine parameters (n_{11} , Q_{11} , a_0 , ϕ , η) and is the instrument on which the industrial turbine is designed. This dependence arises from extensive experimental research carried out on Kaplan turbine models, leading to a library of optimized characteristics for the specific flows and heads of these turbines types.

1. Introduction

The Kaplan turbine operates with mobile blades of the wicket gate and the runner based on an optimal correlation between the opening of the wicket gate and runner blades. The paper describes the HydroHillChart application - Kaplan module, designed for the calculation of the hill chart for Kaplan hydraulic turbine models, by processing the measured data on the test rig. The Kaplan module interface and menu are also described, input data are presented graphically and helical characteristics are calculated for each runner blade " ϕ " position, ultimately getting the hill chart of the model. This diagram is the basis for calculating the optimal correlation between the opening of the wicket gate and runner blades. Because the entire turbine operating range cannot be explored through measurements, the measurements are punctually made at a constant parameter and from the parametric curve interpolation, the hill chart of the model arises. The HydroHillChart application - Kaplan module is a computer tool specialized in obtaining the hill chart diagram using cubic spline interpolation functions. Based on measurements made on several Kaplan turbine models, it can be a computerized library usable in the design of Kaplan industrial turbines. The application was developed in the Python programming language, while the mathematical tool used for interpolation is the cubic spline type function.

2. The Kaplan module

The Kaplan turbine option from the main menu displays a window with a specific Kaplan module interface, (Fig.1), composed of: toolbar, measured data table called **Measured points** (in which measured data for a model runner is loaded) and the table called **Intersection with efficiency constant values** (where the application stores values that result from the intersection of primary curves with constant efficiency).



The screenshot shows a software window titled "Processing of measurements performed on the Kaplan turbine". It features a toolbar with icons for New, Open, Library, Info, n11, Fi, n11-Fi, Envelope, Hill Chart, Excel, Word, and Exit. Below the toolbar are two data tables.

ID point	n11 [rot/min]	Q11 [m3/s]	ao [mm]	Eta [%]	Fi [gr]	Removed point
1	119.26000	0.16678	3.5000	19.4300	-10.0000	<input checked="" type="checkbox"/>
2	119.26000	0.23306	5.5000	54.6200	-10.0000	<input type="checkbox"/>
3	119.26000	0.30895	8.0000	71.7300	-10.0000	<input type="checkbox"/>
4	119.26000	0.35384	10.0000	78.9900	-10.0000	<input type="checkbox"/>
5	119.26000	0.38736	12.0000	82.7500	-10.0000	<input type="checkbox"/>
6	119.26000	0.41318	14.0000	83.8500	-10.0000	<input type="checkbox"/>
7	119.26000	0.43179	16.0000	84.2800	-10.0000	<input type="checkbox"/>
8	119.26000	0.44006	17.0000	84.5100	-10.0000	<input type="checkbox"/>
9	119.26000	0.44668	18.0000	84.4800	-10.0000	<input type="checkbox"/>
10	119.26000	0.45469	19.0000	84.4900	-10.0000	<input type="checkbox"/>

	Q11 [m3/s]	n11 [rot/min]	Eta [%]	ao [mm]
1	0.4579	119.2600	85.0000	17.3268
2	0.4741	119.2600	85.5000	17.4199
3	0.4901	119.2600	86.0000	17.5252
4	0.5063	119.2600	86.5000	17.6449
5	0.5228	119.2600	87.0000	17.7821
6	0.5399	119.2600	87.5000	17.9410
7	0.5579	119.2600	88.0000	18.1282
8	0.5771	119.2600	88.5000	18.3538
9	1.7368	119.2600	88.5000	40.6150
10	0.5985	119.2600	89.0000	18.6367

Figure 1. The interface of Kaplan module

The measured data is taken from Excel and placed in the table called **Measured points**, by completing the following fields:

- **ID point** - represents the current number for the measured point;
- **n₁₁ [rot/min]** - represents the unitary speed;
- **Q₁₁ [m³/s]** - represents the unitary flow;
- **a_o [mm]** - represents the wicket gate opening;
- **Eta=η [%]** - represents the efficiency;
- **Fi [gr]** - represents the angular opening of the runner blades;
- **Removed point** – allows the removal of a measured point, by selecting a **Check Box**.

3. The Kaplan module toolbar

The Kaplan module toolbar is located at the top of the window and includes control buttons marked with specific icons, (Fig.1), which fulfill the following functions:



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



New - create a new database for Kaplan runners; the following information need to be completed: turbine type name, database filename, the period when the measurements took place, the person responsible for the performed measurements, additional information; the measurement values are taken from an Excel file.



Open - opening and loading an existing database for Kaplan runners; after this operation, the **Measured points** table, (Fig.1), will be emptied and then rewritten with the values from the selected database.



Library - to open a Kaplan database from the saved library;



Info - provides information about the current database; turbine type name, database filename, the period when the measurements took place, the person responsible for the performed measurements, the file from which the measured data was taken, number of measured and eliminated points, the minimum and maximum values for unitary speed, unitary flow, efficiency, wicket gate and blade runner opening;



n11 - primary data visualization in graphic form for $n_{11}=\text{const}$: 3D curves $\eta = f(n_{11}, Q_{11})$ and $a_o = f(n_{11}, Q_{11})$, respectively 2D parametric curves $\eta = f(Q_{11})$ and $a_o = f(Q_{11})$, (Fig.2), (Fig.3), (Fig.4), (Fig.5);



Fi - primary data visualization in graphic form for $\phi=\text{const}$: 3D curves $\eta = f(n_{11}, Q_{11})$ and $a_o = f(n_{11}, Q_{11})$, respectively 2D parametric curves $\eta = f(Q_{11})$ and $a_o = f(Q_{11})$, (Fig.6), (Fig.7), (Fig.8), (Fig.9);



n11-Fi - primary data visualization in graphic form for $n_{11}=\text{const}$ & $\phi=\text{const}$: 3D curves $\eta = f(n_{11}, Q_{11})$ and $a_o = f(n_{11}, Q_{11})$, respectively 2D parametric curves $\eta = f(Q_{11})$ and $a_o = f(Q_{11})$;



Envelope - calculating the envelope for $n_{11}=\text{const}$ value;



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



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



Word - graphics export in a Word file;



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

4. The Graphics Toolbar

For each graph generated by the **HydroHillChart** software, at the bottom of the window, a toolbar with command buttons marked with specific icons can be found, which perform the following functions:



Home - Return to initial view;



Back - Back to previous view;



Forward - Forward to the next view;



Pan - Left click and hold to zoom, zoom in/out with the right mouse button pressed;



Zoom - Enlarge selected area;



Subplots - Chart configuration;



Save - Save chart format: EPS; JPG, PGF, PDF; PNG, PS; RAW, SVG, TIF.

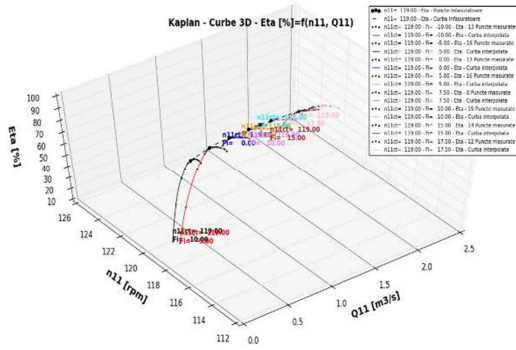


Figure 2. $\eta = f(n_{11}, Q_{11})$ at $n_{11}=119$ rpm

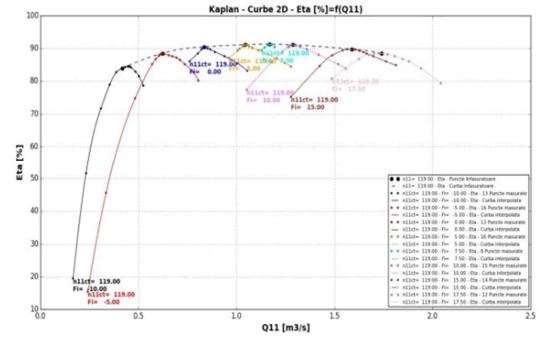


Figure 3. $\eta = f(Q_{11})$ at $n_{11}=119$ rpm

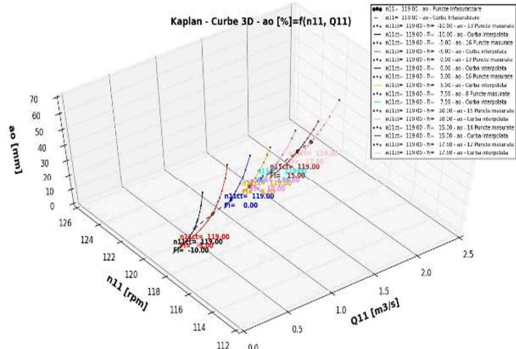


Figure 4. $a_o = f(n_{11}, Q_{11})$ at $n_{11}=119$ rpm

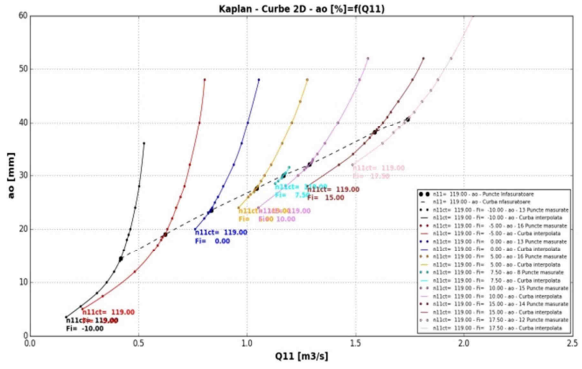


Figure 5. $a_o = f(Q_{11})$ at $n_{11}=119$ rpm

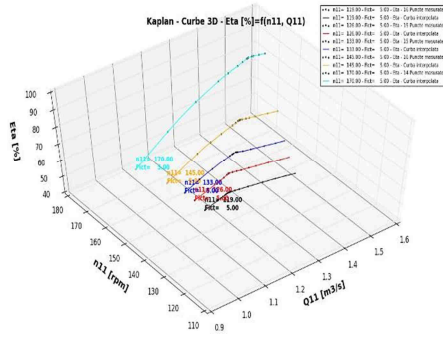


Figure 6. $\eta = f(n_{11}, Q_{11})$ at $\varphi = +5^\circ$

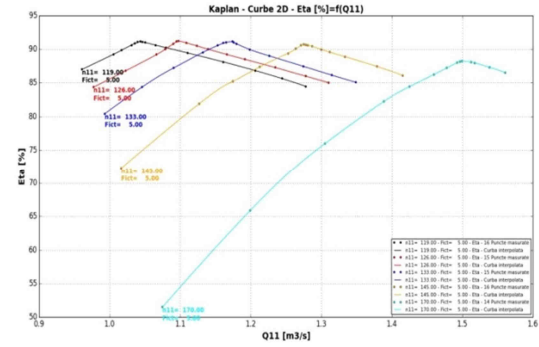


Figure 7. $\eta = f(Q_{11})$ at $\varphi = +5^\circ$

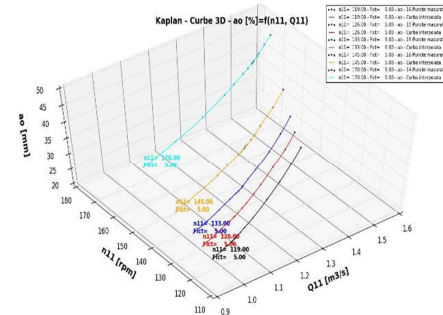


Figure 8. $a_o = f(n_{11}, Q_{11})$ at $\varphi = +5^\circ$

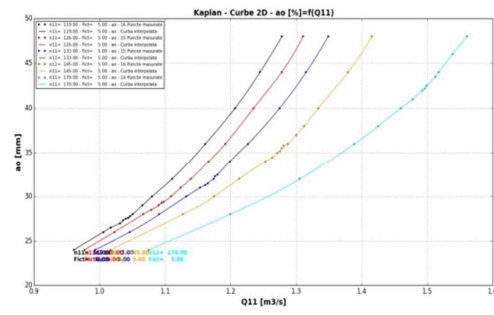


Figure 9. $a_o = f(Q_{11})$ at $\varphi = +5^\circ$

5. The Envelope option

The **Envelope** button is dedicated to generate the envelope curve for multiple runner angle positions φ at an imposed n_{11} unitary speed. For each position " φ " of the runner blades, the efficiency curves and wicket gate opening are plotted as a function of the flow rate. The further step is to trace the curve that follows the maximum points corresponding to the " φ " positions of the runner blades. Pressing the **Envelope** button opens a window whose interface is shown in (Fig.10).



Figure 10. The Envelope interface

The window is provided at the top of the screen a toolbar with command buttons marked with specific icons, which performs the following functions:



Home - Return to initial view;



Zoom - Enlarge selected area;



Pan - Left click and hold to zoom, zoom in/out with the right mouse button pressed;



Save - Save chart format: EPS; JPG, PGF, PDF; PNG, PS; RAW, SVG, TIF.



Reset - To reset the envelope curve;



Fi points - To view the points of the blade runner angle φ ;



Previous Fi - To return to the previous blade runner angle φ ;



Next Fi - To access to the next blade runner angle φ ;



Previous POINT - To select the previous point on the curve as the point of the envelope for the current blade runner φ ;



Next POINT - To select the next point on the curve as the point of the envelope for the current blade runner φ ;



Save / Exit - To save the envelope curve to Kaplan runner database;



Cancel - Exit without save the envelope curve.

Within this window is shown the envelope at the selected unitary speed n_{11} , where the point of tangency between the curve at a certain position φ of the runner blades and the envelope is initially calculated as the maximum point on the efficiency curve. This point can be changed by positioning the cursor on the efficiency curve in the location where the intersection point between the envelope and the efficiency curve will be moved. Defining the new point is done either by pressing the **Previous POINT** or **Next POINT** icon or by pressing the middle button of the mouse. The hill chart calculation for a Kaplan runner involves determining the envelope for each individual unitary speed n_{11} . The envelope generated for the unitary speed $n_{11}=119$ rpm is shown in (Fig.11). Additionally, this window shows the following curves: $\eta = f(Q_{11})$ (Fig.12), $a_o = f(Q_{11})$ (Fig.13), $\varphi = f(Q_{11})$ (Fig.14) and also the 2D / 3D envelopes for all unitary speed values, (Fig.15), (Fig.16).

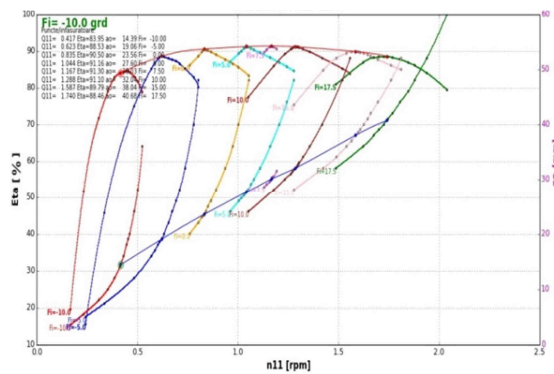


Figure 11. The envelope at $n_{11}=119$ rpm

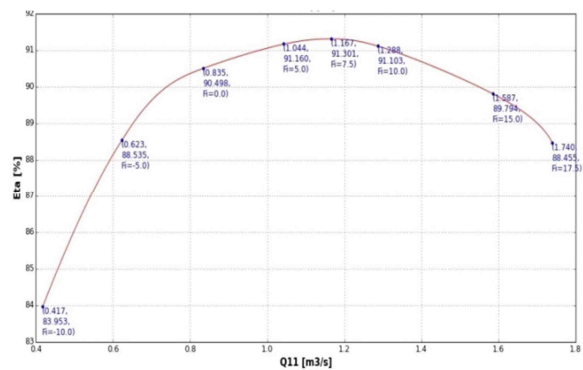


Figure 12. $\eta = f(Q_{11})$ at $n_{11}=119$ rpm

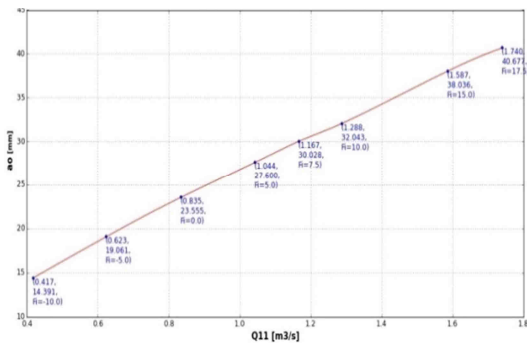


Figure 13. $a_o = f(Q_{11})$ at $n_{11}=119$ rpm

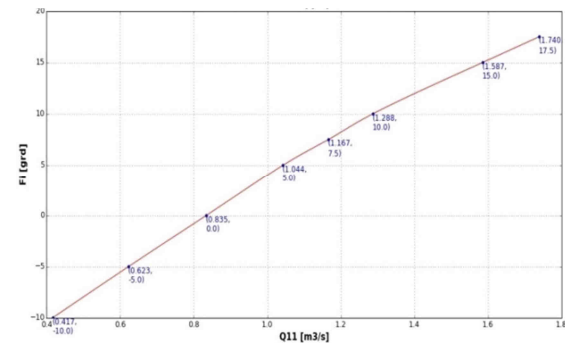


Figure 14. $\varphi = f(Q_{11})$ at $n_{11}=119$ rpm

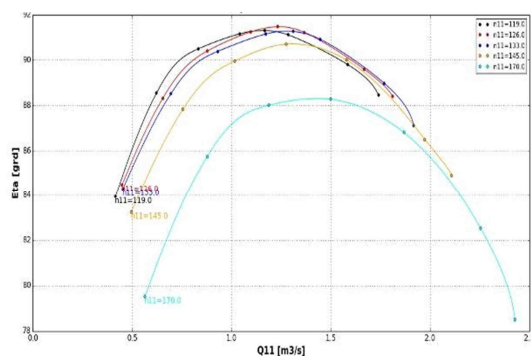


Figure 15. The 2D envelopes for Kaplan runner

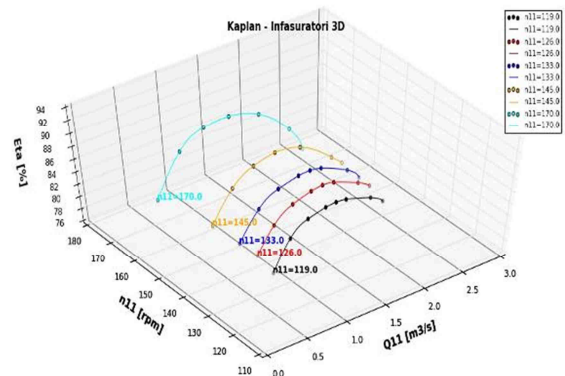


Figure 16. The 3D envelopes for Kaplan runner

6. The Hill Chart option

The **Hill Chart** button is dedicated to generate the helical or the hill chart. Accessing this button will open a window that provides information about the minimum and maximum efficiency in the current database and allows to impose the minimum, the maximum and the step efficiency, for which the helical or the hill chart will be calculated and plotted. Also in this window, particular values of intersection efficiency values can be specified and the display color scheme can be selected. The 3D surface $\eta = f(n_{11}, Q_{11})$ and the helical chart generated for blade runner angle $\varphi=17.5^\circ$ is shown in (Fig.17) and (Fig.18). The hill chart is shown in the (Fig.19) ÷ (Fig.21) as surface, 3D and 2D curves.

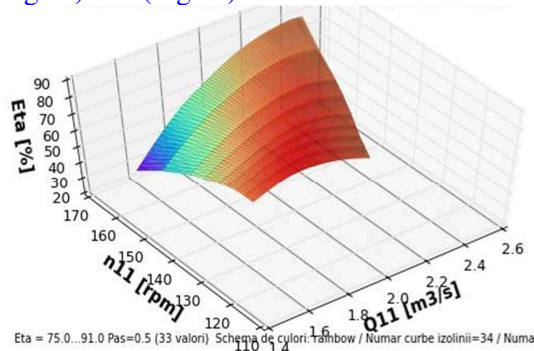


Figure 17. The 3D surface $\eta = f(n_{11}, Q_{11})$ at $\varphi=17.5^\circ$

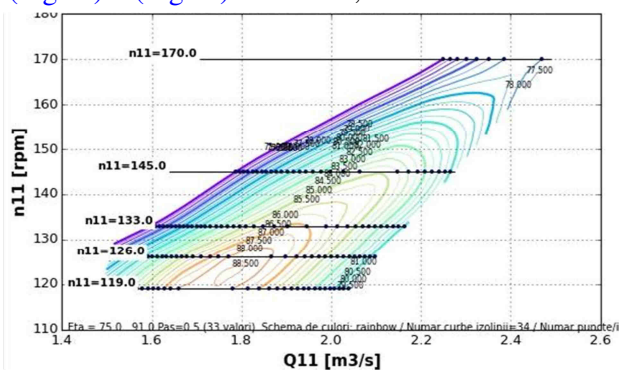


Figure 18. The helical chart $\eta = f(n_{11}, Q_{11})$ at $\varphi=17.5^\circ$

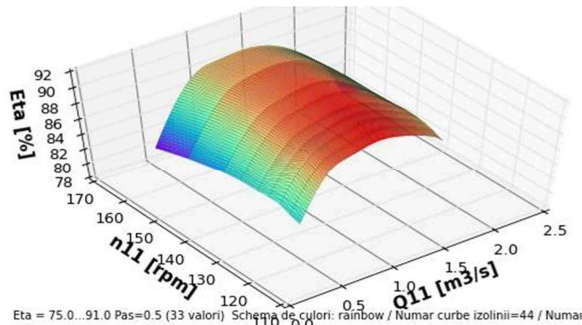


Figure 19. The 3D hill chart surface $\eta = f(n_{11}, Q_{11})$

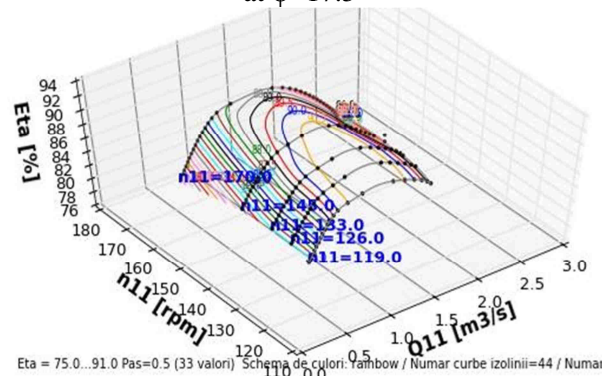


Figure 20. The 3D hill chart curves $\eta = f(n_{11}, Q_{11})$

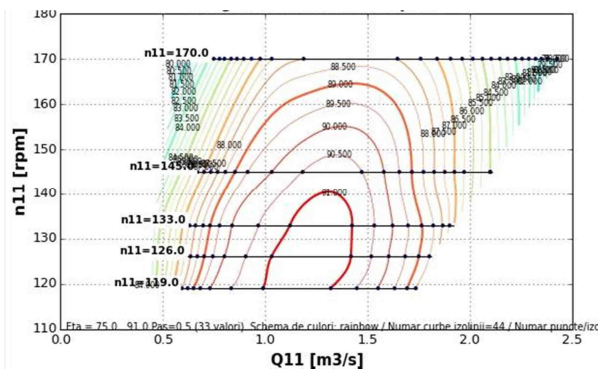


Figure 21. The 2D hill chart curves $\eta = f(n_{11}, Q_{11})$

7. Conclusions

The paper presents HydroHillChart application [6] - Kaplan module that allows the calculation of the hill chart for Kaplan hydraulic turbine models. For turbines with double settings, the tests are based on the stepwise change of the runner blade angle or the opening a_o of the wicket gate. 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 [7]. 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 [8], **matplotlib** - a python 2D plotting library which produces publication quality figures [9], **SQLite** – a database engine, **SciPy** - a Python-based ecosystem of open-source software's for mathematics, science and engineering.

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