THE OPERATION DIAGRAM CALCULUS OF HYDRAULIC TURBINES USING HYDROHILLCHART - DEX MODULE

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ABSTRACT The operation diagram is the main document of the prototype turbine exploitation, which shows the constant curves of the efficiency, wicked gate opening and power in H-Q coordinates. This diagram is obtained from the model hill chart by transposing the results from model to prototype through scale-up relations. The paper presents the DEX module, included in the HydroHillChart software and used to calculate the operation diagram.

KEYWORDS *Turbine, Hill Chart, Operation diagram, Software.*

Introduction

The paper presents the DEX module included in the Python software, called HydroHillChart [1]. The HydroHillChart software is designed to calculate the turbine model hill chart (Pelton, Francis and Kaplan) and the operation diagram (DEX) for the industrial turbine prototype, based on energetic primary data obtained through turbine model measurements on the test rig. The HydroHillChart software was created based on Python – a high-level programming software and its related modules: wxPython [2] - a graphical user interface toolkit for the Python programming language, matplotlib [3] - a python 2D plotting library which produces publication quality figures, SQLite – a database engine, SciPy - a Python-based ecosystem of open-source software for mathematics, science, and engineering. The curve interpolations are calculated with the help of cubic spline functions. The results of the software consist in graphical curves and numerical results which can be viewed in HydroHillChart and exported to Excel files with a template structure and also to Word files. The software is fitted with zooming instruments (fit, pan, zoom in, zoom out), spline curves interpolations, graph intersections with constant X or Y values, a function that saves the graph as an image file and one that modifies the general/graph setting.

1 Scale-up model efficiency from model to prototype

According to the IEC 995 standard [4], the difference between the hydraulic efficiency of two similar points A and B, of the prototype and model turbine diagram, for a different Reynolds number, is calculated with the following formulas:

$$\Delta\eta_{hA-B} = \delta_{ref} \cdot \left[\left(\frac{Re_{uref}}{Re_{uA}}\right)^{0.16} - \left(\frac{Re_{uref}}{Re_{uB}}\right)^{0.16}\right] \qquad (1)$$

$$\delta_{ref} = \frac{1-\eta_{hoptM}}{\left(\frac{Re_{uref}}{Re_{uoptM}}\right)^{0.16} + \frac{1-\nu_{ref}}{\nu_{ref}}} \qquad (2)$$

where:

- Re_{uoptM} – is the Reynolds number on the hill chart point of the turbine model, where the maximal efficiency was measured;
- $Re_u = \frac{u \cdot D}{\nu}$ (3)
- "u" is the peripheral velocity, "D" is the runner diameter and "ν" is the kinematic viscosity of the water;
- ν_{ref} – is the ratio between relative scalable losses and relative total losses, for the optimal hydraulic efficiency point at the Reynolds number equal to $Re_{uref} = 7x10^6$. For Francis turbines ν_{ref}= 0.7 and for axial or diagonal turbines (Kaplan, bulb, Deriaz) with adjustable or fixed runner and wicket gate blades: ν_{ref}= 0.8.
- $Re_{uref} = 7x10^6$.

In the effective calculus of model to prototype transposal of the hydraulic efficiency, we have the correspondence between: $Re_{uA} \Rightarrow Re_{uM}$ and $Re_{uB} \Rightarrow Re_{uP}$.

The procedure of the transposal formulas includes the following stages [5], [6]:

- obtaining, from model tests of the maximal hydraulic efficiency value η_{hoptM}, the calculus of the correspondent Reynolds number Re_{uoptM} and the δ_{ref} value with formula (2);
- the calculus of the difference between model and prototype efficiency $\Delta\eta_h$, with the help of two methods:
  - a) the model to prototype hydraulic efficiency transposal in one step;
  - b) the model to prototype hydraulic efficiency transposal in two steps;

- the calculus of the hydraulic efficiency of the prototype, for the entire guaranteed range, with the formula:

$$\eta_{hP} = \eta_{hM} + \Delta\eta_h \quad (4)$$

The hydraulic efficiency measured on the model η_{hMi} for different Reynolds numbers Re_{uMi}, are scaled-up directly to the prototype, in one step, admitting Re_{uP}=const., with formula (5). In such a manner of transposal, $\Delta\eta_{hi}$ is calculated for every Re_{uMi}.

$$\Delta\eta_{hi} = \Delta\eta_{hMi\rightarrow P} = \delta_{ref} \cdot \left[\left(\frac{Re_{uref}}{Re_{uMi}}\right)^{0.16} - \left(\frac{Re_{uref}}{Re_{uP}}\right)^{0.16} \right] \quad (5)$$

The hydraulic efficiency measured on the model η_{hMi} for different Reynolds numbers Re_{uMi}, can be scaled-up to the prototype, through the next two steps:

- in the first step, the hydraulic efficiency measured on the model η_{hMi} for different Reynolds numbers Re_{uMi}, is transposed to a constant value Re_{uM*}, preferably fixed in the domain Re_{uMi} with the formula:

$$\Delta\eta_{hMi\rightarrow M*} = \delta_{ref} \cdot \left[\left(\frac{Re_{uref}}{Re_{uMi}}\right)^{0.16} - \left(\frac{Re_{uref}}{Re_{uM*}}\right)^{0.16} \right] \quad (6)$$

- in the second step, the transposed hydraulic efficiency of the model η_{hMi}, for a constant Reynolds number Re_{uM*}, is scaled-up to the prototype, for a Reynolds number $Re_{uP}$with the formula:

$$\Delta\eta_{hM*\rightarrow P} = \delta_{ref} \cdot \left[\left(\frac{Re_{uref}}{Re_{uM*}}\right)^{0.16} - \left(\frac{Re_{uref}}{Re_{uP}}\right)^{0.16} \right] \quad (7)$$

The head, the discharge and the power of the prototype are corrected with the following formulas:

$$H_P = \left(\frac{g_M}{g_P}\right) H_M \left(\frac{n_P \cdot D_P}{n_M \cdot D_M}\right)^2 \left(\frac{\eta_{hoptM}}{\eta_{hoptP}}\right) \quad (8)$$

$$Q_P = \left(\frac{g_P}{g_M}\right)^{\frac{1}{2}} Q_M \left(\frac{H_P}{H_M}\right)^{\frac{1}{2}} \left(\frac{D_P}{D_M}\right)^2 \left(\frac{\eta_{hoptP}}{\eta_{hoptM}}\right)^{\frac{1}{2}} \quad (9)$$

$$P_P = P_M \left(\frac{\rho_P}{\rho_M}\right) \left(\frac{g_P}{g_M}\right)^{\frac{3}{2}} \left(\frac{H_P}{H_M}\right)^{\frac{3}{2}} \left(\frac{D_P}{D_M}\right)^2 \left(\frac{\eta_{hP}}{\eta_{hM}}\right) \left(\frac{\eta_{hoptP}}{\eta_{hoptM}}\right)^{\frac{1}{2}} \quad (10)$$

2 The interface of the DEX module

The operation diagram can be calculated using a number of general applications which require a considerable workload.

The DEX module [7], included in the HydroHillChart software, is dedicated to operation diagram calculus, according to the model to prototype hydraulic efficiency transposal in one step.

The DEX interface is presented in figure 1 with the following elements: the toolbar, the input data table, the calculated values table (in optimal point) and the calculated values table for the operation diagram (the range values imposed for parametrical curves of the efficiency, power and wicked gate opening).

The input data for the DEX module is presented in table 1 while the toolbar icons are presented in table 2.

The bottom of the DEX window contains a table where the application places the values of:

- the points loaded from the database with measurements ($ID\ Point, n_{11}, Q_{11}, a_o, \eta_{hM}$);
- the calculated parameters of the model (speed n_M, discharge Q_M, power P_{hM}, Reynolds number Re_{uM});
- the calculated parameters of the prototype (the efficiency difference $\Delta\eta_{hi}$, the prototype efficiency η_{hP}, head H_P, discharge Q_P, power P_P, wicked gate opening a_{oP}).

Tab. 1 The input data of DEX module

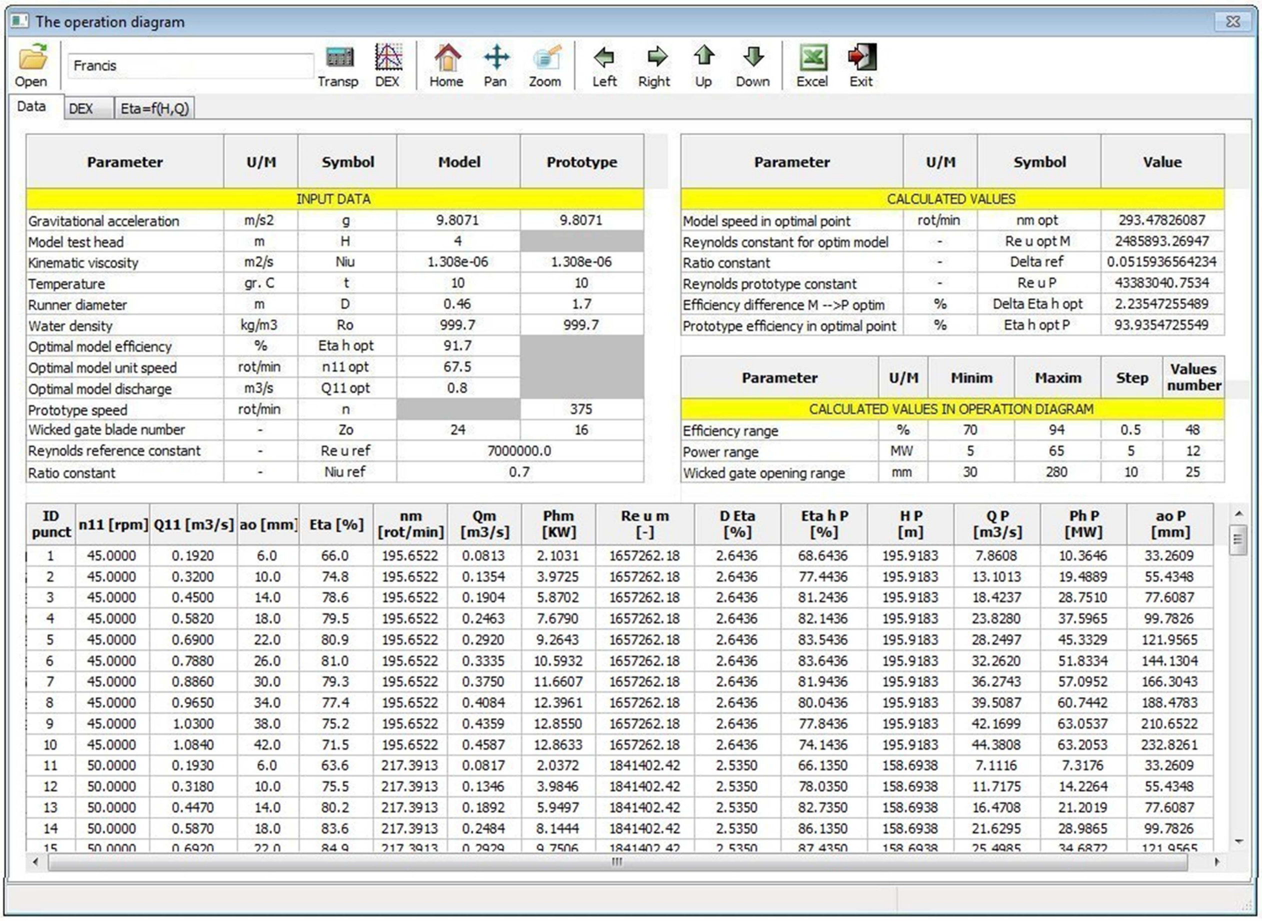
Parameter	U/M	Description
g_M, g_P	m/s^2	gravitational acceleration of the model and prototype
H_M	m	the head where measurements were made
ν_M, ν_P	-	kinematic viscosity for model and prototype
t_M, t_P	ºC	the water temperature at which the model was tested in the laboratory and the prototype water working temperature
D_M, D_P	m	the model and prototype diameter
Z_{oM}, Z_{oP}	no.	the number of wicked gate blades for model and prototype
ρ_M, ρ_P	kg/m^3	the water density of the model and prototype
η_{hoptM}	%	the optimum efficiency of the model
n_{11opt}	rpm	the optimum unit speed of the model
Q_{11opt}	m^3/s	the optimum unit discharge of the model
n_P	rpm	the speed of the prototype
Re_{uref}	-	the reference Reynolds constant = $7x10^6$
ν_{ref}	-	the ratio constant; $\nu_{ref} = 0.7$ for Francis turbine, $\nu_{ref} = 0.8$ for other type of turbines
ID point	-	the ID number of the measured point
n_{11}	rpm	the unit speed of the model
Q_{11}	m^3/s	the unit discharge of the model
a_o	mm	the wicked gate opening
η_{hM}	%	the model efficiency

Tab. 2 The toolbar icons of DEX module

Toolbar control		Description
	Open	Load an existing database with measurements
		Field reserved for the DEX name
	Transp	Button for parameters scale-up from model to prototype in one step
	DEX	Button for the operation diagram calculation
	Home	Return to initial view
	Pan	Left click & hold to zoom, zoom in/out with the right mouse button pressed
	Zoom	Enlarge selected area
	Left	Rotate to the left the 3D scale-up curves $\eta_{hP} = f(Q_P, H_P)$
	Right	Rotate to the right the 3D scale-up curves $\eta_{hP} = f(Q_P, H_P)$
	Up	Rotate up the 3D scale-up curves $\eta_{hP} = f(Q_P, H_P)$
	Down	Rotate down the 3D scale-up curves $\eta_{hP} = f(Q_P, H_P)$
	Excel	Export the results in an Excel file
	Exit	Return to the main window of the HydroHillChart software

To calculate the operation diagram, one must go through the following steps:

- load the database with model measurements ($ID\ Point, n_{11}, Q_{11}, a_o, \eta_{hM}$) by pressing the **Open** button; the values are placed in the bottom table of the DEX window;
- fill the values for the model/prototype in the input data table: g_M, g_P, H_M, ν_M, ν_P, t_M, t_P, D_M, D_P, Z_{oM}, Z_{oP}, ρ_M, ρ_P, η_{hoptM}, n_{11opt}, Q_{11opt}, n_P, Re_{uref}, ν_{ref};
- press the **Transp** button to calculate the model and prototype parameters (n_M, Q_M, P_{hM}, Re_{uM}) ($\Delta\eta_{hi}$, η_{hP}, H_P, Q_P, P_P, a_{oP});
- fill the range values imposed for the parametrical curves of the efficiency, power and wicked gate opening;
- press the **DEX** button to calculate the operation diagram, view the results and export them to an Excel file.



Parameter	U/M	Symbol	Model	Prototype
INPUT DATA				
Gravitational acceleration	m/s2	g	9.8071	9.8071
Model test head	m	H	4	
Kinematic viscosity	m2/s	Niu	1.308e-06	1.308e-06
Temperature	gr. C	t	10	10
Runner diameter	m	D	0.46	1.7
Water density	kg/m3	Ro	999.7	999.7
Optimal model efficiency	%	Eta h opt	91.7	
Optimal model unit speed	rot/min	n11 opt	67.5	
Optimal model discharge	m3/s	Q11 opt	0.8	
Prototype speed	rot/min	n		375
Wicked gate blade number	-	Zo	24	16
Reynolds reference constant	-	Re u ref	7000000.0	
Ratio constant	-	Niu ref	0.7	

Parameter	U/M	Symbol	Value
CALCULATED VALUES			
Model speed in optimal point	rot/min	nm opt	293.47826087
Reynolds constant for optim model	-	Re u opt M	2485893.26947
Ratio constant	-	Delta ref	0.0515936564234
Reynolds prototype constant	-	Re u P	43383040.7534
Efficiency difference M -->P optim	%	Delta Eta h opt	2.23547255489
Prototype efficiency in optimal point	%	Eta h opt P	93.9354725549

Parameter	U/M	Minim	Maxim	Step	Values number
CALCULATED VALUES IN OPERATION DIAGRAM					
Efficiency range	%	70	94	0.5	48
Power range	MW	5	65	5	12
Wicked gate opening range	mm	30	280	10	25

ID punct	n11 [rpm]	Q11 [m3/s]	ao [mm]	Eta [%]	nm [rot/min]	Qm [m3/s]	Phm [KW]	Re u m [-]	D Eta [%]	Eta h P [%]	H P [m]	Q P [m3/s]	Ph P [MW]	ao P [mm]
1	45.0000	0.1920	6.0	66.0	195.6522	0.0813	2.1031	1657262.18	2.6436	68.6436	195.9183	7.8608	10.3646	33.2609
2	45.0000	0.3200	10.0	74.8	195.6522	0.1354	3.9725	1657262.18	2.6436	77.4436	195.9183	13.1013	19.4889	55.4348
3	45.0000	0.4500	14.0	78.6	195.6522	0.1904	5.8702	1657262.18	2.6436	81.2436	195.9183	18.4237	28.7510	77.6087
4	45.0000	0.5820	18.0	79.5	195.6522	0.2463	7.6790	1657262.18	2.6436	82.1436	195.9183	23.8280	37.5965	99.7826
5	45.0000	0.6900	22.0	80.9	195.6522	0.2920	9.2643	1657262.18	2.6436	83.5436	195.9183	28.2497	45.3329	121.9565
6	45.0000	0.7880	26.0	81.0	195.6522	0.3335	10.5932	1657262.18	2.6436	83.6436	195.9183	32.2620	51.8334	144.1304
7	45.0000	0.8860	30.0	79.3	195.6522	0.3750	11.6607	1657262.18	2.6436	81.9436	195.9183	36.2743	57.0952	166.3043
8	45.0000	0.9650	34.0	77.4	195.6522	0.4084	12.3961	1657262.18	2.6436	80.0436	195.9183	39.5087	60.7442	188.4783
9	45.0000	1.0300	38.0	75.2	195.6522	0.4359	12.8550	1657262.18	2.6436	77.8436	195.9183	42.1699	63.0537	210.6522
10	45.0000	1.0840	42.0	71.5	195.6522	0.4587	12.8633	1657262.18	2.6436	74.1436	195.9183	44.3808	63.2053	232.8261
11	50.0000	0.1930	6.0	63.6	217.3913	0.0817	2.0372	1841402.42	2.5350	66.1350	158.6938	7.1116	7.3176	33.2609
12	50.0000	0.3180	10.0	75.5	217.3913	0.1346	3.9846	1841402.42	2.5350	78.0350	158.6938	11.7175	14.2264	55.4348
13	50.0000	0.4470	14.0	80.2	217.3913	0.1892	5.9497	1841402.42	2.5350	82.7350	158.6938	16.4708	21.2019	77.6087
14	50.0000	0.5870	18.0	83.6	217.3913	0.2484	8.1444	1841402.42	2.5350	86.1350	158.6938	21.6295	28.9865	99.7826
15	50.0000	0.6920	22.0	84.9	217.3913	0.2929	9.7506	1841402.42	2.5350	87.4350	158.6938	25.4985	34.6872	121.9565

Fig. 1 The DEX interface.

3 The operation diagram calculation for Francis model

This chapter presents two operation diagrams, known as O1 and O2, calculated for different input data, based on the same Francis model experimental points, measured for n_{11}=const. The following representations, generated with the HydroHillChart – Francis module [8], [9], are presented for the selected Francis model:

- figure 2 presents the 3D curves $\eta_M = f(Q_{11}, n_{11})$ for a unit speed constant parameter n_{11} ;
- figure 3 presents the $\eta_M = f(Q_{11}, n_{11})$ surface;
- figure 4 presents the model hill chart – 2D curves plot;
- figure 5 presents the model hill chart – 2D contour plot;
- figure 6 presents the model hill chart – 3D curves plot.

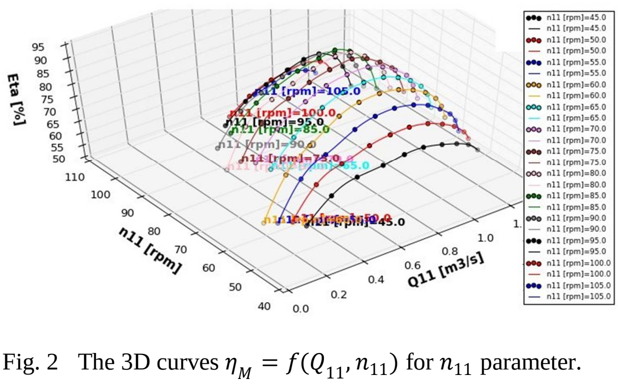


Fig. 2 The 3D curves $\eta_M = f(Q_{11}, n_{11})$ for n_{11} parameter.

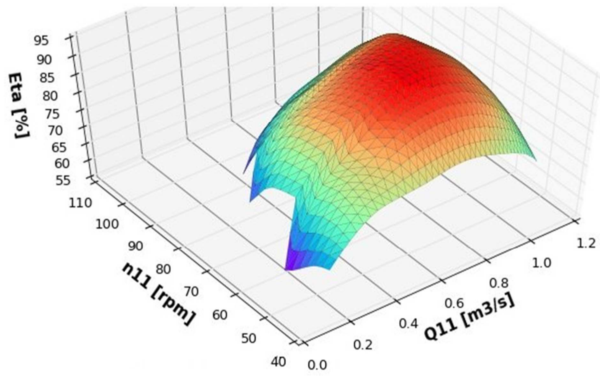


Fig. 3 The $\eta_M = f(Q_{11}, n_{11})$ surface.

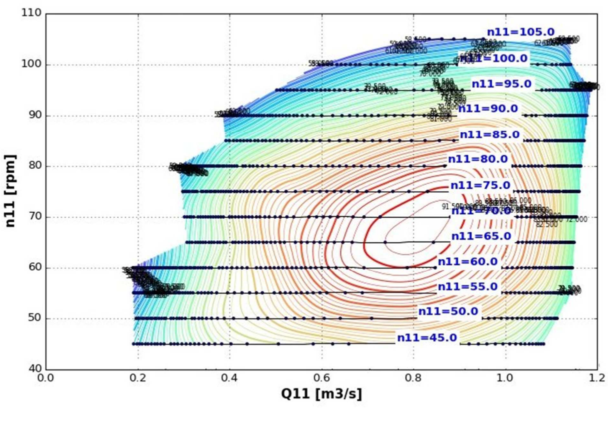


Fig. 4 The model hill chart – 2D curves plot.

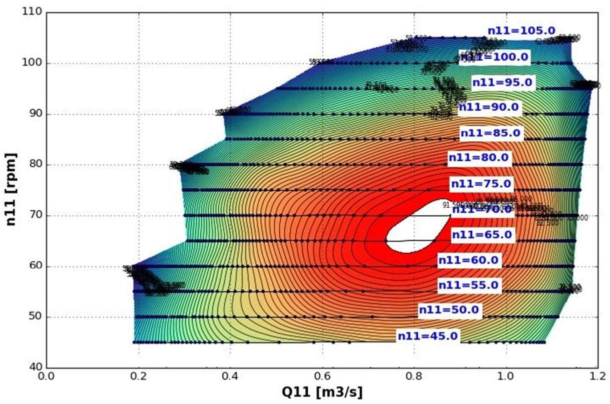


Fig. 5 The model hill chart – 2D contour plot.

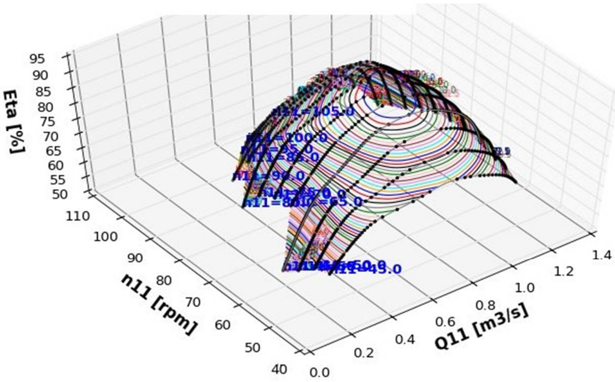


Fig. 6 The model hill chart – 3D curves plot.

The parameters for the calculation of the operation diagram O1 & O2 are presented numerically in table 3.

Tab. 3 The operation diagram parameters

Parameter	U/M	Model		Prototype		
		Sym-bol	Values	Sym-bol	O1 Values	O2 Values
Gravitational acceleration	m/s^2	g_M	9.807	g_P	9.807	9.807
Measurement head	m	H_M	4	-	-	-
Kinematic viscosity	-	ν_M	1.308 x 10^6	ν_P	1.308 x 10^6	1.308 x 10^6
Temperature	^{o}C	t_M	10	t_P	10	10
Runner diameter	m	D_M	0.46	D_P	1.7	1.06
The wicked gate blade	no.	Z_{oM}	24	Z_{oP}	16	16
Water density	kg/m^3	ρ_M	999.7	ρ_P	999.7	999.7
Optimum efficiency	%	η_{hoptM}	92.4	-	-	-
Optimum unit speed	rpm	n_{11opt}	67.5	-	-	-
Optimum unit discharge	m^3/s	Q_{11opt}	0.8	-	-	-
Speed of the prototype	rpm	-	-	n_P	375	600
Reynolds constant	-	Re_{uref}	$7\ x\ 10^6$			
The ratio constant	-	ν_{ref}	0.7			

Through the scale-up operation (**Transp** button), the 3D curves $\eta_M, P_{hM,} a_{oM} = f(Q_{11}, n_{11})$ of the model are transposed to prototype 3D curves: $\eta_{hP} = f(Q_P, H_P)$, figure 7, $P_{hP} = f(Q_P, H_P)$, $a_{oP} = f(Q_P, H_P)$.

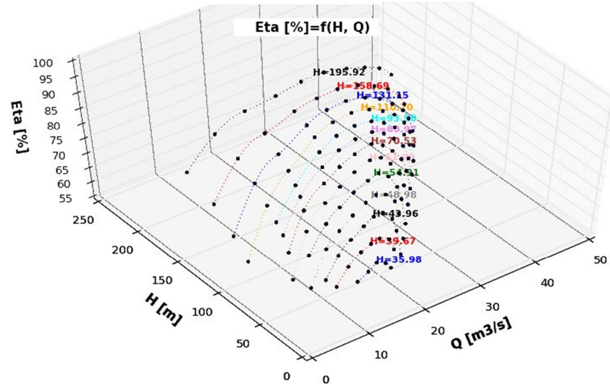


Fig. 7 The scale-up 3D curves $\eta_{hP} = f(Q_P, H_P)$.

By intersecting the prototype 3D curves $\eta_{hP}, P_{hP}, a_{oP} = f(Q_P, H_P)$ with constant values (**DEX** button), the DEX module calculates the operation diagrams O1 & O2 presented in figures 8 and 9.

The optimal points of the calculated operation diagrams O1 & O2 are presented in table 4.

Tab. 4 The optimal points of the operation diagram O1 & O2

Parameter	D_P	n_P	H_P	Q_P	η_P	P_P
UM	m	rpm	m	m^3/s	%	MW
O1	1.7	375	90	22.5	93.5	20
O2	1.06	600	90	8.5	93.5	7

The numerical and graphical results can be exported to an Excel file, where the overlay of the two operation diagrams O1 & O2 can be generated, figure 10.

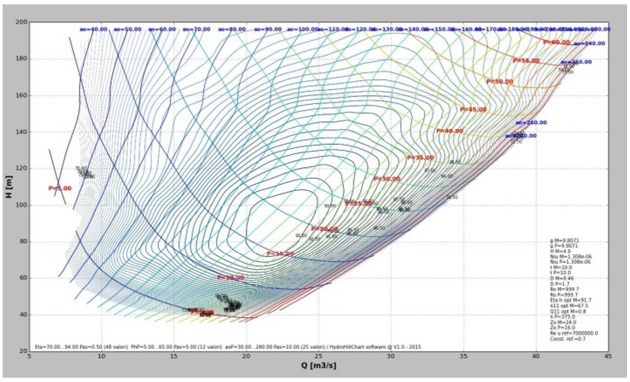


Fig. 8 The O1 operation diagram.

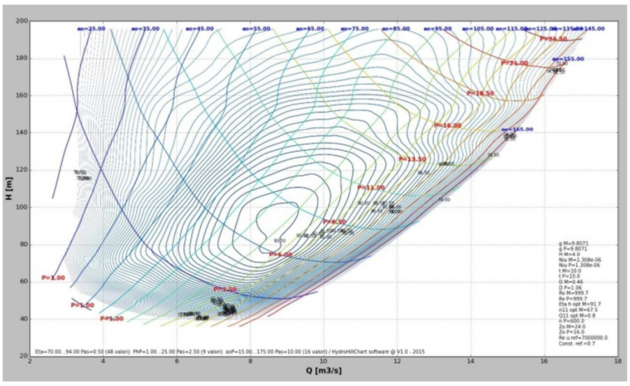


Fig. 9 The O2 operation diagram.

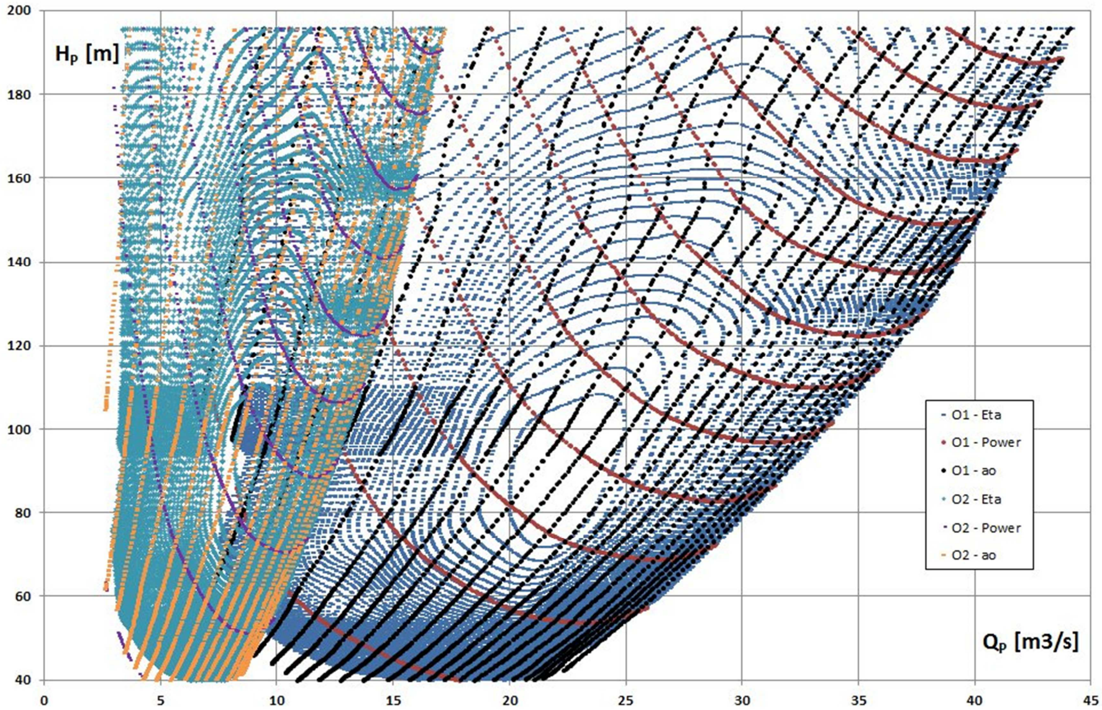


Fig. 10 The overlay operation diagram O1 & O2.

4 Conclusion

The paper presents the interface of the DEX module used to calculate the operation diagram, a module which is included in the Python software, called HydroHillChart.

Based on the same Francis model measurements, two operation diagram O1 & O2 are calculated. By comparing the two charts, one can obtain the various extensions and their placement in the $Q_P - H_P$ plane along with the different position of the optimal points, which highlights the prototype turbine capability to operate in multiple head-discharge-power ranges, for different values of the runner diameter and speed.

More information about the HydroHillChart software can be viewed on [10] or on YouTube for a 'HydroHillChart' keyword search.

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References

[1] Nedelcu, D. and Ghican (Bostan), A.," The Calculation of the Pelton and Francis Turbine Hill Chart Using the HydroHillChart Software", Hidraulica Magazine, No. 4/2015, pp. 7-16, ISSN 1453-7303, http://hidraulica.fluidas.ro/.

[2] Rappin, N., Dunn, R., "wxPython in Action", Manning Publications Co., 2006.

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

[4] International Electrotechnical Comission, "Determination of the prototype performance from the model acceptance tests of hydraulic machines with consideration of scale effects", IEC standard, Publication 995(1991).

[5] ********** - Performance conversion method for hydraulic turbines and pumps, JSME S008, 1989.

[6] Câmpian C. Viorel, Bleier, I., Nedelcu, D., Lăcătuşu, T., "The old and energetical upgrade turbines efficiencies of the Iron Gates I power plant", The Proceedings of the Fifth International Conference on HYDRAULIC MACHINERY AND HYDRODYNAMIC, Vol. I, Timişoara, 18-20 octombrie, pp 67-74, 8 pg, 2000.

[7] Ghican (Bostan), A., "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, Romania, 2015.

[8] Nedelcu, D., Ghican (Bostan), A., Periş-Bendu, F., "HydroHillChart – Francis module. Software for calculating universal characteristic of Francis hydraulic turbines","Eftimie Murgu" University Annals, Year XXI, NR. 1, ISSN 1453 - 7397, Reşiţa, 2015.

[9] Ghican (Bostan), A., Nedelcu, D., Periş-Bendu, F. , "Calculation of universal characteristics for Francis runner models using the HydroHillChart - Francis module software"Eftimie Murgu" University Annals, Year XXI, NR. 1, ISSN 1453 - 7397, Reşiţa, 2015.

[10] http://www.cchapt.ro/HydroHillChart.htm