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The Hill Chart Calculation for Francis Runner Models using the HydroHillChart - Francis Module Software

In practice, for the design of hydraulic turbines, laboratory tests performed on reduced scale models of turbines are recommended. The optimisation of a turbine model requires extensive experimental research on several variants of geometry, the improvement of efficiency at an industrial scale which will lead to substantial economic benefits because of the extended life of the turbine. Warranty conditions arisen from model tests will be verified by additional tests performed on industrial prototypes at specific points agreed between the supplier and the customer. The purpose of these tests is the experimental determination of the relationships between the basic parameters of the operating turbine for different operating conditions. The graphic expression of these relationships represent the hill chart of the turbine which is valid for the whole turbine family similar to the tested model.

Keywords: *turbine, runner, Francis, hill chart*

1. Introduction

The **HydroHillChart** application was created using the Python programming language and its associated modules [1]. The Francis module is an integral part of this application and it allows the hill chart calculation for Francis runners, based on the measurements of the model or the calculation of the operating diagram, if the measured parameters were transposed to the prototype.

Using the **HydroHillChart - Francis module** software, the hill chart for the following models of Francis runners will be drawn:

- RO 75-702 runner with a diameter D = 460 mm and 13 runner baldes [2];
- RO140 runner with a diameter D = 515 mm and 16 runner blades [3].

For these runners, the input data was taken from literature as discrete points of the existing characteristics in order to compare them with the characteristics calculated by the **HydroHillChart - Francis module** software.

The input data required by the **HydroHillChart - Francis module** software is as follows:

- **ID punct** - serial number of the measuring point;
- **n_{11}** [rot/min] - unitary speed;
- **Q_{11}** [m3/s] - unitary flow;
- **a_o [mm]** - wicked gate opening;
- **η** [%] – efficiency.

2. The calculation of the hill chart for RO 75-702 runner

For the RO 75-702 runner, input data was taken from [2], page 296, as discrete points of the existing hill chart, Figure 1 and Table 1, in order to recalculate it with the **HydroHillChart** - Francis module software. The **Puncte măsurate** table was completed with data taken from an Excel file totaling a number of 84 points, figure 2. In this table, the **Punct eliminat** column allows the removal of a point, by activating a **Check Box** control type. The measurements were performed for ten constant openings of the wicked gate: a_0=14, 18, 22, 26, 30, 34, 38, 42, 46, 50 mm. The calculation of the hill chart is done for n_{11}=const. in the n_{11}=50 ÷100 domain with a step of 5 rot/min.

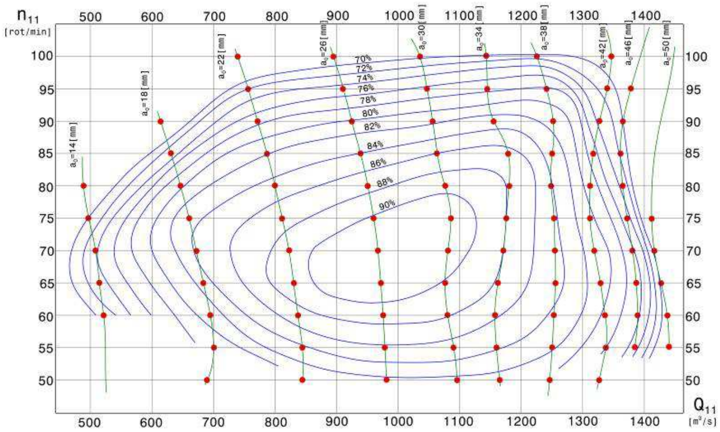
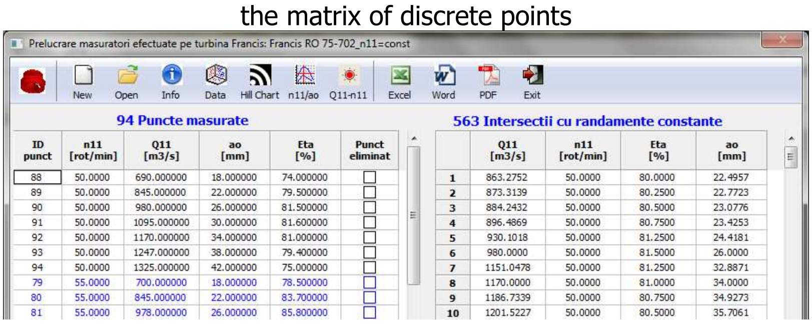


Figure 1. The RO 75-702 runner hill chart and the matrix of discrete points


Prelucrare masuratori efectuate pe turbina Francis: Francis RO 75-702_n11=const

New Open Info Data Hill Chart n11/ao Q11-n11 Excel Word PDF Exit

94 Puncte masurate

ID punct	n11 [rot/min]	Q11 [m3/s]	ao [mm]	Eta [%]	Punct eliminat
88	50.0000	690.000000	18.000000	74.000000	☐
89	50.0000	845.000000	22.000000	79.500000	☐
90	50.0000	980.000000	26.000000	81.500000	☐
91	50.0000	1095.000000	30.000000	81.600000	☐
92	50.0000	1170.000000	34.000000	81.000000	☐
93	50.0000	1247.000000	38.000000	79.400000	☐
94	50.0000	1325.000000	42.000000	75.000000	☐
79	55.0000	700.000000	18.000000	78.500000	☐
80	55.0000	845.000000	22.000000	83.700000	☐
81	55.0000	978.000000	26.000000	85.800000	☐

563 Intersectii cu randamente constante

	Q11 [m3/s]	n11 [rot/min]	Eta [%]	ao [mm]
1	863.2752	50.0000	80.0000	22.4957
2	873.3139	50.0000	80.2500	22.7723
3	884.2432	50.0000	80.5000	23.0776
4	896.4869	50.0000	80.7500	23.4253
5	930.1018	50.0000	81.2500	24.4181
6	980.0000	50.0000	81.5000	26.0000
7	1151.0478	50.0000	81.2500	32.8871
8	1170.0000	50.0000	81.0000	34.0000
9	1186.7339	50.0000	80.7500	34.9273
10	1201.5227	50.0000	80.5000	35.7061

Figure 2. Table **Puncte măsurate** for RO 75-702 runner

Table 1.

ID_POINT	n11	Q11	ao[mm]	η (%)	ID_POINT	n11	Q11	ao[mm]	η (%)	ID_POINT	n11	Q11	ao[mm]	η (%)
1	100	740.00	22.00	63.80	32	80	800.00	22.00	84.70	63	65	1077.00	30.00	90.10
2	100	895.00	26.00	67.40	33	80	950.00	26.00	87.40	64	65	1160.00	34.00	87.60
3	100	1040.00	30.00	69.40	34	80	1075.00	30.00	89.20	65	65	1255.00	38.00	84.50
4	100	1145.00	34.00	70.50	35	80	1180.00	34.00	87.70	66	65	1330.00	42.00	81.00
5	100	1225.00	38.00	70.80	36	80	1254.00	38.00	84.00	67	65	1390.00	46.00	76.50
6	100	1348.00	42.00	68.00	37	80	1310.00	42.00	79.00	68	65	1420.00	50.00	70.00
7	95	755.00	22.00	72.00	38	80	1365.00	46.00	73.20	69	60	525.00	14.00	71.00
8	95	912.00	26.00	74.80	39	75	497.00	14.00	70.00	70	60	695.00	18.00	81.00
9	95	1048.00	30.00	76.50	40	75	660.00	18.00	82.80	71	60	840.00	22.00	87.00
10	95	1146.00	34.00	77.80	41	75	814.00	22.00	87.20	72	60	975.00	26.00	89.00
11	95	1245.00	38.00	78.00	42	75	960.00	26.00	90.20	73	60	1082.00	30.00	88.10
12	95	1340.00	42.00	71.20	43	75	1080.00	30.00	91.40	74	60	1158.00	34.00	86.30
13	95	1382.00	46.00	67.00	44	75	1175.00	34.00	88.30	75	60	1253.00	38.00	83.60
14	90	612.50	18.00	66.20	45	75	1255.00	38.00	84.40	76	60	1335.00	42.00	79.90
15	90	770.00	22.00	77.00	46	75	1312.00	42.00	80.40	77	60	1390.00	46.00	75.80
16	90	926.00	26.00	80.10	47	75	1375.00	46.00	74.80	78	60	1430.00	50.00	68.10
17	90	1057.00	30.00	81.90	48	75	1412.00	50.00	67.20	79	55	700.00	18.00	78.50
18	90	1157.00	34.00	83.00	49	70	508.00	14.00	73.70	80	55	845.00	22.00	83.70
19	90	1251.00	38.00	81.20	50	70	672.00	18.00	83.90	81	55	978.00	26.00	85.80
20	90	1330.00	42.00	73.80	51	70	825.00	22.00	88.90	82	55	1090.00	30.00	85.30
21	90	1365.00	46.00	70.00	52	70	967.00	26.00	92.50	83	55	1163.00	34.00	84.10
22	85	630.00	18.00	73.00	53	70	1080.00	30.00	91.50	84	55	1250.00	38.00	82.00
23	85	786.00	22.00	81.70	54	70	1168.00	34.00	88.20	85	55	1335.00	42.00	78.50
24	85	940.00	26.00	84.10	55	70	1256.00	38.00	84.60	86	55	1383.00	46.00	74.20
25	85	1065.00	30.00	86.00	56	70	1320.00	42.00	81.00	87	55	1430.00	50.00	66.00
26	85	1179.00	34.00	86.40	57	70	1383.00	46.00	76.30	88	50	690.00	18.00	74.00
27	85	1253.00	38.00	83.00	58	70	1412.00	50.00	70.00	89	50	845.00	22.00	79.50
28	85	1315.00	42.00	76.90	59	65	516.00	14.00	73.30	90	50	980.00	26.00	81.50
29	85	1360.00	46.00	71.70	60	65	683.00	18.00	83.00	91	50	1095.00	30.00	81.60
30	80	485.00	14.00	65.00	61	65	833.00	22.00	89.00	92	50	1170.00	34.00	81.00
31	80	647.00	18.00	79.70	62	65	972.00	26.00	91.80	93	50	1247.00	38.00	79.40
										94	50	1325.00	42.00	75.00

The plotting of the hill chart is performed in several steps. In the first stage, measured primary parametric curves intersect the imposed effciency values. These points are stored in the **Intersectii cu randamente constante** table, Figure 2. Primary curves $\eta = f(a_0)$ and $Q_{11} = f(a_0)$ are shown in Figures 3-13. Figures 14-16 show the $\eta = f(n_{11}, Q_{11})$ 3D curves, as well as the $\eta = f(Q_{11})$ and $a_o = f(Q_{11})$ 2D curves for n_{11}=const.

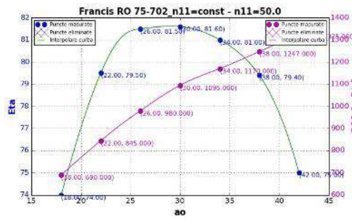


Figure 3. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=50

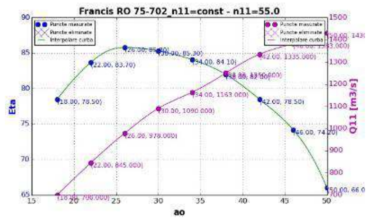


Figure 4. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=55

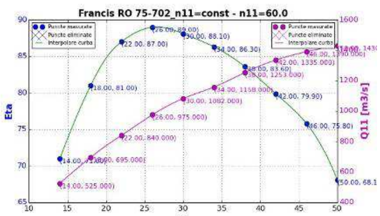


Figure 5. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=60

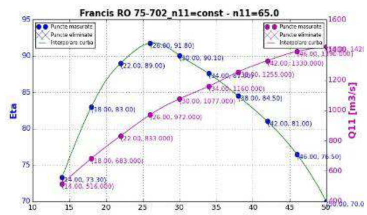


Figure 6. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=65

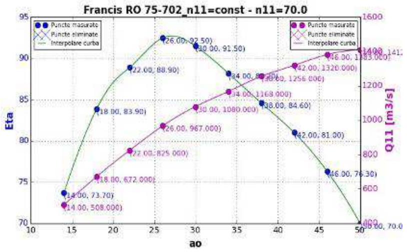


Figure 7. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=70

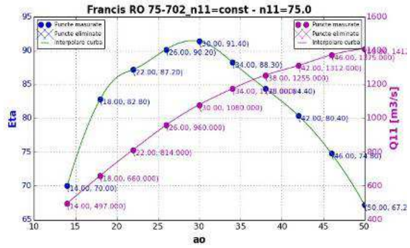


Figure 8. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=75

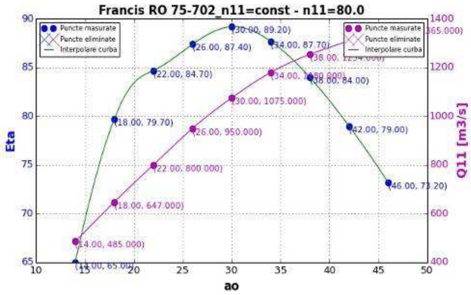


Figure 9. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=80

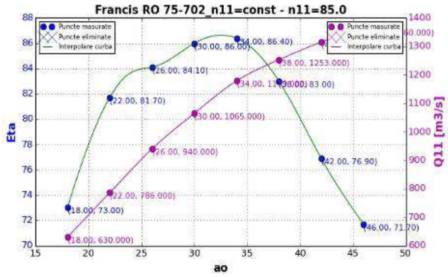


Figure 10. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=85

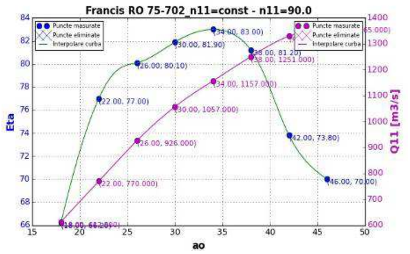


Figure 11. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=90

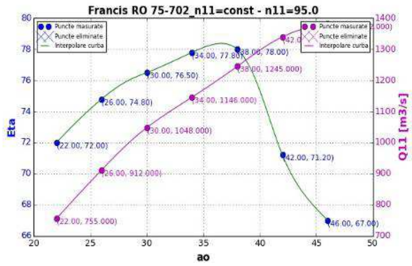


Figure 12. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=95

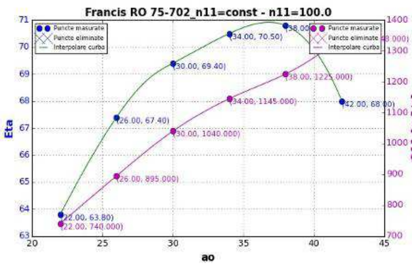


Figure 13. $\eta = f(a_o)$ and $Q_{11} = f(a_o)$ 2D curves for n_{11}=100

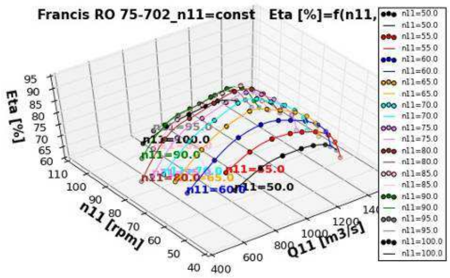


Figure 14. $\eta = f(n_{11}, Q_{11})$ 3D curves for n_{11}=const.

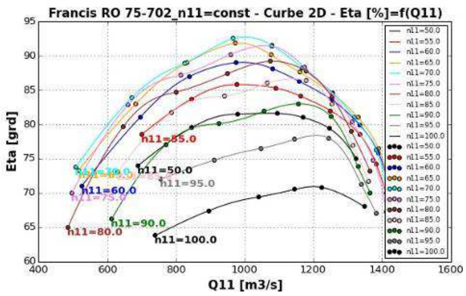


Figure 15. $\eta = f(Q_{11})$ 2D curves for n_{11}=const.

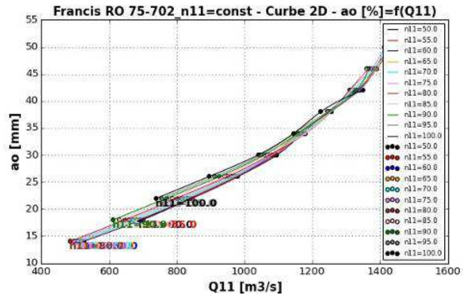


Figure 16. $a_o = f(Q_{11})$ 2D curves for n_{11}=const.

In the second stage, surface $\eta = f(n_{11}, Q_{11})$ is intersected with constant efficiency values. For a set of input data considered to be measured for n_{11}=const., Figure 17 shows the $\eta = f(n_{11}, Q_{11})$ 3D surface, Figure 18 shows the 3D intersection curves with constant efficiency values while Figure 19 shows the hill chart.

Field efficiency values for the RO 75-702 runner are fitted between 63.8 and 92.5%. The hill chart was calculated for 94 values imposed in the η =80 ÷ 92.5% domain with a step of 0.25%.

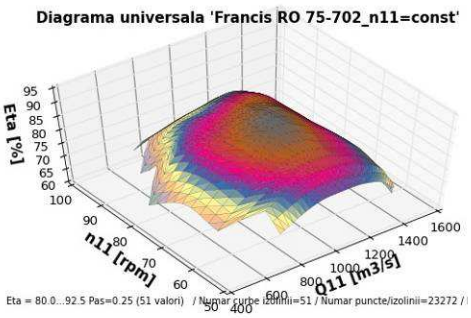


Figure17. $\eta = f(n_{11}, Q_{11})$ 3D surface for n_{11}=const.

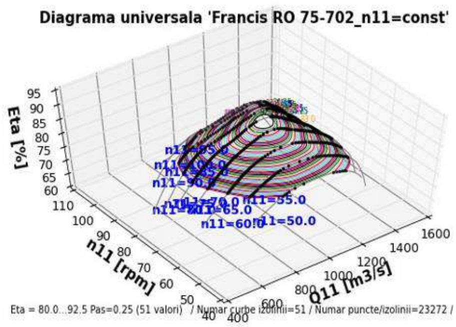


Figure18. Intersection curves with constant efficiency values for n_{11}=const.

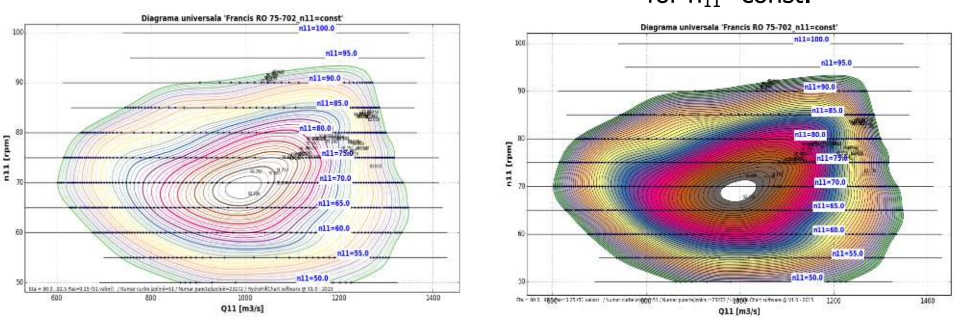


Figure19. Universal characteristic for the RO 75-702 runner for n_{11}=const.

3. The calculation of the hill chart for RO140 runner

For the RO140 runner, input data was taken from [3], page 69, as discrete points of the existing hill chart, Figure 20 and Table 2, in order to recalculate it with the **HydroHillChart** - Francis module software.

In the **Puncte măsurate** table, 77 measured values were loaded. The measurements were performed for the following openings of the wicked gate: a_o=16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56 mm. The calculation of the hill chart, using the **HidroHillChart** - **Francis module** software, is made for a_0=const.

Measured primary parametric curves intersect the imposed effciency values and the obtained points are stored in the **Intersectii cu randamente constante** table, Figure 21. Primary curves $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ are shown in Figures 22-32.

Figures 33-35 show the $\eta = f(n_{11}, Q_{11})$ 3D curves, as well as the $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_0=const.

For a set of input data measured at a_0=const., Figure 36 shows the $\eta = f(n_{11}, Q_{11})$ 3D surface, Figure 37 shows the 3D intersection curves with constant efficiency values while Figure 38 shows the hill chart.

Field efficiency values for the RO140 runner are fitted between 63.5 and 92.5%. The hill chart was calculated for 77 values imposed in the η =75 ÷ 92.5% domain with a step of 0.25%.

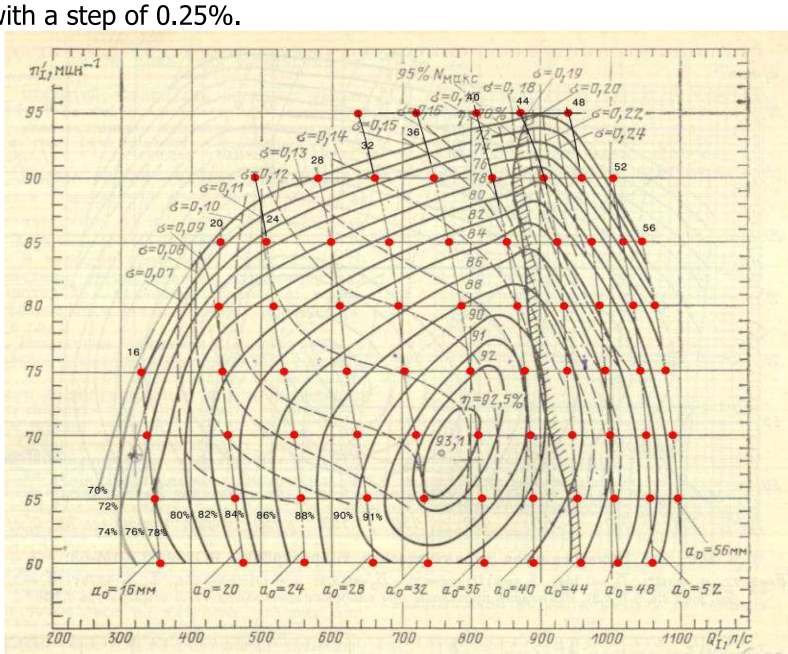
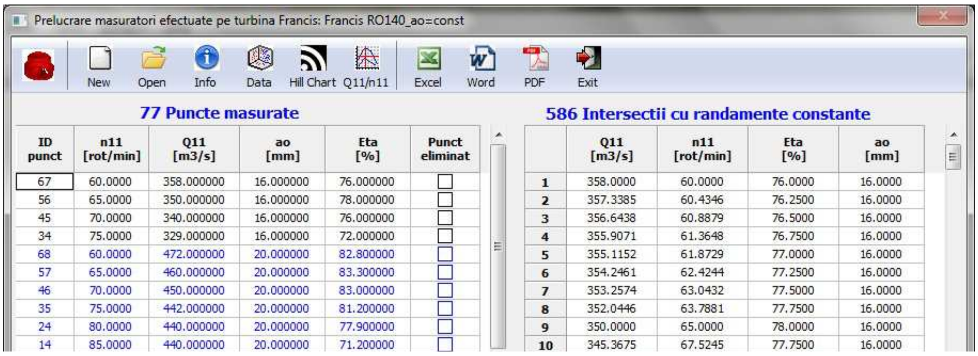


Figura 20. The RO140 runner hill chart and the matrix of discrete points



Prelucrare masuratori efectuate pe turbina Francis: Francis RO140_ao=const

New Open Info Data Hill Chart Q11/n11 Excel Word PDF Exit

77 Puncte masurate

ID punct	n11 [rot/min]	Q11 [m3/s]	ao [mm]	Eta [%]	Punct eliminat
67	60.0000	358.000000	16.000000	76.000000	☐
56	65.0000	350.000000	16.000000	78.000000	☐
45	70.0000	340.000000	16.000000	76.000000	☐
34	75.0000	329.000000	16.000000	72.000000	☐
68	60.0000	472.000000	20.000000	82.800000	☐
57	65.0000	460.000000	20.000000	83.300000	☐
46	70.0000	450.000000	20.000000	83.000000	☐
35	75.0000	442.000000	20.000000	81.200000	☐
24	80.0000	440.000000	20.000000	77.900000	☐
14	85.0000	440.000000	20.000000	71.200000	☐

586 Intersectii cu randamente constante

	Q11 [m3/s]	n11 [rot/min]	Eta [%]	ao [mm]
1	358.0000	60.0000	76.0000	16.0000
2	357.3385	60.4346	76.2500	16.0000
3	356.6438	60.8879	76.5000	16.0000
4	355.9071	61.3648	76.7500	16.0000
5	355.1152	61.8729	77.0000	16.0000
6	354.2461	62.4244	77.2500	16.0000
7	353.2574	63.0432	77.5000	16.0000
8	352.0446	63.7881	77.7500	16.0000
9	350.0000	65.0000	78.0000	16.0000
10	345.3675	67.5245	77.7500	16.0000

Figura 21. Table **Puncte măsurate** for RO140 runner

Table 2.

ID punct	n_{11} [rot/min]	Q_{11} [m^3/s]	a_0 [mm]	η [%]	ID punct	n_{11} [rot/min]	Q_{11} [m^3/s]	a_0 [mm]	η [%]	ID punct	n_{11} [rot/min]	Q_{11} [m^3/s]	a_0 [mm]	η [%]
1	95	635.00	32.00	63.50	27	80	693.00	32.00	85.90	53	70	1000.00	48.00	86.00
2	95	720.00	36.00	66.00	28	80	786.00	36.00	88.00	54	70	1049.00	52.00	83.00
3	95	807.00	40.00	68.10	29	80	867.00	40.00	89.00	55	70	1087.00	56.00	79.10
4	95	874.00	44.00	69.60	30	80	932.00	44.00	86.80	56	65	350.00	16.00	78.00
5	95	941.00	48.00	68.30	31	80	985.00	48.00	83.40	57	65	460.00	20.00	83.30
6	90	490.00	24.00	66.50	32	80	1030.00	52.00	79.30	58	65	555.00	24.00	87.20
7	90	580.00	28.00	70.10	33	80	1060.00	56.00	75.70	59	65	645.00	28.00	90.40
8	90	660.00	32.00	73.10	34	75	329.00	16.00	72.00	60	65	730.00	32.00	92.20
9	90	748.00	36.00	75.70	35	75	442.00	20.00	81.20	61	65	817.00	36.00	91.40
10	90	831.00	40.00	77.90	36	75	534.00	24.00	84.70	62	65	889.00	40.00	89.60
11	90	902.00	44.00	79.00	37	75	623.00	28.00	87.10	63	65	955.00	44.00	87.50
12	90	960.00	48.00	74.40	38	75	707.00	32.00	89.60	64	65	1006.00	48.00	85.50
13	90	1003.00	52.00	68.50	39	75	800.00	36.00	91.80	65	65	1056.00	52.00	82.70
14	85	440.00	20.00	71.20	40	75	877.00	40.00	90.90	66	65	1094.00	56.00	79.00
15	85	505.00	24.00	74.80	41	75	942.00	44.00	88.40	67	60	358.00	16.00	76.00
16	85	598.00	28.00	78.00	42	75	993.00	48.00	85.60	68	60	472.00	20.00	82.80
17	85	679.00	32.00	80.60	43	75	1040.00	52.00	82.00	69	60	560.00	24.00	87.00
18	85	769.00	36.00	82.90	44	75	1075.00	56.00	78.20	70	60	655.00	28.00	89.50
19	85	852.00	40.00	84.50	45	70	340.00	16.00	76.00	71	60	735.00	32.00	90.25
20	85	920.00	44.00	83.80	46	70	450.00	20.00	83.00	72	60	818.00	36.00	89.40
21	85	975.00	48.00	79.80	47	70	546.00	24.00	86.80	73	60	890.00	40.00	87.90
22	85	1018.00	52.00	74.70	48	70	635.00	28.00	89.50	74	60	957.00	44.00	86.00
23	85	1042.00	56.00	70.00	49	70	720.00	32.00	91.40	75	60	1010.00	48.00	84.00
24	80	440.00	20.00	77.90	50	70	810.00	36.00	92.50	76	60	1060.00	52.00	81.00
25	80	520.00	24.00	80.90	51	70	884.00	40.00	90.70	77	60	1100.00	56.00	77.00
26	80	612.00	28.00	83.50	52	70	950.00	44.00	88.50					

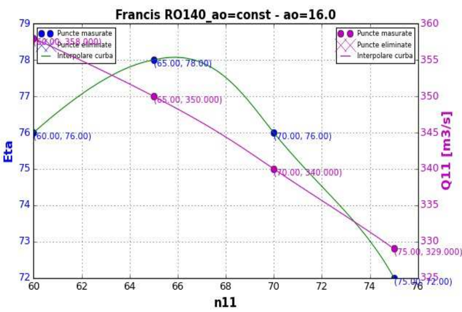


Figure 22. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=16

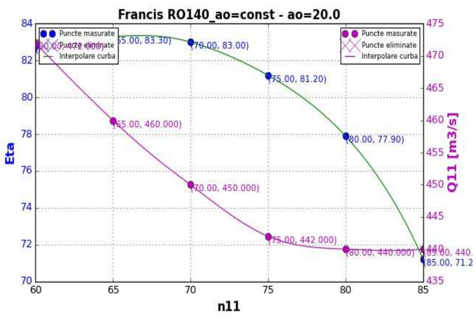


Figure 23. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=20

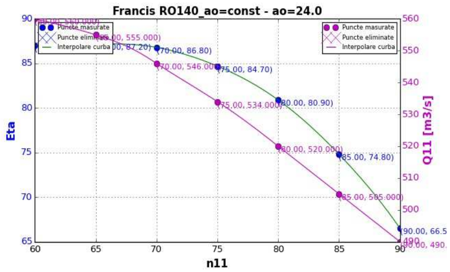


Figure 24. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=24

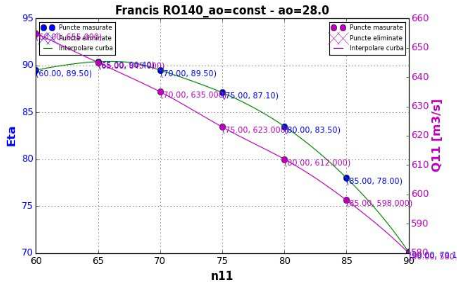


Figure 25. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=28

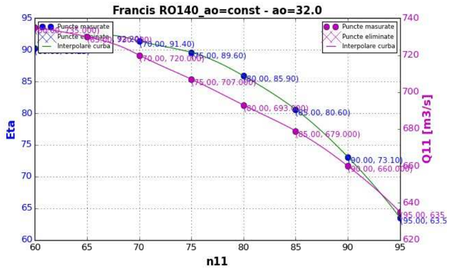


Figure 26. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=32

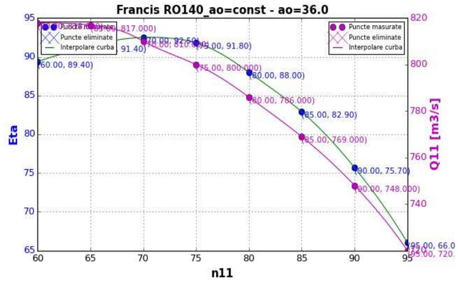


Figure 27. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=36

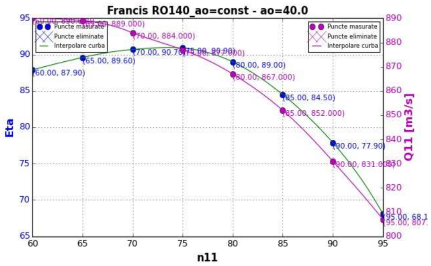


Figure 28. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=40

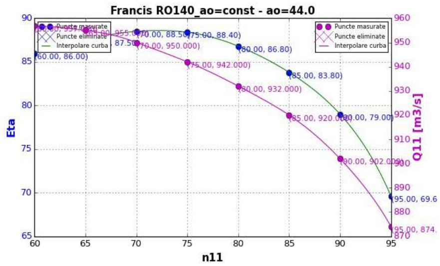


Figure 29. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=44

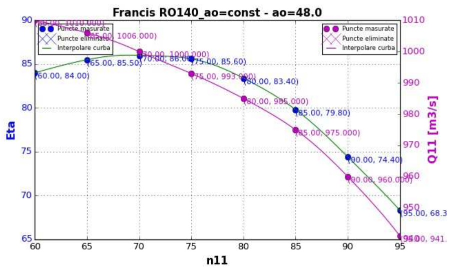


Figure 30. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=48

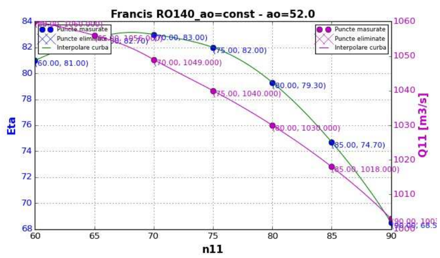


Figure 31. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=52

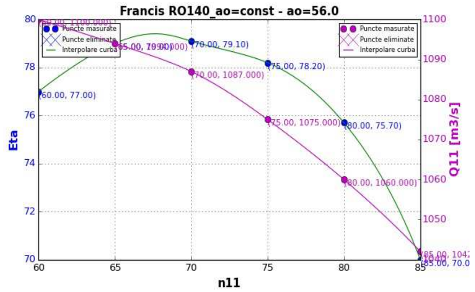


Figure 32. $\eta = f(n_{11})$ and $Q_{11} = f(n_{11})$ 2D curves for a_o=56

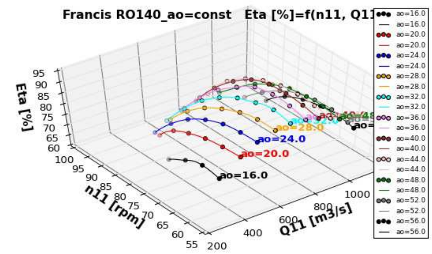


Figure 33. $\eta = f(n_{11}, Q_{11})$ 3D curves for a_0=const.

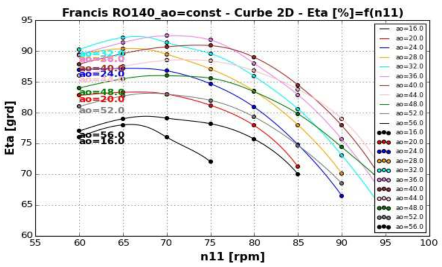


Figure 34. $\eta = f(n_{11})$ 2D curves for a_o=const.

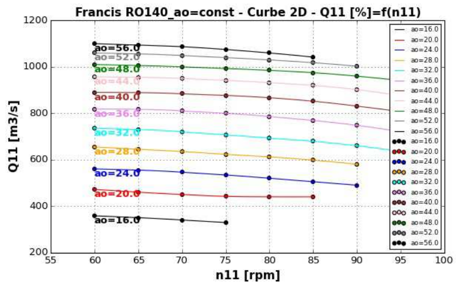


Figure 35. $Q_{11} = f(n_{11})$ 2D curves for a_o=const.

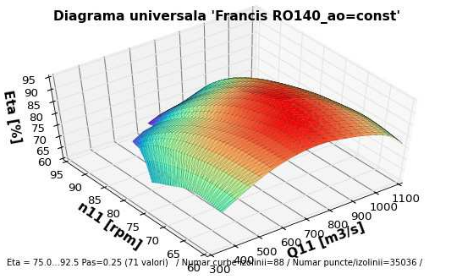


Figura 36. $\eta = f(n_{11}, Q_{11})$ 3D surface for a_o=const.

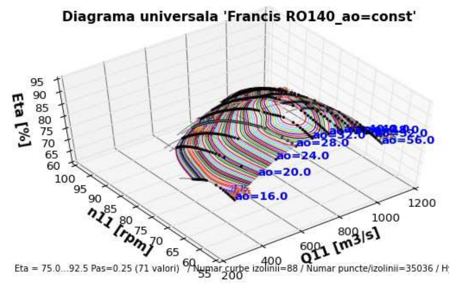


Figura 37. Intersection curves with constant efficiency values for a_o=const.

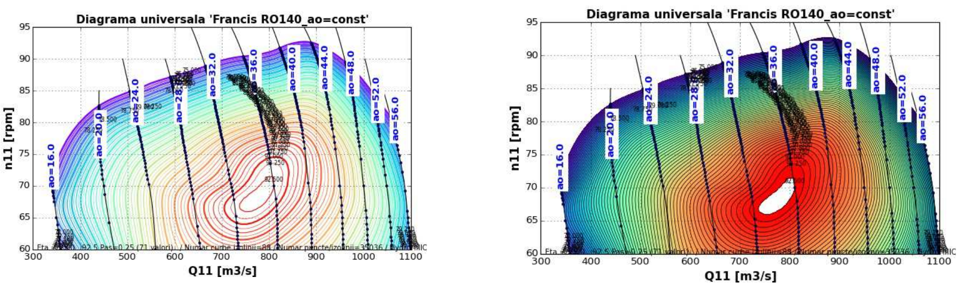


Figura 38. Universal characteristic for RO140 runner at a_o=const.

4. Conclusions

The paper presents the universal characteristics that were calculated using the **Hydro Hill Chart** - **Francis module** software for two models of Francis runners: the RO 75-72 runner and the RO140 runner. The comparison of characteristics taken from literature with those calculated with the **HydroHillChart** - Francis module software confirms the correctness of the interpolation algorithms that were used and recommends this software as a useful tool in processing measurement data on models of industrial turbines and in turbine design.

Printing space does not allow the presentation of all the possibilities offered by the software, more information is available in reference [4].

5. Acknowledgments

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