CONTRIBUTION TO HYDRAULIC TURBINES DRAFT TUBE DESIGN

Prof.univ.dr.ing. Mircea BARGLAZAN[1], Prof.univ.dr.ing. Ilare BORDEASU[2]

[1] "Politehnica" University of Timisoara, mbarglazan@yahoo.com

[2] "Politehnica" University of Timisoara, ilarica59@gmail.com

Abstract: *The paper is devoted to parametric design of reaction hydraulic turbines draft tube. Knowing the hydraulic turbine runner data and location there are determined the draft tube length, cross sections geometry and shape. The efficiency (recovery coefficient) of this divergent special pipe in function of geometric and kinematic parameters is established. The analytical formulas obtained are useful for design and local hydrodynamic flow numerical analysis. The obtained design formulas fits for power plants with one or small number of hydro-units or for micro-power-plants.*

Keywords*: hydraulic turbines, draft tube, geometric and hydrodynamic parameters, draft tube design and optimization*

1. Introduction

Draft tube is an important part of the Francis and Kaplan hydraulic turbines. It's roles are to recover the exit hydraulic energy of the water from the runner and to install the hydraulic turbines in an convenient position (from economical and non-cavitational point of view).
Researches about hydrodynamic flow in draft tubes are present in the last IAHR Symposiums and Conferences (Beijing 1994, Valencia 1996, Singapore 1998, North Carolina 22000, Lausanne 2002, Stuttgart 2003,..,Timişoara 2010). A lot of books and articles (authors like N. Kovalev, S. Granovschi, J. Raabe, ed. R. Krishna, J. Giesecke, A. Bărglăzan, and reviews like Trudî VIGM) give design statistical data and empirical dimensions about draft tube geometry and operation.

List of symbols

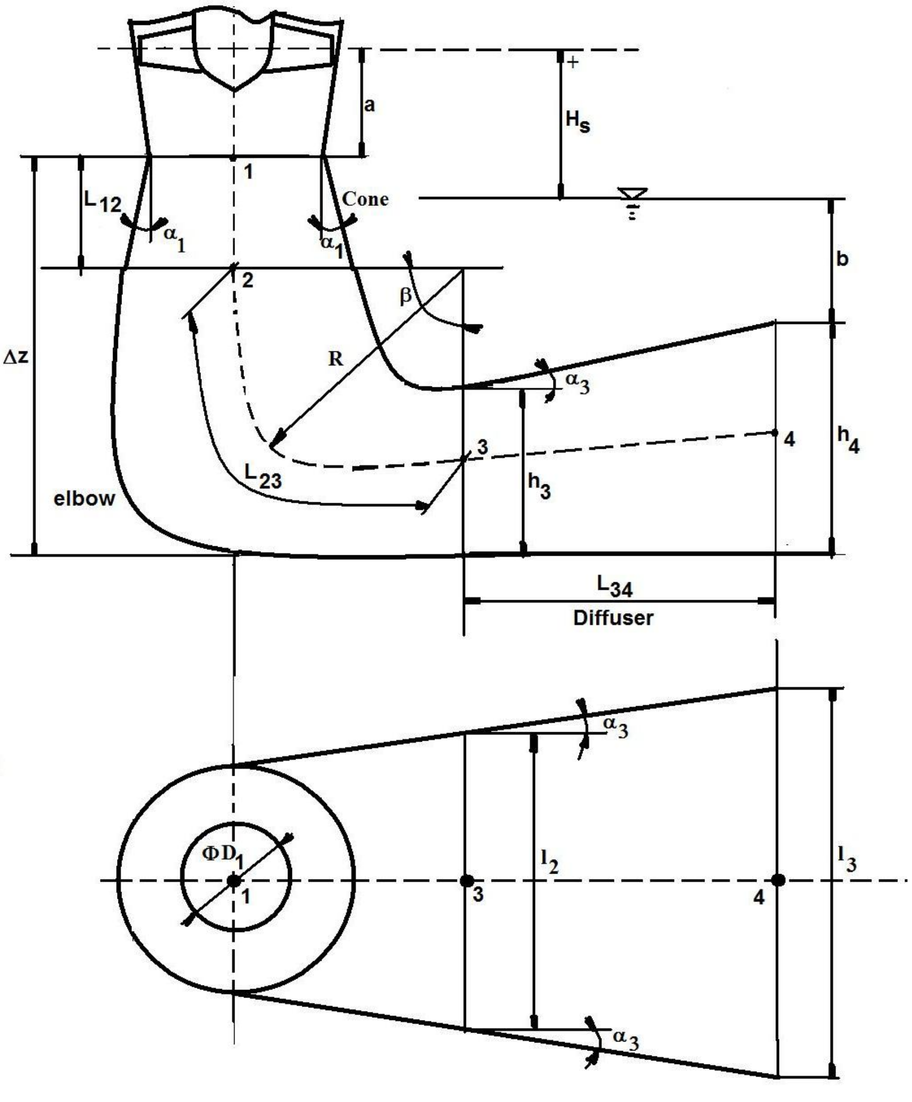
D – diameter of draft tube cross section,
L- length of the draft tube,
h – highness of draft tube diffuser,
l – breadth of the draft tube diffuser,
α- angle of the draft tube divergence,
Δz / D – draft tube relative deepness,
β - elbow angle,
R – elbow curvature radius,
H_s- suction head of the hydraulic turbine,
a – runner vertical height in respect of draft tube entrance,
b - draft tube exit depth in respect of the tail water level,
Δ A / L – gradient of cross section area along the draft tube,
v – mean axial velocity of the flow in the draft tube,
H_T – hydraulic turbine head,
Q – rate of flow,
p – pressure,

2. Draft tube parameters

The draft tube is a special divergent pipe in which it is necessary to maintain the attached flow inside in order to obtain a good hydrodynamic efficiency. Taking into account the variety of the

draft tube parts it is introduced a compromise between its position, divergence degree and length in order to obtain an optimal operation.
The draft tube design will be realized with the following assumptions:

- draft tube shape is presented in Fig. 1, and its geometry fits to hydro-plants with one or small number of hydro-units.
- divergence gradient of the draft tube cross sections area is constant inside the cone, elbow and diffuser but different between these parts.



The draft tube geometry and hydrodynamics is considered in the frame of the following parameters:

- the optimal divergence angle of the cone , α_1, is accepted from [3] and equal with:

$$\alpha_1 = 6^o \ldots 8^o \tag{1}$$

- the divergence angle of three faces of the diffuser (in accord with Fig. 1), α_3 ,

$$\alpha_3 = \alpha_1 \tag{2}$$

- The draft tube deepness, n, the most important parameter after [4] is:

$$n = \frac{\Delta z}{D_1} = 2...4 \tag{3}$$

The “n” value is an indirect function of the hydraulic turbine suction head and the local conditions for the position of the hydro-plant. Its value is determined from a technical-economical problem.

A first estimation, from figure 1 dimensions chain and relation (3):

$$n = \frac{H_s + b - a + h_4}{D_1} \tag{4}$$

Here H_s is evaluated form rel. (8), approximately b = 1 <m> and a first guess is:

$$h_4 = D_1 \tag{5}$$

Nowadays smaller values for “n” are usually used.
The draft tube elbow makes the transition from vertical flow to horizontal flow and the change from a circular cross section to a rectangular section. The degree of cross section distortion, Y, is defined:

$$Y = \frac{h_3}{D_2} \approx 0,5 \tag{6}$$

- the curvature angle of the elbow, β, is usually 90º but can be also greater.

The flow velocities ratio from exit to entrance of the draft tube, B, is established in function of the estimated performances attended from the hydraulic turbine. So:

$$B = \frac{v_4}{v_1} = \frac{1}{4}...\frac{1}{5} \tag{7}$$

- the suction head of the hydraulic turbine, H_s after [1] is:

$$H_s = \frac{\frac{p_{at} - p_{vs}}{\rho \cdot g} - \sigma_i \cdot H_T}{H_T} \tag{8}$$

Knowing the atmospheric pressure, p_{at}, the saturation pressure of the water vapour, p_{vs}, which is a function of liquid temperature, the critical cavitation coefficient of the hydraulic turbine, σ_i , and the turbine head, H_T, the suction head is possible to be calculated.
Other variants of draft tubes like one with a leg inside the diffuser and/or unsymmetrical diffuser are easy adapted to the above conditions and developments.

3. Draft tube parameters calculus

The length of the draft tube is:

$$L_{dt} = L_{12} + L_{23} + L_{34} \tag{9}$$

From Fig. 1 the cone length, L_{12}, is determined through the relation:

$$\Delta z = L_{12} + R + \frac{h_3}{2} \tag{10}$$

considering also

$$D_2 = D_1 + 2 \cdot L_{12} \cdot tg(\alpha_1) = \frac{1 + 2 \cdot n \cdot tg(\alpha_1)}{1 + (2 \cdot w + Y) \cdot tg(\alpha_1)} \cdot D_1 \quad (11)$$

and with relations (3) and (4) results:

$$L_{12} = \frac{\left[n - \left(w + \frac{Y}{2} \right) \right]}{1 + \left(2 \cdot w + Y \right) \cdot tg\left(\alpha_1 \right)} \cdot D_1 \quad (12)$$

The cone cross section gradient, x, is:

$$x = \frac{\Delta A_{21}}{L_{12}} = \frac{\pi}{4} \cdot \frac{D_2^2 - D_1^2}{L_{12}} \quad (13)$$

The mean elbow length, L_{23}, has the formula :

$$L_{23} = \beta \cdot R = \beta \cdot w \cdot \frac{1 + 2 \cdot n \cdot tg(\alpha_1)}{1 + (2 \cdot w + Y) \cdot tg(\alpha_1)} \cdot D_1 \quad (14)$$

Obtained from the curvature radius:

$$R = w \cdot D_2 \quad (15)$$

Often value is w = 1.

The divergence degree, x , calculated with the help of relation (13) results:

$$x = \pi \cdot tg\left(\alpha_1 \right) \cdot \frac{1 + \left(n + w + \frac{Y}{2} \right) \cdot tg\left(\alpha_1 \right)}{1 + \left(2 \cdot w + Y \right) \cdot tg\left(\alpha_1 \right)} \cdot D_1 \quad (16)$$

The diffuser entrance height "h_3", after relations (3), (10) and (12):

$$h_3 = Y \cdot \frac{1 + 2 \cdot n \cdot tg(\alpha_1)}{1 + (2 \cdot w + Y) \cdot tg(\alpha_1)} \cdot D_1 \quad (17)$$

Following the indication from [8] the diffuser length is recommended to be:

$L_{34} = (4. . .5) \cdot D_1$ for radial-axial hydraulic turbines and

$L_{34} = (4…4,5) \cdot D_1$ for axial hydraulic turbines.

In the Case Study (chapter 6) the diffuser length is equal with:

$$L_{34} = 5 \cdot D_1 \quad (18)$$

The diffuser exit dimensions are "h_4":

$$h_4 = h_3 + L_{34} \cdot tg\left(\alpha_3\right) \quad (19)$$

And "l_4" from continuity equation between the cross sections 1 and 4:

$$l_4 = \frac{\pi \cdot D_1^2}{4 \cdot B \cdot h_4} \quad (20)$$

The diffuser entrance breadth is:

$$l_3 = l_4 - 2 \cdot L_{34} \cdot tg\left(\alpha_3\right) \quad (21)$$

So all the parameters of the draft tube are determined.
As an application see the Case study results in Table 1.

4. Draft tube efficiency calculus

The efficiency (recovery coefficient) formula:

$$\eta_{dt} = \frac{\left(v_1^2 - v_4^2\right) - 2 \cdot g \cdot h_{dt}}{v_1^2} \quad (22)$$

expresses this quality criteria as a dependence from entrance axial velocity, v_1 ,exit velocity, v_4 , and the hydraulic losses, h_{dt} , of the draft tube.
Entrance velocity is a function of hydraulic turbine runner and rate of flow. Exit velocity from the draft tube is accepted v_4 = 1...2,5 <m/s> in order to obtain high recovery coefficient [8].
The draft tube losses are composed from the con losses, h_c , the elbow losses, h_e ,and the diffuser losses, h_d . So:

$$h_{dt} = h_c + h_e + h_d \quad (23)$$

Using formulas given in [3], [5] and [24]:

- the cone losses are:

$$h_c = \left\{ \frac{\lambda_{12}}{8 \cdot \sin\left(\alpha_1\right)} \cdot \left[1 - \left(\frac{D_1}{D_2} \right)^4 \right] + 3,2 \cdot \left[tg\left(\alpha_1\right) \right]^{1,25} \cdot \left[1 - \left(\frac{D_1}{D_2} \right)^2 \right]^2 + \left(\frac{D_1}{D_2} \right)^4 \right\} \cdot \frac{v_2^2}{2 \cdot g} \quad (24)$$

- the elbow losses may be approximated:

$$h_e = \varsigma_e \cdot a' \cdot b' \cdot c' \cdot \frac{v_m^2}{2 \cdot g} \quad (25)$$

with the loss coefficient ς_e = 0,73 : for R/D_2 = w =1 corresponds a' = 0,3 ; for β = π / 2 , b' = 1 and for l_3 / b_3 = 2 , c' =0,4.

The mean velocity of the flow, v_m:

$$v_m = \frac{v_2 + v_3}{2} \tag{26}$$

and from rate of flow definition:

$$v_2 = \frac{4 \cdot Q}{\pi \cdot D_2^2} \tag{27}$$

respectively

$$v_3 = \frac{Q}{l_3 \cdot h_3} \tag{28}$$

The diffuser losses, considering the conical approximation for its geometry, is:

$$h_d = \left\{ \frac{\lambda_{34}}{8 \cdot \sin(\alpha_3)} \cdot \left[1 - \left(\frac{l_3 \cdot h_3}{l_4 \cdot h_4} \right)^2 \right] + 3,2 \cdot \left[tg(\alpha_3) \right]^{1,25} \cdot \left(1 - \frac{l_3 \cdot h_3}{l_4 \cdot h_4} \right)^2 + \left(\frac{l_3 \cdot h_3}{l_4 \cdot h_4} \right)^2 \right\} \cdot \frac{v_4^2}{2 \cdot g} \tag{29}$$

For numerical calculus

$$\begin{aligned} & \frac{v_4}{v_1} = B \quad ; \quad \lambda_{12} = \lambda_{34} = 0,02 \quad ; \quad \alpha_1 = \alpha_3 = 6^0 \quad ; \\ & \frac{v_2}{v_1} = \left(\frac{D_1}{D_2} \right)^2 \quad ; \quad \frac{v_m}{v_1} = \frac{1}{2} \cdot \left(\frac{D_1}{D_2} \right)^2 \cdot \left(1 + \frac{\pi \cdot D_2^2}{4 \cdot l_3 \cdot h_3} \right) \\ & \frac{l_3 \cdot h_3}{l_4 \cdot h_4} = B \cdot \left(\frac{D_2}{D_1} \right)^2 \cdot \frac{4 \cdot l_3 \cdot h_3}{\pi \cdot D_2^2} \end{aligned} \tag{30}$$

The results are given in Table 2
With these data it is possible to establish the draft tube recovery degree.

5. Cavitation verification

Knowing all the before mentioned data it is possible to verify the hydro-unit (vertical) position is correct from cavitation point of view in respect of the tail water level.

$$b = L_{12} + R + \frac{h_3}{2} + a - H_s - h_4 \tag{31}$$

If the condition of the hydraulic turbine good operation : b = 1 <m> is not fulfilled there are one of the next possibilities : to modify "n" or "L_{12}", eventually "R" or "β " or "α_3".

6 . Case study

Table 1

	β = 90º ; B = 1 / 5 ; w = 1							
α_1	6º (0,1047 rad)				10º (0,1745 rad)			
n	2		4		2		4	
Y	0,5	0,7	0,5	0,7	0,5	0,7	0,5	0,7
D_2 / D_1	1,1248	1,1064	1,4578	1,4339	1,1836	1,1553	1,6730	1,6331
L_{12} / D_1	0,5939	0,5063	2,1778	2,0640	0,5206	0,4404	1,9087	1,7954
L_{23} / D_1	1,7669	1,7380	2,2899	2,2524	1,8591	1,8147	2,6280	2,5652
x / D_1	0,3508	0,3478	0,4058	0,4018	0,6047	0,5969	0,7402	0,7292
h_3 / D_1	0,5624	0,7745	0,7289	1,0037	0,5918	0,8087	0,8365	1,1431
l_3 / D_1	2,5587	2,7579	2,0780	1,5170	2,4637	1,8923	1,8322	1,3025
L_{34} / D_1	5	5	5	5	5	5	5	5
h_4 / D_1	1,0879	1,3	1,2544	1,5292	1,1173	1,3342	1,362	1,6686
l_4 / D_1	3,6097	3,0207	3,129	2,568	3,1547	2,9433	2,8832	2,3535

If some of the restrictions of the results aren't fulfilled a possibility is to modify "B".

Table 2

	B	η_{dt}
w = 1 **β = π / 2** **n = 2** **Y = 0,5** α_1 **= 6º** $L_{34} = 5 \cdot D_1$	1/5	0,8813
	1/6	0,8964
	1/7	0,9055
	1/8	0,9114
	1/9	0,9154
	1/10	0,9183

7. Conclusions

The draft tube parameters permit to characterize in an unique analytical mode this hydraulic turbine element.
There was established formulas like : (10), (11), (15), (17), (18), (19), (21),(24) and (25) which enables to calculate the geometrical parameters of the draft tube.With the relation (29) it is possible to maximize the draft tube recovery coefficient knowing the cost of draft tube erection.
Despite the flow inside the draft tube is far of being uniform but more and more irregular during the evolution in the draft tube, the method developed in the issue is a good start – in the assumed hypothesis – for design and analysis of the draft tube.
These results - obtained by case study chapter – are the base for local flow analysis through numerical methods for turbulent streams.

References

[1] A, Bărglăzan, Maşini hidraulice, ed. I.P. Timişoara, vol.1,vol. II, 1952.
[2] M. Bărglăzan, Turbine hidraulice şi trasmisii hidrodinamice, ed. Politehnica Tmş. 2000
[3] B. Nekrassov, Cours d'hydraulique, ed. Langue Etrangeres, Moscou, 1980.
[4] P. Henry, Turbomachines hydrauliques, Press Polytechniques Lausanne, 1992.
[5] P. G. Chiselev, Indreptar pentru calcule hidraulice, ed. Energetica, Bucureşti, 1953.
[6] J. Raabe, Hydropower, VDI Verlag, Dusseldorf, 1986.
[7] V. V. Barlit, Ghidravliceschie turbinî, Izd. Vîşcia şcola, Kiev, 1977.
[8] ed. R. Krishna, Hydraulic Design of Hydraulic Machinery, Avebury, Aldershot, 1997.
[9] J. Giesecke, ..,Wasserkraftanlagen, Springer, Heidelberg, 2009.
[10] N. M. Şciapov, Vîgodneişaia dlina otsasîvaiuşcei trubî ghidroturbin, Trudî VIGM XXIII, Maşghiz, Moscva, 1959.
[11] I. E. Idelcic, Îndrumător pentru calculul rezistenţelor hidraulice, ed. Tehnică, Bucureşti, 1984.
[12] N. N. Kovalev, Ghidroturbinî, Izd. Maşinostroenie, Leningrad, 1971
[13] L. Ia. Bronstein, .., Spravocinic constructora ghidroturbin, Izd. Maşinostroenie, Leningrad, 1971.
[14] S. Granovschi, .., Construcţii i rasciot ghidroturbin, Izd. Maşinostroene, Leningrad, 1971