COMPUTER SIMULATION OF HYDRAULIC POWER PLANTS

Alberto Benato, Alex Pezzuol, Anna Stoppato, Renzo Tosato
Department of Mechanical Engineering
Via Venezia, 1 I 35131 PADOVA (Italy)
anna.stoppato@unipd.it; renzo.tosato@unipd.it

Abstract: In the present workshop, with a single mathematical tool it is possible to predict the performances of several configurations of Pelton turbines under different operating conditions. .

1. Introduction

For converting hydraulic energy into electrical energy, turbines are used and power plants are characterised by:

1. Higher investment cost than thermal power plants.

However, they have several advantages:

2. High efficiency. Potentially constant supply of energy of water.
3. No atmospheric pollution, easy maintenance.

Pelton turbines are suitable for a range of heads H of about 150-2000 m. Fig 1 shows a large Pelton wheel with its buckets. The runner consists of double hemispherical cups fitted on its periphery.

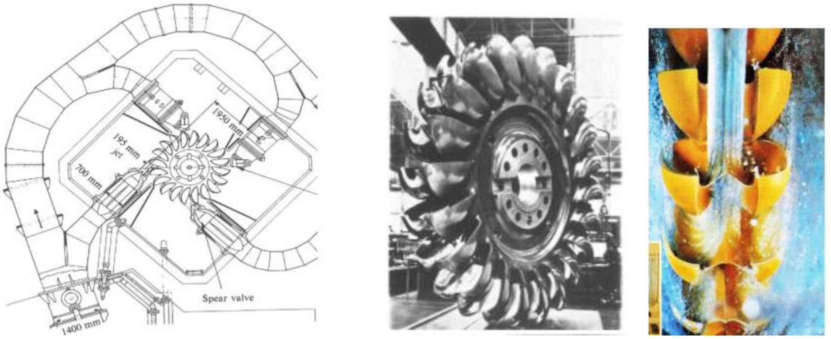


Figure 1 A large Pelton with four jets, wheel and water jet that impinges the buckets.

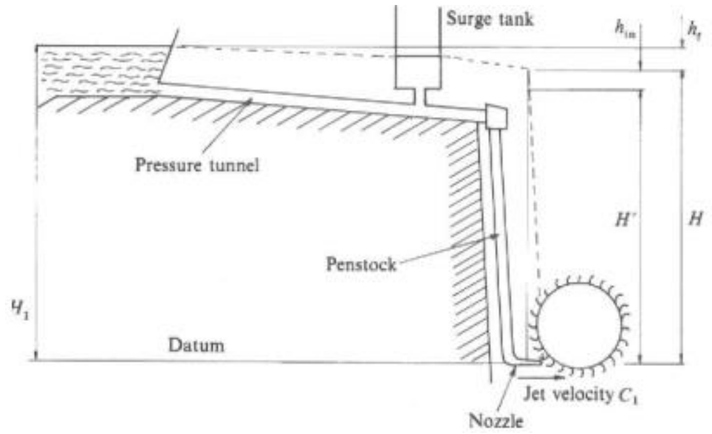


Figure 2: Sketch of a power plant with a Pelton turbine

The supply water comes from a constant head reservoir at elevation H (see Fig. 2). The water jet is characterised by a velocity c1 and it is at atmospheric pressure.

The water falls vertically into the lower channel and the whole energy transfer from nozzle outlet to tailrace takes place at atmospheric pressure.

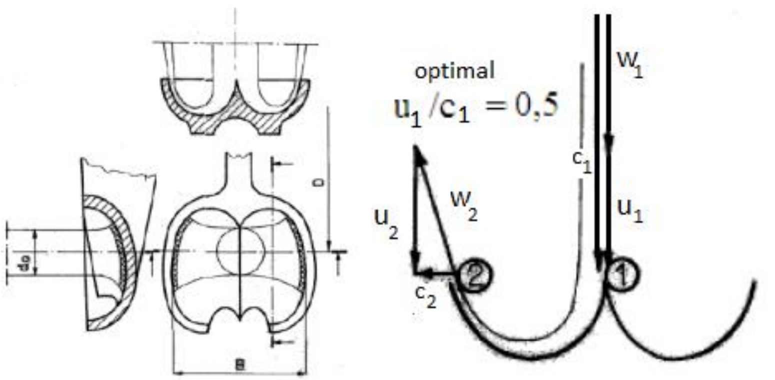


Figure 3 Velocity triangles. At the inlet and outlet of the bucket for optimal u/c1 = 0,5 Speed triangles of the flow of water (Fig. 4), for the optimal value of u/c1=0,5

The operating characteristics of Pelton turbines, under the design conditions, are the head **H** (m), the flow of water **Qtot** (m3/s) and number of revolutions **n** (revolutions/min).

The aim of this work is to present a single tool (easiest and most productive software **for students** Mathcad, MATLAB or MS excel) able to predict the performances of several configurations of Pelton turbines under some conditions (flow of water and number of rounds per second nominals and not nominals).

The change in momentum of water produces an impulse on the blades of the wheel of Pelton Turbine. This impulse generates the torque and rotation in the shaft. To obtain the optimum output from the Pelton Turbine the product of torque received by the wheel by the angular velocity must be maximum. It is obtained when the velocity u is half of c1.

The amount of water discharges from the nozzle is controlled by a needle valve provided inside the nozzle. For a constant water flow rate from the nozzles the speed of turbine changes with changing loads on it. For quality hydroelectricity generation the turbine should rotate at a constant speed u.

To keep the speed constant despite the changing loads on the turbine, water flow rate through the nozzles is changed. To control the gradual changes in load servo controlled spear valves are used in the jets to change the flow rate.

Following table (fig. 5) shows the values of **Q**, **H** and **n** of 6 Pelton turbines installed in the world, with the power from 3.6 MW to 110 MW. These six turbines have different sizes, speeds, pressures, forces.

2. Drawing of Pelton turbines

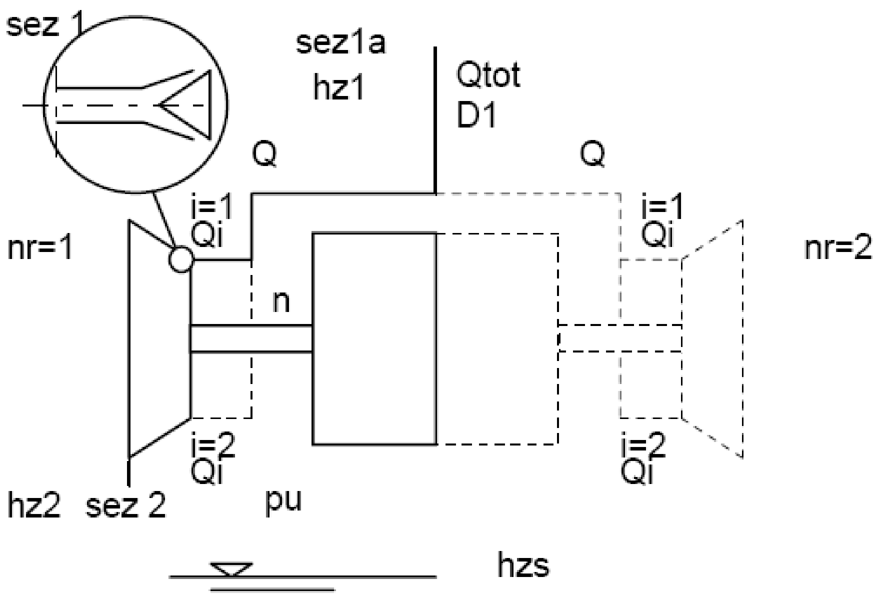


Figure 4 Schematic diagram of an alternator connected with nr = 1 or 2 Pelton wheels, with i = 1 or 2 .. 6 jets

3. Table with the essential data of 6 Pelton plants

Pelton Plant		Rated power to the alternator Ptot= kW	Motor Jump	Number of wheels per alternator nr=	i=	volume flow rate of turbine Qtot=	revolutions per minute	D1a=
Boazzo Italy	ca= 0	5.51×10^4	H= 727 m	1	1	8.75	300 rpm	1 m
Venaus Italy	ca= 1	1.912×10^4	1.02×10^3	1	1	2.25	500 rpm	0.52 m
Vomano Italy	ca= 2	7×10^4	H= 655 m	1	1	12.5	337.5 rpm	0.95 m
Ketenger Italy	ca= 3	3.658×10^3	H= 270 m	2	2	1.61	600 rpm	0.4 m
Kemano Canada	ca= 4	1.029×10^5	H= 760 m	1	4	16	327 rpm	1 m
Restetutio Peru	ca= 5	7.53×10^4	H= 257	1	6	33.4	200 rpm	1 m

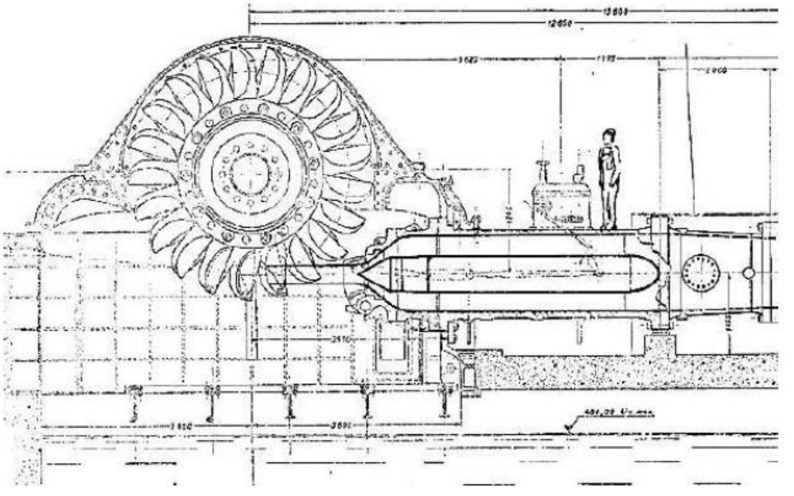
Figure 5: **D**ifferent data of 6 plants having nr = 1 or 2 Pelton wheels, with nozzle i = 1 or 2 .. 6 jets, flow rate: Qtot= 1.61-33.4 .m3/s.

4. Program PELTON 12 maggio 2017 rid.MCD

The following mathcad (PELTON01.MCD) program allows to determine the characteristics, starting from 7 data. The increase of water temperature in the distributor will be also calculated.

File DATAPELTONrid.PRN

ca	Pt	H	n.wheels	n.jetsi	Qtot	n	Dvalv
-	kW	m	-	-	m3/s	rounds/min	m
0	55100	727	1	1	8.75	300	1
1	19120	1020	1	1	2.25	500	0.52
2	70000	655	1	1	12.5	337.5	0.95
3	3658	270	2	2	1.61	600	0.4
4	102900	760	1	4	16	327	1
5	75300	257	1	6	33.4	200	1



We need to define additional units $\text{rounds} := \text{rad}\cdot 2\cdot\pi$ $\% := \frac{1}{100}$

Strarting from the 7 data of a turbine (Fig. 6) :
1 the nominal transmitted power Ptot of the alternator,
2 the engine head (H), the number of rotating wheels for alternator (nr),
3 the number of wheels per alternator nr
4 the number nozzle (s) for the wheel,
5 the nominal flow rate (Qtot) of the turbine,
6 the number of revolutions per minute (n)
7 the diameter D1a of the

The aim is to determine
-- the approximate values of the
-- geometric characteristics of 7 Pelton turbines and distributors with Doble plug,
-- some performacies.

The values of 7 variable are assigned by copying the file (DATAPELTONrid.PRN) in the matrix of 6 rows data (one line per turbine) and 7 columns. Switching from one to another by assigning turbine into ca variable value of ca = 0 or 1, or 6

: = Indicates that the result values are assigned the task of writing to his right.
= pointing right the value of the variable.

$ca := 0$ $ca = 0$

Boazzo hydroelectric power plant

data := READPRN("DATAPELTONrid.prn")

$$\text{data} = \begin{pmatrix} 0 & 5.51\times10^{4} & 727 & 1 & 1 & 8.75 & 300 & 1 \\ 1 & 1.912\times10^{4} & 1.02\times10^{3} & 1 & 1 & 2.25 & 500 & 0.52 \\ 2 & 7\times10^{4} & 655 & 1 & 1 & 12.5 & 337.5 & 0.95 \\ 3 & 3.658\times10^{3} & 270 & 2 & 2 & 1.61 & 600 & 0.4 \\ 4 & 1.029\times10^{5} & 760 & 1 & 4 & 16 & 327 & 1 \\ 5 & 7.53\times10^{4} & 257 & 1 & 6 & 33.4 & 200 & 1 \end{pmatrix}$$

data with unit of measure	assigns the variable value and the unit of measure	shows the value of the variable in different units of measurement
I) Rated power transmitted to the alternator	$Ptot := data_{ca,1}\cdot kW$	$Ptot = 5.51\times10^{7}\,kg\,m^{2}\,sec^{-3}$
II) Motor Jump	$H := data_{ca,2}\cdot m$	$H = 727\,m$
III) Number of wheels per alternator	$nr := data_{ca,3}$	$nr = 1$
IV) Number of nozzles per wheel	$i := data_{ca,4}$	$i = 1$
V) Total volume flow rate of turbine	$Qtot := data_{ca,5}\cdot\frac{m^3}{sec}$	$Qtot = 8.75\,m^{3}\,sec^{-1}$
VI) Number of revolutions per minute	$n := data_{ca,6}\cdot\frac{rounds}{min}$ $n = 31.416\,sec^{-1}$	$n = 300\,\frac{rounds}{min}$

We must take reliable values of additional variables or parameters

Water density	$\rho o := 1000\cdot\frac{kg}{m^3}$	$\rho o = 1\times10^{3}\,kg\,m^{-3}$
Nozzle velocity coefficient	$\varphi := 0.97$	$\varphi = 0.97$
VII) Diameter and area of penstock	$D1a := data_{ca,7}\cdot m$	$D1a = 1\,m$
	$A1a := \frac{\pi\cdot D1a^2}{4}$	$A1a = 0.785\,m^2$
VIII) Volume flow rate for each wheel	$Q := \frac{Qtot}{nr}$	$Q = 8.75\,m^{3}\,sec^{-1}$
IX) Flow rate per nozzle	$Qi := \frac{Qtot}{nr\cdot i}$	$Qi = 8.75\,m^{3}\,sec^{-1}$
Xa) level of surface ofthedischargechannel	$hzc := 0\cdot m$	$hzc = 0\,m$
Xb) level of the input section	$hz1 := 4\cdot m$	$hz1 = 4\,m$

Xc) level of the output section	$hz2 := 4 \cdot m$	$hz2 = 4\,m$
XIa) static pressure at output	$p2 := 0 \cdot Pa$	
XIIa) residual velocity output (negligible)	$c2 := 0 \cdot \frac{m}{sec}$	
XIIb) Total head at output	$ht2 := \frac{p2}{g \cdot \rho o} + \frac{c2^2}{2 \cdot g} + hz2$	$ht2 =$

CALCULATION OF FEATURES:

1 overall hydraulic power	$Pitot := g \cdot \rho o \cdot Qtot \cdot H$	$Pitot = 6.238 \times 10^7\,kg\,m^2\,se$ $Pitot = 6.238 \times 10^4\,kW$
2 hydraulic power per wheel	$Pi := g \cdot \rho o \cdot Q \cdot H$	$Pi = 6.238 \times 10^7\,kg\,m^2\,sec^{-}$ $Pi = 6.238 \times 10^4\,kW$
3 mechanical power transmitted by each wheel	$P := \frac{Ptot}{nr}$	$P = 5.51 \times 10^7\,kg\,m^2\,sec^{-3}$ $P = 5.51 \times 10^4\,kW$
4 total efficiency of the turbine	$\eta := \frac{P}{Pi}$	$\eta = 0.883$
5 power losses per wheel (hydraulic leaks + mechanical).)	$Pr := Pi - P$	$Pr = 7.283 \times 10^6\,kg\,m^2\,sec^{-}$ $Pr = 7.283 \times 10^3\,kW$
6 total losses of turbine (hydraulic leaks + mechanical).	$Prtot := Pitot - Ptot$	$Prtot = 7.283 \times 10^6\,kg\,m^2\,se$ $Prtot = 7.283 \times 10^3\,kW$
7 Total Losses Pr per Pi	$iPr := \frac{Pr}{Pi}$	$iPr = 0.117$ $iPr = 11.674\,\%$

8 Conditions in the penstock

8.1 total height	$ht1a := H + ht2$	$ht1a = 731\,m$
8.2 speed in conduct	$c1a := \frac{Q}{A1a}$	$c1a = 11.141\,m\,sec^{-1}$
8.3 kinetic height	$hc1a := \frac{c1a^2}{2 \cdot g}$	$hc1a = 6.328\,m$
8.4 piezometric height	$hp1a := ht1a - hc1a - hz1$	$hp1a = 720.672\,m$
8.5 piezometric quota	$zp1a := hp1a + hz1$	$zp1a = 724.672\,m$
8.6 static pressure	$p1a := hp1a \cdot g \cdot \rho o$	$p1a = 7.067 \times 10^6\,kg\,m^{-1}\,sec^{-2}$ $p1a = 7.067 \times 10^6\,Pa$ $p1a = 69.75\,atm$
8.7 ratio of the pressure head and piezometric quota	$rp1a := \frac{hp1a}{zp1a}$	$rp1a = 0.994$

9 Condition of the jet

9.1 total theoretical energy	$ht1t := ht1a$	$ht1t = 731\,m$
9.2 theoretical spead of the jet	$c1t := (2 \cdot g \cdot H)^{0.5}$	$c1t = 119.411\,m\,sec^{-1}$
9.3 theoretical kinetic energy	$hc1t := \frac{c1t^2}{2 \cdot g}$	$hc1t = 727\,m$
9.4 effettive velocity	$c1 := \varphi \cdot c1t$	$c1 = 115.828\,m\,sec^{-1}$
9.5 effective kinetic energy	$hc1 := \frac{c1^2}{2 \cdot g}$	$hc1 = 684.034\,m$
9.6 theoretical diameter of the jet	$d0t := \left(\frac{Qi}{c1t} \cdot \frac{4}{\pi}\right)^{0.5}$	$d0t = 0.305\,m$
9.7 effective diameter of the jet	$d0 := \left(\frac{Qi}{c1} \cdot \frac{4}{\pi}\right)^{0.5}$	$d0 = 0.31\,m$
9.8 loss of energy in the nozzle	$hr := \left(1 - \varphi^2\right) \cdot H$	$hr = 42.966\,m$
9.9 loss hr compared to H	$ihr := \frac{hr}{H}$	$ihr = 0.059$ $\quad ihr = 5.91\,\%$
9.10 efficiengy of nozzle	$\eta u := \varphi^2$	$\eta u = 0.941$ $\quad \eta u = 94.09\,\%$
9.11 loss of power in the nozzles of a single wheel	$Pri := g \cdot \rho o \cdot Q \cdot hr$	$Pri = 3.687 \times 10^6\,kg\,m^2\,sec^{-3}$ $Pri = 3.687 \times 10^3\,kW$
9.12 loss in the nozzles of all the wheels	$Prit := nr \cdot Pri$	$Prit = 3.687 \times 10^6\,kg\,m^2\,sec^{-3}$ $Prit = 3.687 \times 10^3\,kW$
9.13 hydraulic loss of the nozzles with respect to the losses of the enthire turbine	$lossnozzle := \frac{ihr}{iPr}$	$lossnozzle = 50.625\,\%$ $lossnozzle = 0.506$

10 INCREASE OF TEMPERATURE of water inside the nozzle

Between the input and the nozzle output the loss Pri of power, by friction of the water, becomes heat transmitted to the flow rate Qi, according to the law of calorimetry:

$$Pri = \rho o \cdot g \cdot Qi \cdot hr = \rho o \cdot g \cdot Qi \cdot H \cdot (1-\varphi^2) = g \cdot \rho o \cdot Qi \cdot H \cdot (1-\eta u) = \rho o \cdot Qi \cdot Cp \cdot DT \quad [W]$$

The temperature jump: $Dt = Pri/(\rho o \cdot Qi \cdot Cp) = g \cdot H \cdot (1-\eta u)/Cp = g \cdot H \cdot (1-\varphi^2)/Cp = g \cdot hr/Cp$

Dt can be calculate in four ways (Dt1, Dt2, Dt3 and Dt4) getting the same value. The last three values did not require knowledge of thr quantities Qi or PRI, but only (g*H, g*hr, Cp).

The specific heat of water $Cp := 1 \cdot \frac{kcal}{kg \cdot K}$ $Cp = 4.187 \times 10^3 \, m^2 sec^{-2} K^{-1}$ $Cp = 1 \times 10^3 \frac{cal}{kg \cdot K}$ $Cp = 4.187 \times 10^3 \frac{joule}{kg \cdot K}$

$Dt1 := \frac{Pri}{(\rho o \cdot Q \cdot Cp)}$ $Dt1 = 0.101\,K$ $Dt2 := g \cdot \frac{H \cdot (1 - \eta u)}{Cp}$ $Dt2 = 0.101\,K$

$Dt3 := g \cdot H \cdot \frac{1 - \varphi^2}{Cp}$ $Dt3 = 0.101\,K$ $Dt4 := g \cdot \frac{hr}{Cp}$ $Dt4 = 0.101\,K$

Dt = Dt1 = Dt2 = Dt3 = Dt4 is always very small ! ! ! ! ! !.