DESIGN CRITERIA APPLIED TO PRESSURISED GRAVITY SYSTEMS

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ABSTRACT

As a rule, hydraulic systems have problems with leaks and ruptures that might result from inadequate design, installation or performance, mechanical behaviour of pipe material and, eventually, accidents that might occur.

The definition of suitable design criteria in gravity pressurised hydraulic circuits, such as water supply and hydropower systems, is of the utmost importance and has become a priority for a good project implementation. The aim of this paper is to systematise practical guidelines for design, in order to create ground rules for control purposes and to protect citizens against ruptures provoked by the dynamic behaviour under normal and extreme operational conditions.

The correct evaluation of these ground rules will depend upon the system type and the safety level to be guaranteed during the system operation. During design stage two main situations must be analysed: the normal operation of the system and the abnormal situations, such as waterhammer and rupture occurrences.

A very promising challenge for the future, concerning pressure control and consequent leakage reduction, is the use of micro-turbines. These devices are particularly appropriated for water conveyance systems with significant head difference levels, having the benefit associated to the renewable energy production.

Key-words: design criteria, pressurised gravity systems, dynamic behaviour

1 - INTRODUCTION

In pressurised gravity systems the pipe is a fundamental component on which depends greatly the safety and operation of the system. Not only does the pipeline allow the transport of fluid and energy from the source to downstream end, but also the transformation from potential energy into piezometric energy.
During its lifetime the pipe will be submitted to several strength and external constraints due to topography, intrinsic characteristics (e.g. pipe weight and temperature variations) and internal tensions. The response of the hydraulic behaviour will be characterised by the piezometric head along the pipe made of steel or other increasing uses of unconventional materials (e.g. fibreglass, PEAD – HDP, concrete and cast iron). In the case of hydropower systems with long hydraulic circuits, part of the conveyance circuit can be in tunnel.

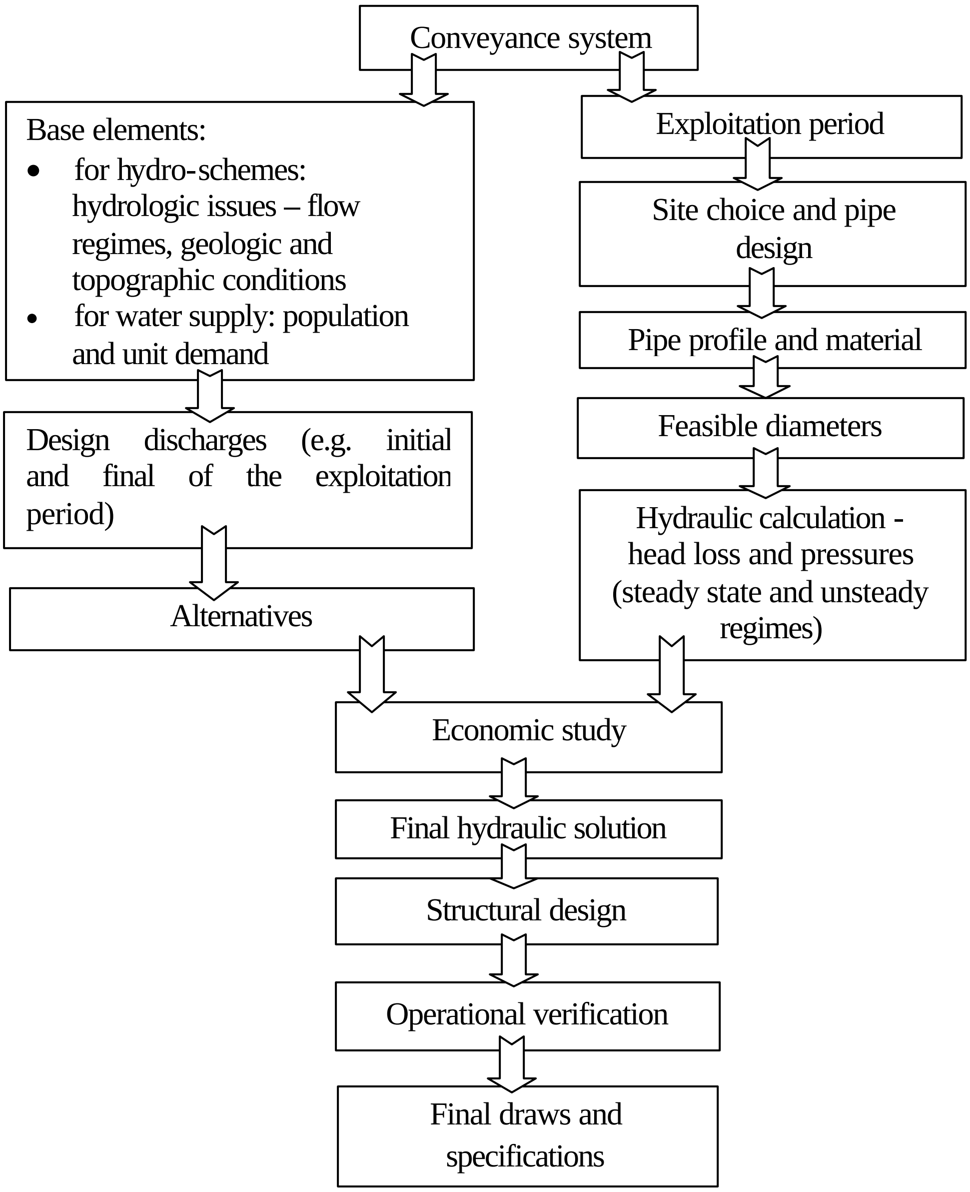


Fig. 1 – General design methodology

A general methodology is presented in Figure 1, with the base requirements applied to hydraulic conveyance systems. In the design Three main design stages can be established during the design process: 1) Preliminary studies; 2) Base Project; 3) Final Project. For each case the design procedures adopted would depend upon the available data, the required detail and the results from the stage before.

2 - DESIGN METHODOLOGY

2.1 - Introduction

General speaking, the following methodology uses information suitable for each system type which presents common remarks that must be considered during different design stages.

In what concerns hydropower systems with long circuits, it is usual to distinguish low-pressure from high-pressure pipes. In any system type, the profile must be adjustable as a function of the minimum pressure envelope, in order to avoid sub-atmospheric conditions.

2.2 - Pipe installation

In lack of other constraints, the project lifetime can be defined, general speaking, around 40 years for civil work components (e.g. pipes, reservoirs and buildings) and 20 years for electromechanical equipment (e.g. motorised valves and control equipment). Frequently, the project lifetime adopted is lower, essentially, due to reasons of economic investment stages, bad system operation for large discharge variations, or difficulty on predicts future discharge variations (e.g. drinking systems).

Along a conveyance pipeline, can be identified several types of devices (THORLEY, 1991): 1) sectioning valves at upstream and downstream end of the pipe; 2) reservoirs; 3) load loss chambers (e.g. in water drinking systems) and powerhouse (i.e. in hydropower systems); 4) bottom discharge valves at the lowest points (in case of sectioned pipe it must be positioned immediately at downstream of section valves, in ascending pipes, or downstream of these valves, in descending pipes, allowing pipe emptying during repair or cleaning; 5) air-valves at the high points of the pipeline, (for sectioned pipe at upstream of ascending pipes or downstream in descending pipes) in order to discharge accumulated air and to allow air admission in case of emptying the pipe, or whenever the pressure decreases, avoiding collapsing or buckling.

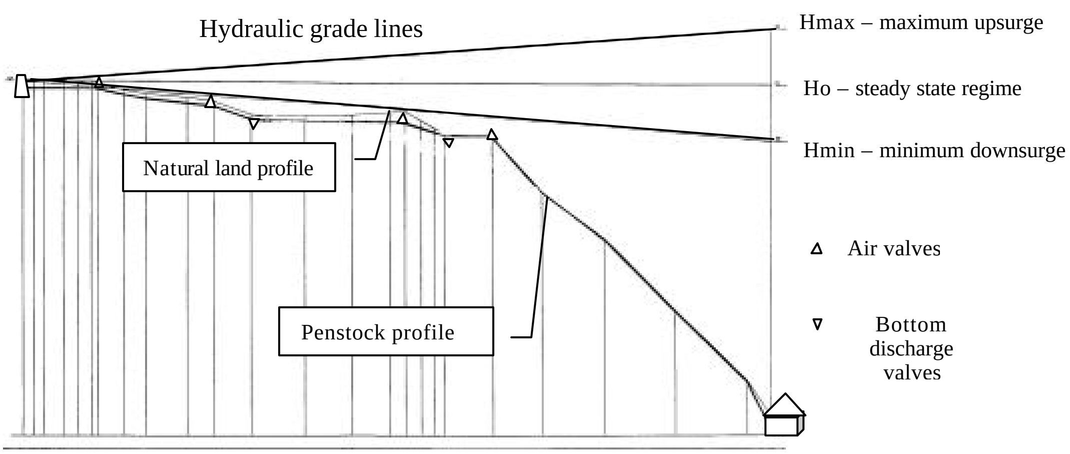


Fig. 2 – Example of a penstock profile of a hydropower system.

It should be emphasised that the highest point of the conduit must be positioned always below the lowest hydraulic gradient line under extreme operating conditions, in order to avoid sub-atmospheric pressures along the conduit (Figure 2). On the other hand, the penstock must be designed to bear the maximum internal pressure due to waterhammer effects during normal and abnormal operational conditions. It is always laid on a stable site and towards the hill-slope. Whenever possible, the pipe must be buried in order to avoid temperature effects, such as pipe expansion or drying, otherwise, these effects must be considered in the pipe design.

The plan pipeline must be chosen according to the minimum distance and for water supply systems it should be installed, whenever possible along roads, although has to attending to the natural land constraints, such as high and low points, side streams and gullies, which impose the construction of crossing structures or inverted siphons.

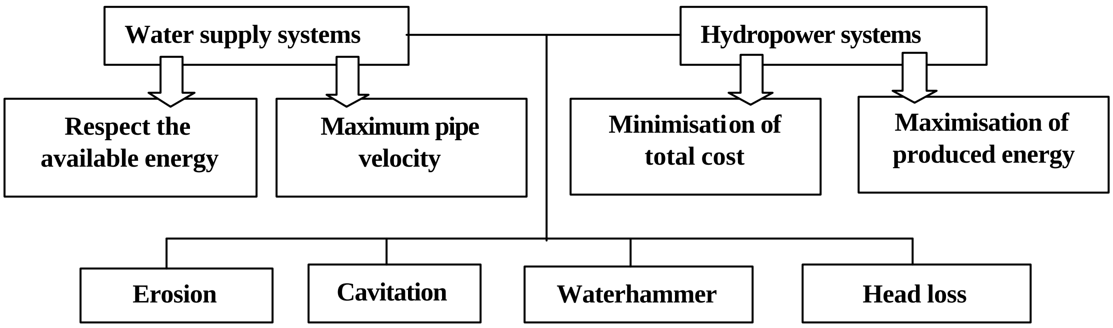


Fig. 3 - Economic design criteria applied to gravity systems

The choice of pipe diameter will be the minimum compatible to the transport of the fluid under required conditions. Nevertheless, the design associated to economic criteria, feasible and safety conditions will depend on the system type (see Figure 3) according to the main objectives.
After discharge fixed, depending on several factors, such as the population consumption and type of regularisation, the diameter must be chosen. The maximum velocity will depend on regulations, but a maximum value of 1.5 m/s is acceptable, although in larger diameter can be used greater values. The headloss must be compatible with the available energy.
The peak duration adopted in the pipe design will influence the discharge and, consequently, the pipe diameter and, inversely, the regularisation reservoir capacity. Thus, the economic solution must obtained and adopted.
The installation of loss energy devices, such as pressure reduction valves or head loss chambers to reduce the pressure in downstream pipes, can be economically advantageous. Alternatively, the energy dissipation can be profited through the installation of micro-turbines or reversible pumps.

2.3- Pipe material

For drinking systems, the pipe material must be appropriated to the potable water transport and for maximum pressures expectable. Can be used the PVC, reinforced concrete, medium and high density polyethylene, fibreglass, reinforced polyester, cast iron, steel and other pipe materials. In pipes not protected and submitted to vibrations and other efforts, the material should be appropriated (i.e. steel or cast iron). Materials susceptible to internal or external corrosion must be conveniently protected according to the nature of the aggressive agent. For drinking water, the internal protection must be made in adequate products in order to avoid water quality impacts.

3 - HYDRAULIC ACTIONS

3.1 - Introduction

The evaluation of hydraulic actions allows the definition of maximum probable internal pressures in different design stages, as a function of hydromechanical equipment characteristics to be installed in different systems. The verification of operational conditions of the global system (pipe/equipment) must be carried out in order to guarantee technical specifications, safety and exploitation criteria adopted in the project.
In preliminary design stages, the verification of necessity of protection devices must be considered, namely through the installation of surge tanks, air vessels, synchronous valves and intermediate reservoirs. These devices have the main purpose of transient pressure control against waterhammer effects.
In some cases, modifications in the pipe installation must be performed, particularly in the elevation pipe position, in order to improve hydraulic pipe behaviour in terms of avoiding over or sub pressures.

3.2 - Steady state regime

The application of Colebrook-White (C-W) formulae or, alternatively, but with less accuracy, the use of empirical formulae (e.g. Gauckler-Manning-Stricler, Hazen-Williams, among others) for head loss characterisation, allow the determination of the hydraulic grade lines (or piezometric lines) corresponding to the operational discharge range. The C-W equation is the more accurate formula to use to determine the friction factor necessary to calculate head loss in pipe flow problems. Nevertheless, its implicit formulation with regard to friction factor makes it difficult to use. An explicit formulation of the C-W equation, much more convenient to handle and with a very accurate approximation (error $\approx$ 0.12%), is presented (SOUSA et al., 1999):

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{k}{3.7D} - \frac{5.16}{Re}\log\left(\frac{k}{3.7D} + \frac{5.09}{Re^{0.87}}\right)\right] \quad (1)$$

Sensitivity analysis must be performed based on roughness value uncertainties due to the variation during the net pipe life.

3.3 - Unsteady conditions

3.3.1 - Introduction

The analysis of unsteady-state regimes induced by discharge controlling devices (the change of device settings) will depend upon the system's importance, its physical characteristics and the design stage. It allows the definition of the most probable extreme piezometric lines (envelopes) during different operational conditions.

In the case of hydropower systems, whenever they were linked to the national electric grid, the constraints associated with isolated systems due to continuous regulation of load-turbine speed will be neglected. The development of expert computer codes allows adopting unconventional solutions through the conception of long conveyance systems (e.g. penstocks) without protection devices namely surge tanks.
The main operational situations either in water supply systems (WSS) or in hydropower schemes (HS) that will generate significant transient pressures are mainly characterised by the following conditions:

- closure and opening of safety and control discharge valves (WSS and HS);
- fast closure of guide vanes or nozzles from reaction and impulse turbines, respectively (HS);
- runaway due to guide vane closure failure and/or sudden load rejection (HS);
- start-up and turbine loading (HS).

Safety coefficients will depend on the type of the manoeuvre: 1) normal; 2) exceptional or emergency type; and 3) accidental or catastrophic. General speaking, for design of gravity systems are adopted the first two types of manoeuvres.
A general methodology, which includes analysis of transients, as the base rule, is presented afterwards (RAMOS et al., 2000):

A- Preliminary, feasibility studies and early design phases.

- Preliminary transient (waterhammer) analysis for basic situations and manoeuvres depending on the type of the project.

  In order to guarantee a feasible and economic solution without special protection devices or to predict operational constraints or the type of protection to be specified later.

B- Detailed design studies for tenders

- Detailed transient analysis and studies for normal and abnormal conditions, including the selected protection systems and the main parameters of the equipment.

  In order to specify the main component characteristics, in what concerns the hydraulic conveyance circuit and the flow control equipment based on estimated equipment characteristics.

C- Final studies for construction and operation

- Detailed transient analysis and computer simulations including the characteristics of the selected equipment and final specifications of civil works.

  In order to verify the safety level of the hydrosystem and to specify operation rules to support the software development for special automation systems.

3.3.2 - Preliminary studies

In a simplified way the use of semi-empirical formula to obtain pressure variations are acceptable. In particular for hydropower schemes the Lein formulation (LEIN, 1965) presents good results:

$$\Delta H_M = K_L \frac{LV}{gT} \tag{2}$$

where:
ΔH_M = maximum variation of piezometric head;
L = pipe length;
V = flow velocity;
T = duration of the manoeuvre;
K_L = empirical parameter, which value depends on the turbine specific speed (e.g. 1.5 for Francis turbine with low-medium specific speed);
g = gravitational acceleration.

The Michaud formula is a particular case for K_L = 2. These methods, as well as Allievi charts are not advisable for advanced design stages, regarding the actual computer code development and knowledge levels. In this stage, the result for the hydraulic grade line envelope are two straight lines and must be printed out together with the conveyance system profile in order to ascertain possible critical points.

3.3.3 - Base project

In this stage the design methodology is improved based on the knowledge of equipment characteristics that will be installed. It might be used a computer code program based on numerical resolution of energy and continuity equations through the method of characteristics (MOC) to simulate the hydraulic performance of the system with different types of components (e.g. valves, turbines, protection devices, among others). The results of simulations are the envelopes of piezometric lines, as well as pressure variations, discharge and velocities along the system. In this way, it is possible to evaluate the time manoeuvre of closing or opening of controlling discharge devices (e.g. guide vanes, nozzles or valves).
Maximum and minimum pressure values, in each pipe cross section, are analysed based on the probable resistance of each pipe branch and on its elevation position, in order to avoid either ruptures or sub-atmospheric pressures occurrence.

3.3.4 - Final project

The final characteristics of the pipe and the equipment are known. Thus, the situations of normal and emergency manoeuvres, such as composite manoeuvres might be performed, as well as the compatibility between the conception, the resistance characteristics and the hydro-mechanic equipment behaviour.
The collaboration between manufacturers of equipment and designers is vital in order to allow the detection of faults, unsafe situations or to mitigate design incompatibilities.

Depending on the importance of the system, different extreme scenarios of accidental cases could be analysed, such as the hydrodynamics of earthquakes or rupture actions.

4 - ANALYSIS OF SPECIAL COMPONENTS

4.1- Pipes

As is well known, the conveyance systems must be designed to resist mechanically the maximum internal pressure due to waterhammer effects during normal and abnormal operational conditions. For small slopes and, especially in plastic pipes, the pipe must be buried in order to avoid temperature effects or these effects must be considered in the pipe design. The critical condition of pipe minimum thickness corresponds to pipe crushing due to sub-atmospheric-pressure by vacuum occurrence. For this condition, when a long steel pipe is forced by an external pressure p_2 greater than internal pressure p_1, creates a differential critical pressure $\Delta p_{cr} = p_2 - p_1$ that can be obtained by the following equation:

$$\Delta p_{cr} = \left(p_2 - p_1\right)_{cr} = \frac{2E}{1-\upsilon^2}\left(\frac{t}{D}\right)^3 \qquad (3)$$

being E (Pa) the steel elasticity modulus, υ the steel Poisson coefficient, t (m) the pipe thickness and D (m) the pipe diameter.

In order to take into account eventual geometric imperfections, according to European Convention for Constructional Steelwork (ECCS), it is proposed the following relation:

$$p_{atm} = \frac{7.35}{F}\Delta p_{cr} \qquad (4)$$

where p_{atm} is the atmospheric pressure (p_{atm} = 10.12×10^4 Pa) and F a safety factor.
Based on equations (3) and (4) the minimum steel pipe thickness (t) for a given diameter (D) will be obtained through the following equation:

$$\frac{t}{D} \geq 19.02\sqrt[3]{\frac{F\left(1-\upsilon^2\right)}{E}} \qquad (5)$$

In order to consider corrosion effects, it is usual to add 1 mm more to the pipe thickness.
For other homogeneous pipe materials, equivalent formulations should be used. In non-homogeneous materials (e.g. fibreglass, reinforced concrete and others) the methodology must be obtained from the pipe manufacturers. In the case of buried pipe it must be analysed the combined effect due to vacuum occurrence and resistance for external loads.

Net forces due to pressure ($_p$), obtained from the most unfavourable conditions, and momentum change ($_m$), for different combination of possible operating conditions are computed as follows:

$$F_{px} = p\,A\left(\cos\theta_1 - \cos\theta_2\right) \qquad F_{py} = p\,A\left(\sin\,\theta_1 - \sin\,\theta_2\right)$$
$$F_{mx} = \rho QU\left(\cos\theta_1 - \cos\theta_2\right) \qquad F_{my} = \rho QU\left(\sin\,\theta_1 - \sin\,\theta_2\right) \tag{6}$$

where p = pressure in the pipe; A = cross-section area of pipe; Q = discharge; θ_1 and θ_2 = angles as shown in Figure 4,

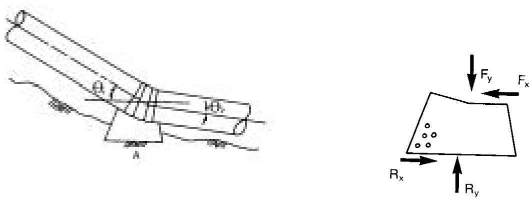


Fig. 4 – Resultant forces produced by weight, pressures and changes in momentum.

in order to design its supporting structures and to verify, at each change of direction, the resistance of junctions and bends (Figure 4).

The presentation of predicted extreme piezometric lines corresponding to the most unfavourable conditions and pipe field test are fundamental for the definition of design specifications (Figure 5).

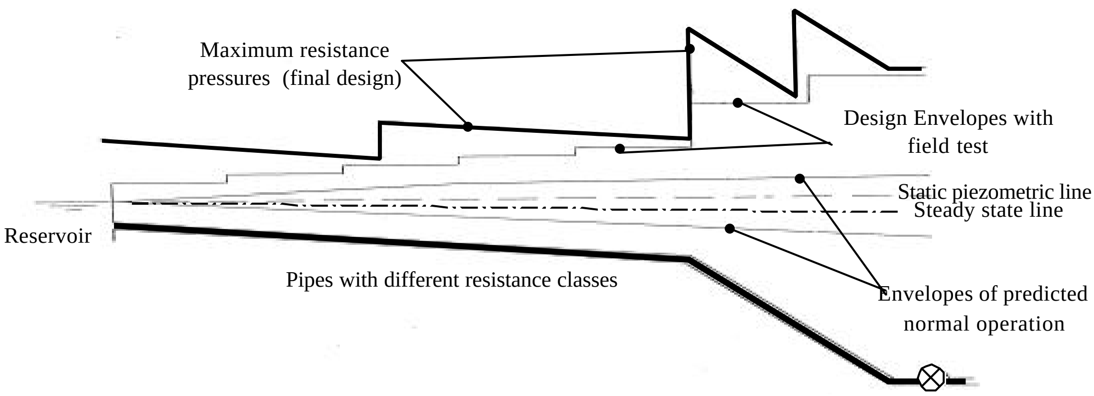


Fig. 5 – Piezometric lines for design and verification

The desired margin between the operating state and the resistance limit of the pipe is defined through safety factors. In order to characterise whether a limit state is exceeded, pressure limit values are defined (Figure 5) through envelopes of predicted operation. Thus, the maximum operating load must be lower than the limit value of the pipeline system. For instance, the limit values do not only depend upon the magnitude of the load (e.g. for thermoplastic materials) but also on the occurrence-frequency at which load is exerted during the lifetime material of the pipe. Thus, the mechanical resistance decreases, not only with the load value, but also essentially through the permanence of loads. Thus, the safety coefficient in order to define the maximum resistance pressure line can be greater than 2, even attaining 4 times the nominal pressure.

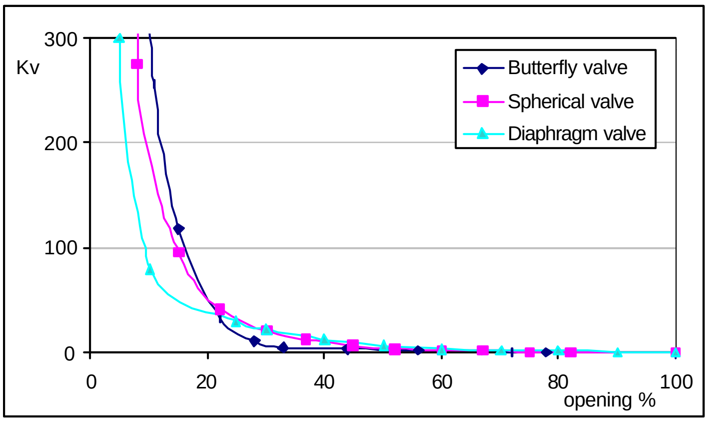
4.2- Valves

The most important elements in the definition of extreme pressures of gravity hydraulic systems are safety and control valves, namely in what concerns the protection of circuits and equipment maintenance.
The discharge through a valve can be characterised by the following equation:

$$Q_v = C_d A_p \sqrt{2g\,\Delta H_v} \qquad (7)$$

with $C_d = \dfrac{1}{\sqrt{K_v}}$ the discharge coefficient of the valve inserted in the pipe that is a function of the valve type (i.e. local head loss coefficient K_v) and the opening percentage, being A_p the reference area (e.g. pipe cross section), and $C_d = \dfrac{1}{\sqrt{K_v + 1}}$ for discharging into the atmosphere.

For butterfly and spherical valves the opening percentage is defined by the ratio of angle position with total opening angle and for diaphragm valve is defined for relative opening.



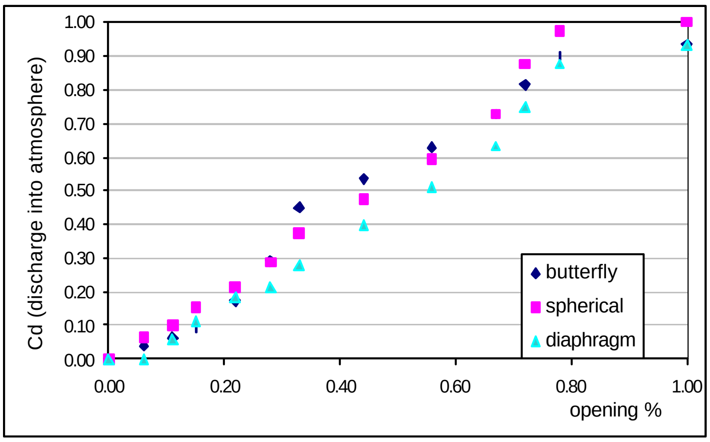
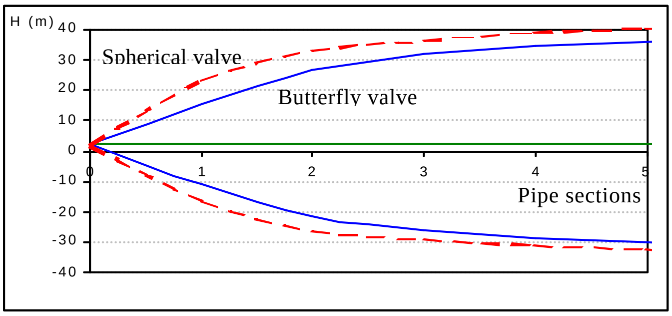


Fig. 6 – Head loss coefficient and discharge coefficient (for a discharge into atmosphere) for different types of valves

Furthermore, the duration of the valve manoeuvre, the diameter and type of law (linear or non-linear) and the actuator type will influence the shape and values of the piezometric line envelopes (Figure 7).

A – Fast manoeuvre (T_C<2L/c) – Envelop of piezometric lines



B – Slow manoeuvre (T_C>2L/c)– piezometric values at valve section

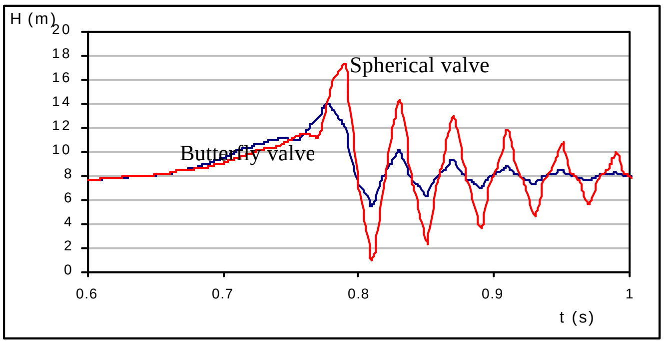


Fig. 7 – Example of the influence of the type of valve in head values

The effective time closure (T_{ef}) is based on the tangent to the point of the curve which dq/dt is maximum (with $q=Q/Q_o$ the relative discharge value):

$$T_{ef} = \Delta Q / \left(\frac{dq}{dt}\right)_{max} \tag{8}$$

where ΔQ is the discharge variation in the hydraulic system and Q_o is the discharge for total opening.

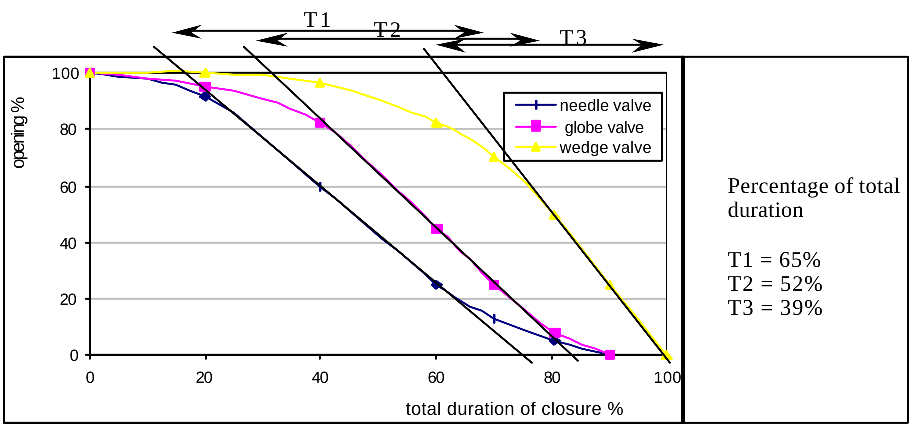


Fig. 8 – Comparison between effective time closure and total time closure of different valves

Water supply systems operate with a range of guaranteed pressures and, whenever exists excess of energy in local sections pressure-reducing valves (PRVs) are installed. These valves have different functions, one of them being the limitation of the downstream pressure. There are several types of PRVs, which the main advantage of non-conventional valves is the capacity to adjust to out-put demand maintaining quasi-uniform pressure. These type of PRVs allow a more efficient service management without consumer damage, leakage reduction, premature pipe ageing by material fatigue and occurrence of ruptures. This solution requires a pilot study with a constant pressure monitoring system.

Hence, upstream of a pressure-reducing valve (PRV) a micro-turbine can be installed (i.e. in series), in order to take advantage of the excess flow energy that, in normal conditions, would be lost (see Figure 9).

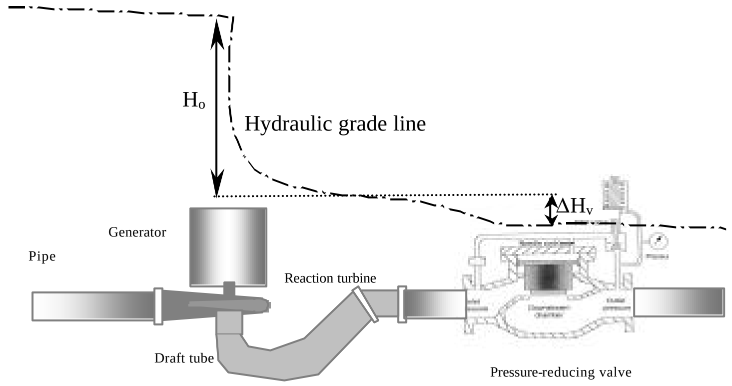


Fig. 9 – Scheme of a micro-turbine installation at upstream a PRV

4.3- Impulse turbines

Hydropower schemes when installed in mountainous regions are typically associated with long penstocks, in order to increase the available head. The hydraulic conveyance circuit at the upstream side of impulse turbines will be influenced by the nozzle control system of the discharge variation imposed through the closure law. This law and the hydraulic penstock characteristics will be very important to the transient pressure analysis. Hence, the disturbance source will be the turbine nozzle, a special type valve or control flow structure by changing the position of the internal part known as the needle. In this case, as in all pressure transients induced by a flow control device placed at the downstream end of a long pipe, it is very important to know the characteristic function for each nozzle (or valve) opening position.

Being the headloss (ΔH) characterised by the following pipe parameter (fL/D) and the kinetic energy head ($V^2/2g$):

$$F_{imp} = \frac{\Delta H}{V^2/2g} = \frac{fL}{D} \tag{9}$$

with f the Darcy-Weisbach friction factor, L the pipe or penstock length, D the pipe or penstock diameter, V the flow velocity in the pipe and g gravitational acceleration, the discharge will depend on the orifice cross-section A_o as follows

$$Q = \frac{A_p \sqrt{2gH_g}}{\sqrt{\frac{fL}{D} + \left(\frac{A_p}{C_d A_o} \right)^2}} \tag{10}$$

where; A_p the pipe cross-section; C_d the discharge coefficient of the orifice (or valve); H_g the goss head.

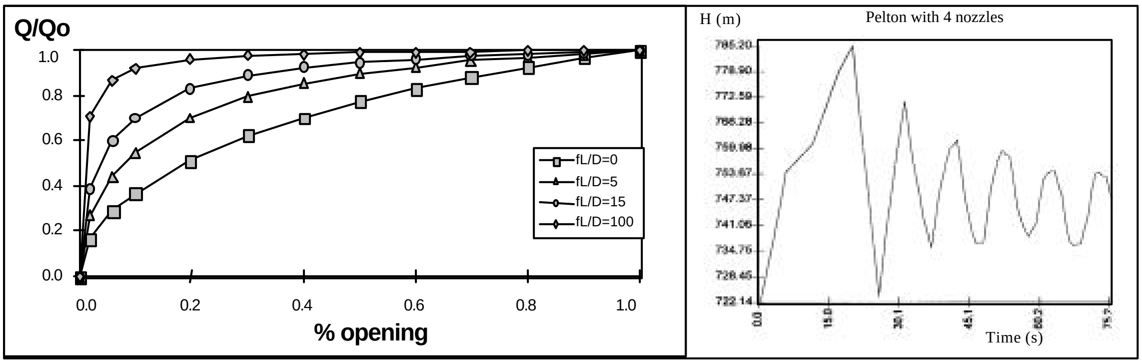


Fig. 10 - Discharge variation for different penstock characteristics and nozzle closures. Head variation in the powerhouse for a typical manoeuvre

Experience (RAMOS, 1995 and RAMOS et al., 2000) show that for high F_{imp} values the flow control can be very difficult to obtain, because the time duration of the physical manoeuvre of the nozzle or valve differs very much of the effective flow change duration T_{ef}, as mentioned for valves (Figure 8 and 10). In this way, for a linear time closure of a nozzle, the discharge variation will be only effective near the complete closed position. The total duration of the mechanical manoeuvre of the nozzle is very different from the effective time of discharge variation. Hence, a theoretical slow manoeuvre ($T_{ef}>T_E$, with $T_E=2L/c$, where c is the wave celerity) can be, in fact, transformed in a fast one (with $T_{ef}<T_E$ and where Q_o is the initial turbine discharge for full open nozzle or the maximum turbine discharge). Summing-up:

- the decrease of fL/D allows the discharge variation be more favourable;
- for large values of fL/D most of the discharge variation only occurs for small values of nozzle opening, at the end of the nozzle manoeuvre.

4.4- Reaction turbines

For low specific speed reaction turbines (i.e. Francis turbines with $Q_{RW}/Q_o < 1$, where Q_{RW} is the turbine discharge at runaway conditions and Q_o the nominal turbine discharge), the overspeed effect provoked by runaway conditions will potentially induce greater overpressures than those induced by just the guide vane closure effect. Hence, these overpressures can be obtained through the chart presented in Figure 11, based on systematic computer simulations for different types of runners (RAMOS, 1995).

The maximum upstream transient head variation will depend on N_s (with $N_s = n_o \frac{\sqrt{P}}{H_o^{1.25}}$) and two other parameters (see Figure 11): T_W/T_m and T_C/T_E, with T_C the closure time of the guide vane.

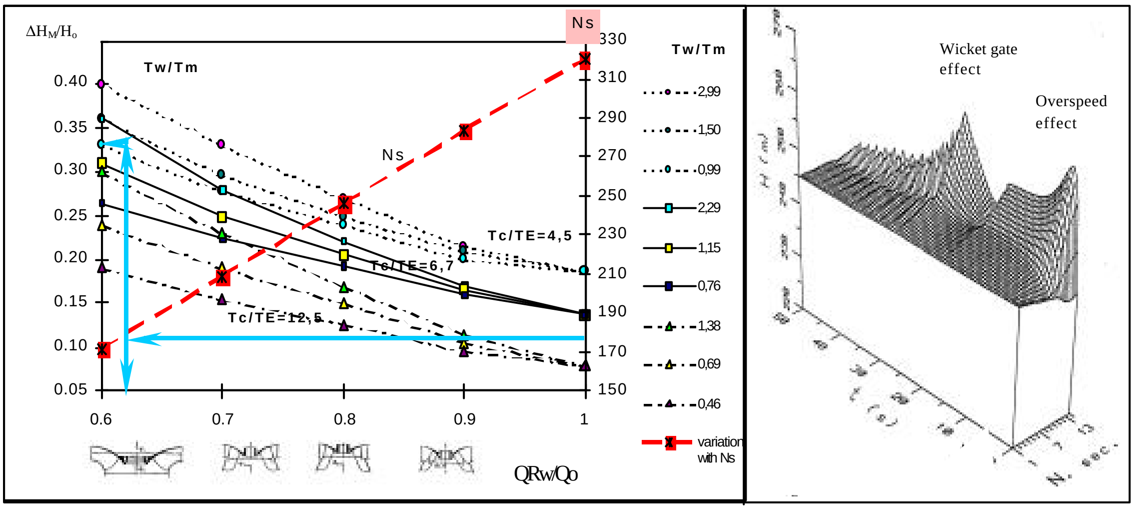


Fig. 11 – Maximum overpressure induced by both the overspeed and gate effects of low specific speed reaction turbines on upstream penstock (RAMOS, 1995).

The inertia machine time constant (or start-up time of rotating masses), T_m, has the order of magnitude of the time for the unit to attain the speed n_o, when submitted to a linear increasing hydraulic power from 0 to P_o, being defined by the following equation:

$$T_m = \frac{WD^2\, n_o^2}{3575\, P_o} x10^{-3} \tag{11}$$

and the hydraulic inertia time constant T_W is defined through the following equation

$$T_W = \frac{L\, V_o}{g\, H_o} \tag{12}$$

where,
L = pipe length (m);
H_o = reference net head (m);
n_o = the nominal runner speed (r.p.m.);
P_o = reference power or full load turbine power (kW);
V_o = initial or final flow velocity (m/s);
WD^2 = 4gI (N m2).

In hydropower plants with long penstocks (or large values of T_W) severe waterhammer troubles can occur. As indicated in Figure 11 (following the example through the arrows), the calculation begins with the N_s turbine value. Moving horizontally the N_s dashed line is reached and the Q_{Rw}/Q_o can be known. Knowing the T_W/T_m value (the relative water and turbine inertia time constants) and selecting the relative wicket closure time T_C/T_E, the relative maximum upsurge variation can be obtained ($\Delta H_M/H_o$). For $Q_{Rw} = Q_o$, the overpressure will only depend on the gate effect. These results allow an approximate evaluation of the maximum overpressure due to a sudden load rejection in Francis turbines. In these cases, both the upstream and downstream water columns must be analysed, in order to avoid excessive overpressure at penstock and at powerhouse or even water column rupture at draft tubes, which may lead to high pressure waves penetrating into the penstock.

5 - FINAL REMARKS

A complete analysis based on the interaction between all components of the system, with specific oscillatory characteristics, allows optimising the more convenient design, under safe, reliable and economic conditions. The up-to-date computer codes tend more and more to be an important tool in successive and integrated analysis, for different design constraints. Accidents due to hydraulic transients can represent an important risk, in what concerns both economic and life losses, as well as, the supply quality without interruptions. The type of analysis will be influenced by the design stage and the complexity of each system.

A classic solution used to minimise the hydraulic transients consists in inserting a surge tank in the hydraulic circuit, in order to reduce the total length of the hydraulic circuit under waterhammer action, or, alternatively, to install an air vessel. However, in some cases, these solutions can not be advisable, because, either the surge tank or the air vessel can be very costly structures and can cause significant environmental impacts. In this way, other solutions must be considered such as: the increasing of the valve (or guide vane) time closure in order to have a slow manoeuvre ($Tc>2L/c$); whenever possible, the use of impulse or reaction turbines, but with greater N_s values or, alternatively, the installation of a flywheel or even relief valves in hydropower systems to control the induced effect due to overspeed occurrence, must be performed.

For each pipe profile, and based on envelope piezometric lines, for the most predictable manoeuvres, the designers will define exploitation rules according to safety levels required and economic constraints. During the final project stage, several simulations and verifications must be performed for different operating conditions, in order to guarantee the structural resistance characteristics of the pipe, hydromechanical equipment and solid anchor supports.

REFERENCES

ALMEIDA, A.B., KOELLE, E. - Fluid Transients in Pipe Networks, C. M. P., Elsevier, 1992.

CHAUDHRY, M.H. - Applied Hydraulic Transients. Second Edition. Van Nostrand Reinhold Company, 1987.

LEIN, G. – The influence of Waterhammer on the Design and Operation of Pumped Storage Plants. Proceedings of the International Symposium on Waterhammer in Pumped Storage projects, ASME, pp.96-122, 1965.

LENCASTRE, A. – Handbook of Hydraulic Engineering. Ellis Horword Limited, John Wiley and Sons, 1987.

PEJOVIC, S., BOLDY, A. P., and OBRADOVIC, D. – Guidelines to Hydraulic Transient Analysis. Gower Technical Press, England, 1987.

RAMOS, H. - Simulation and Control of Hydrotransients at Small Hydroelectric Power Plants. Ph.D. Thesis. Technical University of Lisbon, Portugal (in Portuguese), 1995.

RAMOS, H. et al. – Guidelines for Design of SMALL HYDROPOWER PLANTS. Western Regional Energy Agency and Network and Department of Economic Development, North Ireland, 2000.

SOUSA, J. et al. – An Explicit Solution to the Colebrook-White Equation Through Simulated Anneling. Water Industry systems: modelling and optimization applications, Vol. II, edited by Dragan A Savic and Godfrey A Walters, University of Exeter, UK, 1999.

THORLEY, A. R. D. – Fluid Transients in Pipeline Systems – D&L George Ltd., England, 1991.

WYLIE, E., STREETER, V. - Fluid Transients in Systems. Prentice Hall, 1993.

SYMBOLOGY

A - cross-section area of pipe (m^2);
A_o - orifice cross-section (m^2);
A_p - pipe cross-section (m^2);
C_d - discharge coefficient of a valve or orifice(-);
D - pipe diameter (m);
E - steel elasticity modulus (Pa);
f - Darcy-Weisbach friction factor (-);
fL/D - pipe parameter (-);
g - gravitational acceleration (m/s^2);
H_g - goss head (m);
H_o - reference net head (m);
K_L - empirical parameter, which value depends on the turbine specific speed;
L - pipe length (m);
n_o - the nominal runner speed (r.p.m.);
N_s – specific speed (r.p.m.);
p - pressure in the pipe (Pa);
P_o - reference power or full load turbine power (kW);
Q - discharge;
t - pipe thickness (m);
T - duration of the manoeuvre (s);
T_C - closure time of the guide vane (s);
T_C/T_E - relative wicket closure time (-);
T_{ef} - effective time closure (s);
T_m - inertia machine time constant (s);
T_W - hydraulic inertia time constant (s);
T_W/T_m - relative water and turbine inertia time constants (-);

V - flow velocity (m/s);
$V^2/2g$ - kinetic energy head (m);
V_o - initial or final flow velocity (m/s);
WD^2 - inertia of rotating mass (= 4gI) (N m2)
ΔH_M - maximum variation of piezometric head;
υ - steel Poisson coefficient,
θ_1 and θ_2 - angles between pipes and horizontal plan (degree).