Surge tank throttles for safe and flexible operation of storage plants

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Abstract

Throttle surge tanks are a part of high head powerplants. The main consequence of a throttle placement is to introduce head losses by accelerating the flow. They make it possible to manage extreme water levels during mass oscillations while increasing water surge, e.g. water hammer, in the headrace tunnel. This phenomenon happens every time the flow discharge is changed in the waterway.

Either throttle is placed during construction to reduce costs or its placement is needed following a refurbishment to adapt the old surge tank geometry to the new design loads. However, the introduction of throttle is often not sufficient to adapt surge tank for important increases of discharge.

This article suggests a review of the existing throttled surge tanks and the establishment of a characterization. The non-exhaustive review focuses mainly on existing plants in Switzerland but also to extend to some existing in the world.

Good knowledge of throttles allows to reduce the steps and durations of throttle design and construction.

1. Introduction

1.1 Background

Most of storage power plants are high head power plants exploiting water heads higher than 200m. Their main function is to provide large amount of energy in a short laps of time and transfer water stored in summer to generate electricity during winter [1]. They provide almost 35% of the total electricity generation in Switzerland in 2015 [2] and take part in the Energy Strategy 2050 decided by the Swiss government due to their key role in the Swiss electricity market. Acording to energy strategy 2050, the mean annual hydropower production has to be increased under present framework conditions by 1.53 TWh/y. and by 3.16 TWh/y. under optimized conditions. Furthermore, the technically feasible hydropower potential in Switzerland is 41.0 TWh/y [3]. Rising existing dam, refurbishing old hydropower plant or adding new turbines are solutions to reach this increase of averaged annual generation.

For storage plants and, thus, for high head plants (Fig.1), it generally leads to an increase of the discharge flowing in the waterway. For significant increase of discharge, the existing waterway or its components must be carefully checked with a one dimensional transient model [4-6].

1.2 Surge tank

A surge tank is an excavation, which is connected to the waterway system and is generally open to the atmosphere [7] (Fig.1). The introduction of surge tanks allows reducing the construction cost of the pressure tunnel by minimising and reflecting the water hammer in/from the pressure shaft [8]. The water hammer generally follows discharge regulations in the power house, e.g. turbine starts or shut-downs. However, these changes lead to mass oscillations between the surge tank and the reservoir [7]. These oscillations could limit new plant operation due to this new response of the waterway.

There are different existing types of surge tanks: simple surge tank (Fig.2 (a)), surge tank with expansion(s) (Fig.2 (b)), throttled surge tanks (Fig.2 (c)) and differential surge tanks (Fig.2 (d)). The last three surge tanks aim

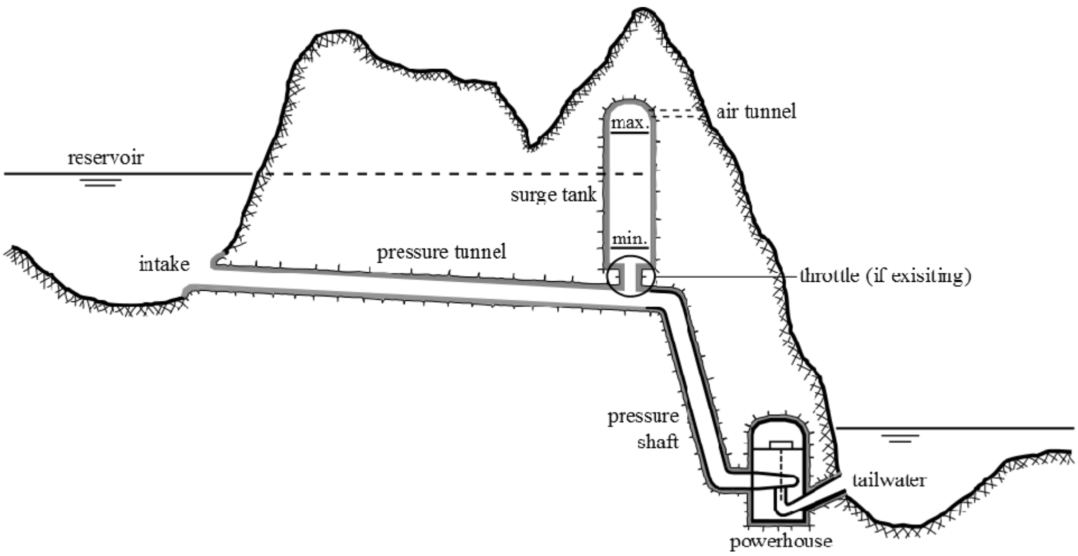


Fig. 1. Schematic view of a high head power plants (courtesy of A.J. Pachoud)

to decrease the duration and the amplitude of the mass oscillations but with different behaviours in comparison with simple surge tanks.

- Surge tanks with expansion(s) (Fig.2 (b)): The expansion allow to decrease the construction cost while insuring the stability. The reduced area of the intermediate shaft has to be as small as possible to accelerate the pressure evolution under the surge tank and to improve the damping of mass oscillations [10]. However, the intermediate shaft should not be smaller than the Thoma cross-section [11].
- Throttled surge tanks (Fig.2 (c)): Placing a throttle, at the entrance of surge, tanks helps to have similar effects to expansion chambers (by accelerating the damping effect of the surge tank).
- Differential surge tanks (Fig.2 (d)): This type of surge tank is often composed of a shaft and a bigger chamber. In case of a total closure, the water level in the shaft is going up rapidly until discharging in the main chamber.

Other types of damping device exist as the air cushion surge tanks mainly present in Norway [10]. This type of surge tanks requires stiff rocks with few cracks to withstand high air pressures and temperature when water compresses the air cushion.

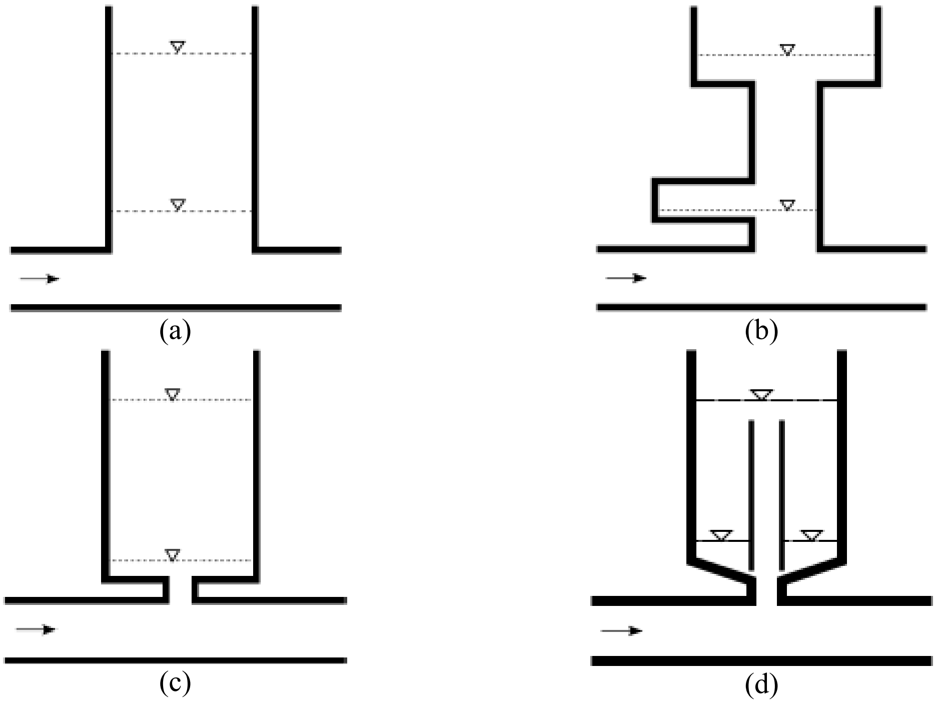
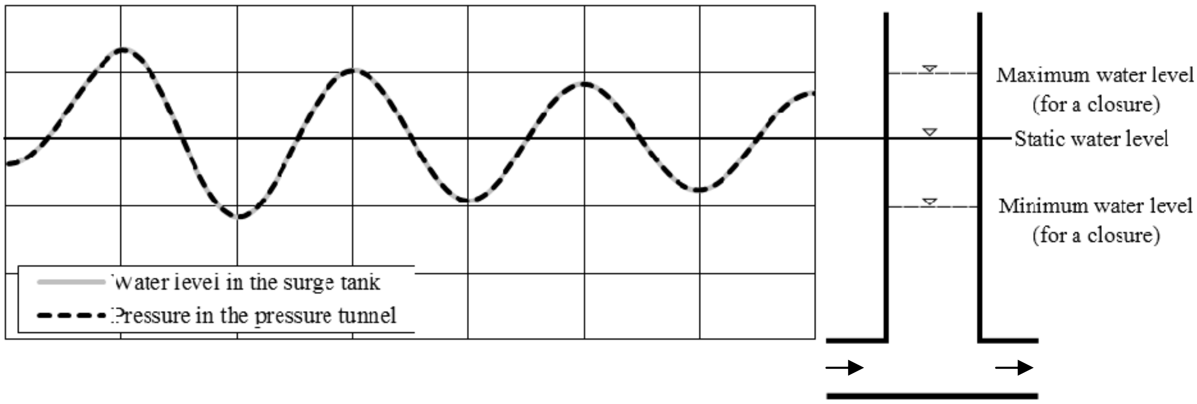


Fig. 2. Different types of surges tanks: (a) Simple surge tank; (b) Surge tanks with expansion(s); (c) Throttled surge tanks and (d) Differential surge tanks (adapted from [9])

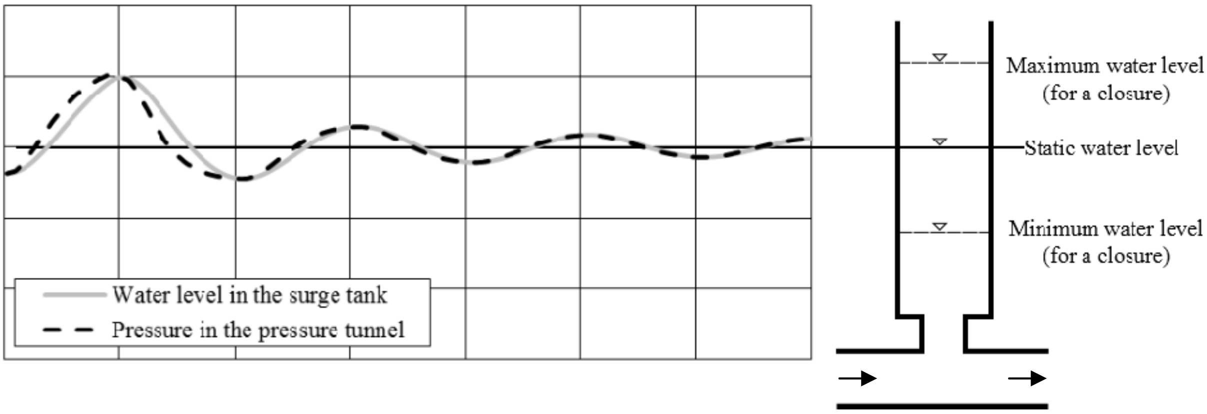
1.3 Throttle

Throttles are hydraulic devices accelerating the water flowing through and producing a given amount of head losses. Depending on the case or need, they may be placed at the entrance [4,9,12] (connection between the surge tank and pressure tunnel) or in the intermediate shaft between expansions [10,13,14,15].

The goal of a placement of a throttle is to keep extreme mass oscillations levels within the surge tank geometry. When the water is flowing in (resp. out) the surge tank through the throttle, a higher (resp. lower) pressure develops which damps the mass oscillations more quickly. The orifice may produce either symmetric or asymmetric head losses [13]. The main disadvantage of the placement of a throttle is that the dynamic pressure produced by the water hammer increases in the pressure tunnel. This increasing is mainly due to restriction of area which stops a fraction of the water hammer before entering in the surge tank. The difference of behaviour between a simple and throttled surge tank are shown schematically in Fig.3. For the throttled surge tank, the pressure increases and decreases faster while maximum and minimum water level decreases and increases.



(a)



(b)

Fig. 3. Schematic view of the evolution of the water level in a: (a) simple and (b) throttled surge tank[11]

1.4 Goal of the study

On one hand, the placement of a throttle could be decided before the construction of the plant and waterway to decrease the construction cost: all other parameters being equal (head, flowing discharge, waterway parameters, etc.), the cross-section of a throttle surge tank are smaller than the cross-section of a simple surge tank. On another hand, a throttle can be placed at the bottom of a surge tank to adapt the waterways to a refurbishment or a slight increase of discharge.

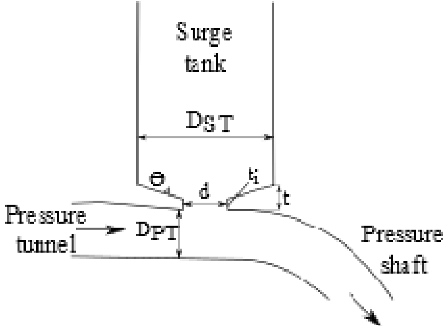
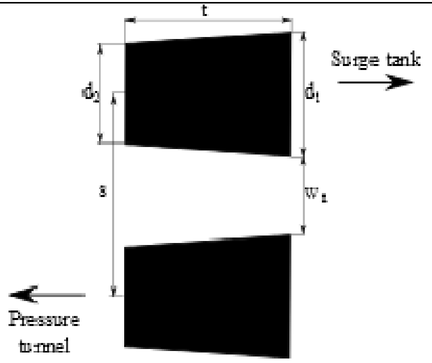
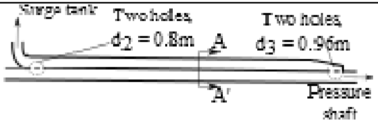
Anyway, for both cases, the main issue is to find a throttle geometry producing the head losses in each flow direction, i.e. surge tank filling and emptying, found with the one dimensional transient model [5,6]. A complete 3D-numerical or physical modelling is often needed to achieve the case-by-case design of throttles [4,12,15-17]. This study tries to categorize existing throttles, highlight main influencing parameters on head losses and give guidelines for future design.

2. Examples of existing throttle

Tab.1 shows different existing throttles in Switzerland and abroad. Different types of throttle can be highlighted from Tab.1:

- There are three with symmetrical openings (Etzelwerk, FMHL+ and Lavey+) and four with asymmetrical openings (Acaray, La Grande Dixence, Guadalami and Wassen I);
- There are two racks of bars, which are here asymmetrical (Amsteg and Gondo). However, there is, at least, one additional throttle with rack in Grimsel II [4].
- One more complex throttle with asymmetrical behaviour is vortex throttle (Kaunertal). However, there are at least five more vortex throttles in Austria [13].

For the asymmetrical throttles, a higher production of head losses is generally needed for the water flowing out of the surge tank (Amsteg, Gondo. La Grande Dixence, Kaunertal and Wassen). Furthermore, the ratio between the throttle openings and the pressure tunnel (or connecting pipe), β[1], varies from 0.383 (Gondo) to 0.89 (Acaray). This parameter is important for the wave transmission during water hammer. The smaller this parameter is, the higher pressure may increase in the pressure tunnel.

	Throttle geometry	Throttle parameters	Plant parameters
Acaray (Paraguay)		-shape: circular hole; -surge tank diameter, D_{ST}: 15.0 m; -pressure tunnel diameter, D_{PT}: 5.4 m; -inner throttle diameter, d: 4.8 m ($\beta=d/D \approx 0.889$); -throttle thickness, t: 1.6 m ($\alpha=t/D \approx 0.296$); -inner throttle thickness, t_i: 1.0 m ($\alpha_i=t_i/D \approx 0.185$); -throttle angle, Θ: 83.3°	-type: storage plant -net head, H: 103 m; -installed power capacity, P: 210 MW
Amsteg [18] (Switzerland)		-shape: 8 trapezoidal bars with a constant spacing s of 0.5 m placed in a connecting tunnel; -opening, w1: 0.22m ($\beta=w_1/s=0.44$); -throttle thickness, t: 0.4m ($\alpha=t/s \approx 0.8$); -throttle angle, Θ: 2.86°	-type: storage plant -discharge, Q: 50 m^3/s; -net head, H: 297 m; -installed power capacity, P: 120 MW
Etzelwerk (Switzerland)		-shape: Four rectangular holes between the pressure tunnel and the lower chamber of the surge tank; -pressure tunnel diameter, D_{PT}: 3.0m -throttle area, A_{TH}: $2xd_1(d_2+d_3)= 5.63m^2$ ($\beta = 0.797$)with d_1 =1.6m, d_2=0.8 and d_3 =0.96; -throttle thickness, t:	-type: storage plant -discharge, Q: 34 m^3/s; -net head, H: 470 m; -installed power capacity, P: 135 MW

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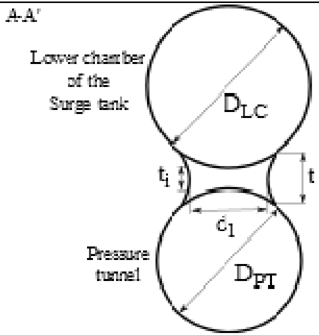
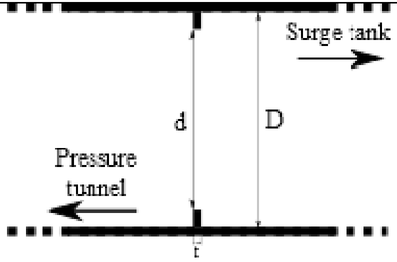
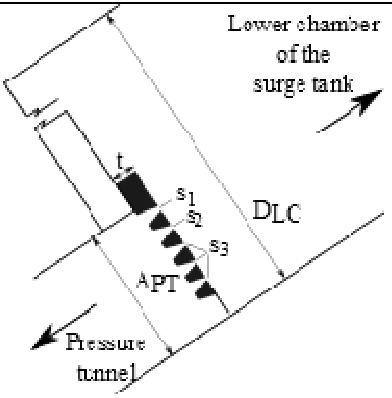
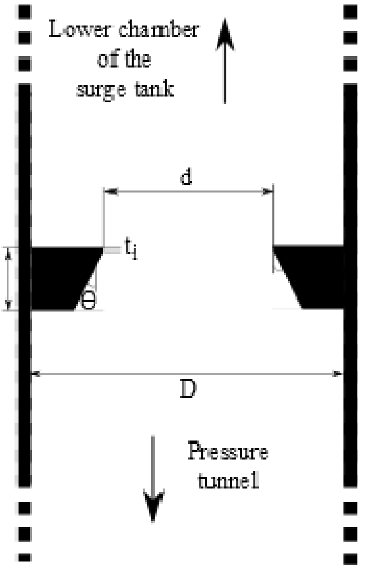
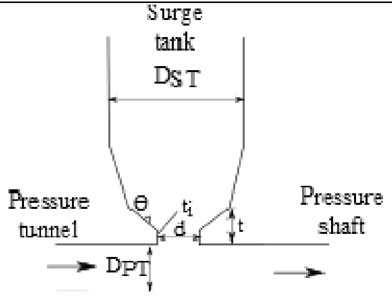
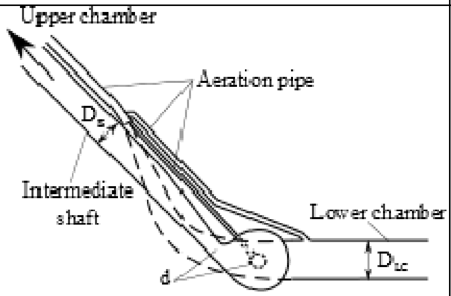
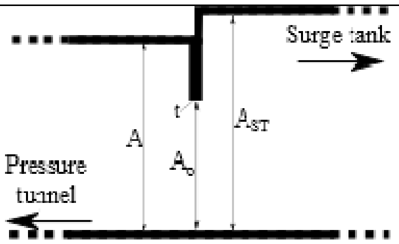
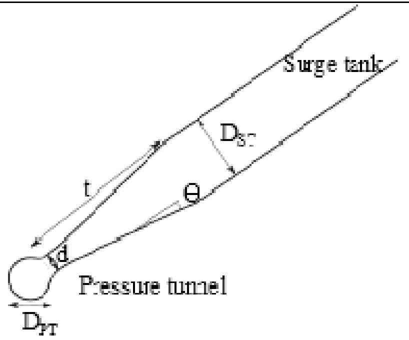
[1] For circular gallery and openings, $\beta=d_o/D_g$ while $\beta=\sqrt{A_o/A_g}$ for other shapes.

		1.25 m ($\alpha = 0.42$); -inner throttle thickness, t_i: 0.5 m (α=0.167);	
FMHL + [12] (Switzerland)	 Note: The throttle is placed in a tunnel connecting the pressure tunnel to the most upstream surge tank	-shape: circular hole; -connecting gallery diameter, D: 2.2 m; -inner throttle diameter, d: 1.69 m ($\beta=\frac{d}{D}\approx 0.768$); - throttle thickness, t_i: 0.09 m ($\alpha=\frac{t}{D}\approx 0.04$); -no throttle angle	-type: pumped storage plant -turbining discharge, Q: 57 m^3/s; -pump discharge, Q: 43 m^3/s; -net head, H: 878 m; -installed power capacity, P: 480 MW
Gondo [4] (Switzerland)	 Note: The throttle is placed at the bottom of the surge tank.	-shape: rack of bars (beams); -pressure tunnel area, A_{PT}: 3.94 m^2; -opening area, A_o: 0.58 m ($\beta = 0.383$) -throttle thickness, t: 0.32 m ($\alpha = 0.09$); -throttle angle, Θ: 12°	-type: storage plant -discharge, Q: 14.7m^3/s; -net head, H: 470m; -installed power capacity, P: 45.4 MW
La Grande Dixence (Switzerland)	 Note: The throttle is placed at the bottom of the surge tank in a short connecting gallery.	-shape: circular hole; -connecting gallery diameter, D: 3.0 m; -inner throttle diameter, d: 1.6 m ($\beta=\frac{d}{D}\approx 0.533$); -throttle thickness, t: 0.6 m ($\alpha=\frac{t}{D}\approx 0.2$); -inner throttle thickness, t_i: 0.03 m ($\alpha=\frac{t}{D}\approx 0.01$); -throttle angle, Θ: 30°	-type: storage plant -discharge, Q: 75m^3/s; -net head, H: 1883m; -installed power capacity, P: 1285 MW

Guadalami (Italy)		-shape: circular hole; -surge tank diameter, D_{ST}: 12.0 m; -pressure tunnel diameter, D_{PT}: 4.5 m; -inner throttle diameter, d: 3.5 m $(\beta=\frac{d}{D}\approx 0.778)$;	-type: pumped storage plant; -net head, H: 170 m; -installed power capacity, P: 80 MW
Kaunertal [19] (Austria)	 Note: sectional view	-shape: vortex throttle; -lower chamber diameter, D_{LC}: 4.0 m; -intermediate shaft diameter, D_{IS}: 3.0 m; -inner throttle diameter, d: 1.64 m $(\beta=\frac{d}{D}\approx 0.41)$;	-type: storage plant -discharge, Q: 48m^3/s; -net head, H: 870m; -installed power capacity, P: 392 MW
Lavey + (Switzerland)		-shape: rectangular hole (4m x 4.2m); -connecting gallery area, A_{CP}: 23m^2 - throttle area, A_o: 16.8 m $(\beta\approx 0.855)$; - throttle thickness, t_i: 0.5 m $(\alpha=0.185)$; -no throttle angle	-type: storage plant -discharge, Q: 220 m^3/s; -net head, H: 34 m; -installed power capacity, P: 90 MW
Wassen I (Switzerland)	 Note: sectional view	-shape: circular throttling; -pressure tunnel diameter, D_{PT}: 2.7 m -inner throttle diameter, d: 1.235 m $(\beta=0.457)$ -throttle thickness, t: 16.7 m $(\alpha=6.18)$; -throttle angle, θ: 10.1°	-type: storage plant -discharge, Q: 24m^3/s; -net head, H: 277 m; -installed power capacity, P: 58 MW

Tab.1. Non-exhaustive review of different existing throttles

4. Different types of throttle

As shown in Section 3, throttles can be divided in, at least, three main categories: orifices, racks or vortex throttles. Each category can be divided in either symmetrical or asymmetrical throttles. This section introduces each category of throttle:

- Orifice: An orifice is a local geometry restrictions which may have different opening shape (circular, rectangular, etc.). The streamline expansion at the downstream is the same in all directions. The orifice shape could be different in each flow direction (see Tab.1: Acaray, La Grande Dixence, etc.). Asymmetrical orifice shape allows introducing asymmetrical head losses up to 1:3 - 1:4 [20]. Moreover, the orifice can be placed in different location in the surge tank: at the bottom (see Tab.1 Acaray and Guadalami), in a connecting gallery (see Tab.1: Lavey+ or La Grande Dixence) or in the intermediate shaft [20]. The main influencing parameters is the contraction ratio β, which is the ratio between the diameter of the opening section and the diameter of the pipe. The head losses is function of β to the 4th power [21].

- Rack throttle: A rack throttle is composed with a framework of parallel spaced bars or beams. The downstream streamlines expansion are forced in one direction. The spaced between each bars can be the same (see Tab.1: Amsteg) or different due to the local geometry at the bottom of the surge tank (see Tab.1: Gondo [4]). The shape of the bars could induce asymmetrical head losses when water flows in or out the surge tank. Head losses are function to the opening ratio B, which are the ratio between the opening and pipe areas (Note: $B=\beta^2$), to the second power.

- Vortex throttle: This type of throttle is mainly present in the Austrian surge tank [13,19]. It allows producing a higher asymmetry ratio up to 1:20 – 1:50 [13,20] due to the complex flow in the vortex throttle (swirling flow). Due to its complex geometry, this type of throttle should not be relevant in the adaptation of a surge tank during the refurbishment of a hydroelectric prower plant.

5. Conclusions

In Switzerland, hydroelectricity has to increase its averaged yearly generation by 7% while 88% of the technically feasible generation is already built. New hydropower plants should be built and existing one should be refurbished where it is possible. Placing a throttle in an existing surge tank is often an efficient and economical way to adapt the waterway to a refurbishment and an increase of discharge. The authors showed in this paper existing throttles geometries for different storage power plants in Switzerland and abroad. Even if throttles are mainly designed case-by-case, three different types of throttle have been highlighted: orifices, racks and vortex throttles.

6. Acknowledgements

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