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Surge Tank Research in Austria and Norway

Abstract

Modern high-head hydropower plants, and especially pumped storage plants (PSP), are designed with increasing high water discharge and higher requirements to flexible operation. To improve the hydraulic performance and allow for more flexible operation, research on surge tank design is conducted in Norway and Austria. A cooperation is established, and this work presents some recent findings. Two types of surge tanks are discussed, the throttled chamber surge tanks (TCST) of Austria, and the air cushion surge tanks (ACST) of Norway. Both represent the current state-of-the-art in these countries. For the TCST, the challenges of long chambers is given special attention.

Wasserschlossforschung in Österreich und Norwegen

Kurzfassung

Moderne Hochdruck-Wasserkraftanlagen, insbesondere Pumpspeicherkraftwerke werden zunehmend mit höheren Ausbauwassermengen und höheren Anforderungen an einen flexiblen Betrieb der Maschinen geplant und gebaut. Zur Optimierung der hydraulischen Parameter des Triebwasserweges wird in Norwegen und Österreich verstärkt an der optimierten Auslegung von Wasserschlössern geforscht. Einige Ergebnisse der Forschungskooperation zwischen der NTNU Trondheim und der TU Graz werden dargelegt. Es werden hierbei das Druckluftwasserschloss und das gedrosselte Zweikammerwasserschloss untersucht und verglichen. Diese beiden Wasserschlosstypen stellen den jeweils aktuellen Wasserschlosstyp von Norwegen bzw. Österreich dar. Für Kammerwasserschlösser werden die Herausforderungen für große Kammerlängen dargestellt.

1 Introduction

In Austria, throttled chamber surge tanks (TCST) have been the state-of-the-art design since the construction of the Kaunertal hydropower plant in 1964 [1]. The TCST is constructed with an upper and a lower chamber, which are slightly inclined to ensure emptying of water. The upper chamber utilizes the differential effect [2], which improves the mass oscillation damping and reduce the overall volume requirements of the surge tank. The position of the upper chamber determines the design pressure in the pressure tunnel. However, in modern surge tanks with long upper and lower chambers, several new challenges arise due to their lengths. This work will especially consider two such challenges: (1) the occurrence of surface waves and waterfalls from the upper chamber, and (2) the behavior of the lower chamber.

The authors from Graz University of Technology have recently conducted several physical scale-model tests of new surge tanks, including PSP Limberg II, PSP Atdorf, PSP Reisseck II and PSP Obervermunt II. The main scope of the model tests is to evaluate the hydraulic losses of the throttles designed, the investigation of the overall hydraulic behavior and safety of the surge tanks. The hybrid modelling approach is applied, which includes a combination of 1D- and 3D-numerical modelling with physical scale-model testing.

A typical Austrian TCST hydropower system is presented in **Figure 1a**. The total area of the main shaft including the aeration shaft is designed regarding the Thoma stability criterion [3]. The throttle is usually situated at the transition from the lower chamber to the main shaft. An aeration shaft is constructed to prevent cavitation and column separation below the throttle during downswing of the mass oscillations. The aeration shaft can in addition improve the water hammer reflection in the surge tank for specific cases.

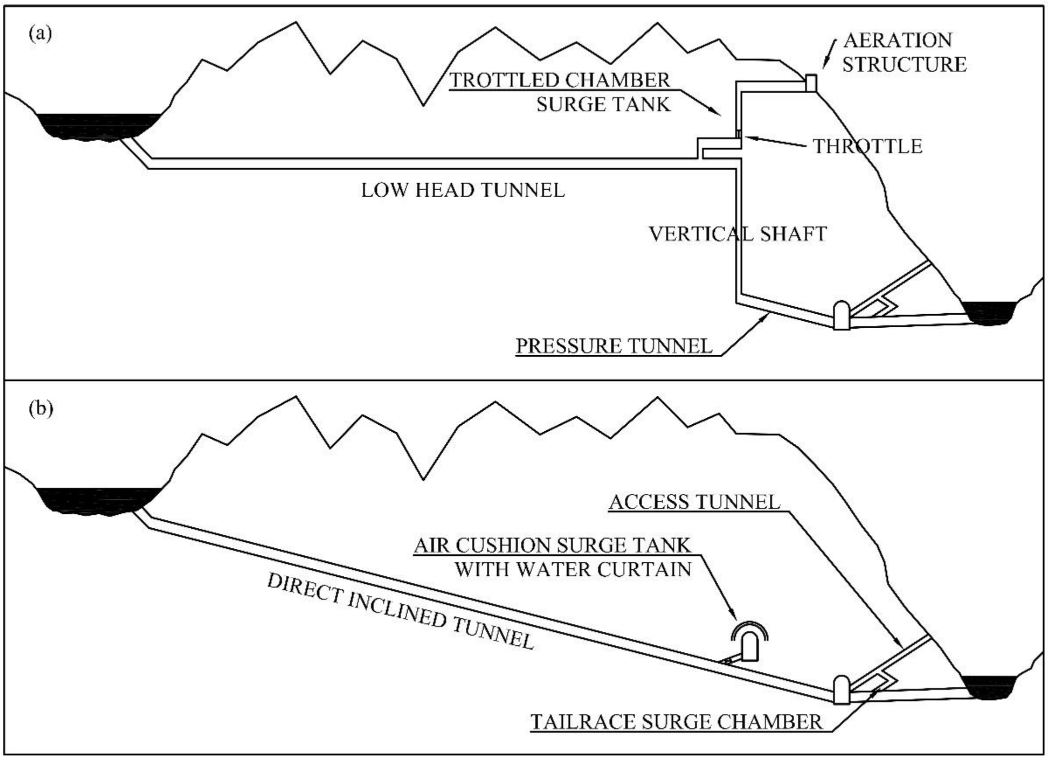


Figure 1: Throttled chamber surge tank (a) and air cushion surge tank (b)

In Norway, the ACST is regarded as state-of-the-art. This surge tank is constructed as an excavated underground rock cavern filled with pressurized air. A total of ten ACSTs exist in Norway, and three are constructed in China [4], [5]. **Figure 1b** presents a typical ACST hydropower system.

However, the ACST has not yet been applied on the high-pressure side of hydropower systems in the alpine region, mainly due to geological reasons. A review of the benefits and challenges related to application of the ACST in the alpine region is therefore carried out, and a comparison between the ACST and the TCST is conducted based on a generic hydropower project.

2 Methods of Surge Tank Investigation

Physical scale-model testing of surge tanks at TU Graz are performed with the Froude law of similitude. 1D-numerical simulations are used for calculation of mass oscillation and water hammer, while 3D-numerical simulations are carried out for calculation of 3D flow regions [11]. **Table 1** gives an overview of the evaluation methods with advantages and disadvantages.

Investigation tools	Advantages	Disadvantages
Physical scale-model test	• Visualization of overall hydraulic behavior • Detection of possible problems such as swirl flows or waterfalls • Proofing the safety against outflow from aeration structure • Representative behavior of the fluid • Measurement of throttle loss	• No similitude for air behavior • No similitude for water hammer • Inflow and outflow from the surge tank is applied in terms of 1D numerical simulations
1D numerical simulation	• Modelling of mass oscillations and water hammer behavior of the complete hydraulic system • Low cost of calculation time • Evaluation of many variants possible	• Assumptions have to be taken in 3D-flow regions • Air intrusion and degassing cannot be evaluated
3D numerical simulation	• Modelling of 3D-flow regions, such as throttles and surface waves • Rough simulation of waterfalls possible • Complete 3D-simulation of the entire surge tank in prototype scale • Investigation of variants • Possibility of multiphase simulations	• Time-consuming calculations and evaluations • Calibration is needed • Multiphase flow simulations require much effort, calibration and research

Table 1: Surge tank investigation tools

It has been experienced that a hybrid modelling approach including a combination of 1D numerical simulations, 3D numerical simulation to investigate hydraulic details, and physical model tests is necessary in order to detect and evaluate all the different hydraulic phenomena occurring in new complex surge tanks.

3 Long Upper Chamber Behavior

Long upper chambers are excavated mainly due to construction benefits. This leads to a more significant differential effect [2], which improves the damping of the mass oscillations. This effect increases with the length of the upper chamber, limited by the demand of complete emptying before the next upswing fills the chamber again.

The upper chambers are constructed as tunnels with free surface flow. In contrast to a lower chamber, the occurrence of pressurized flow should be avoided. The filling and emptying process is mainly driven by the inclination and the length of the tunnel. The aeration structure is established at the transition to the atmosphere, where water spilling is prevented and air ventilation ensured. The volume of the upper chambers is designed for the volume demand regarding multi shifting load-case operation of the power plant [1].

As long upper chambers are governed by free surface flow conditions, the occurrence of a significant surface wave should be expected during filling. In addition, the emptying process results in column separation between the upper chamber and the main shaft, which results in a waterfall. The size of a filling wave in order to prevent overflow can be reduced by structural means such as steps or beams [6], and by optimum inclination of the upper chamber. In the example of surge tank Krespa for PSP Obervermunt II, an inclination of 1.5 % was found for an appropriate performance.

Figure 2 presents three different possible surge tank upper chamber geometries, at a time-step after surface wave reflection from aeration structure (left) and its returning towards the main shaft (right). This upper chamber has a length of 310 meters and a diameter of 7 meters, and is filled with about 210 m³/s during peak discharge. The upper alternative in Figure 2 has an inclination of 1 %. The ideal inclination (middle layout) of 1.5 % could be determined from the 3D numerical simulations and was later confirmed by physical scale-model tests. The use of deflectors was also investigated (lower alternative). Figure 2 visualizes that for upper chambers, not only a safety factor regarding volume is necessary, but also the surface wave behavior has to be safely reflected at the aeration building.

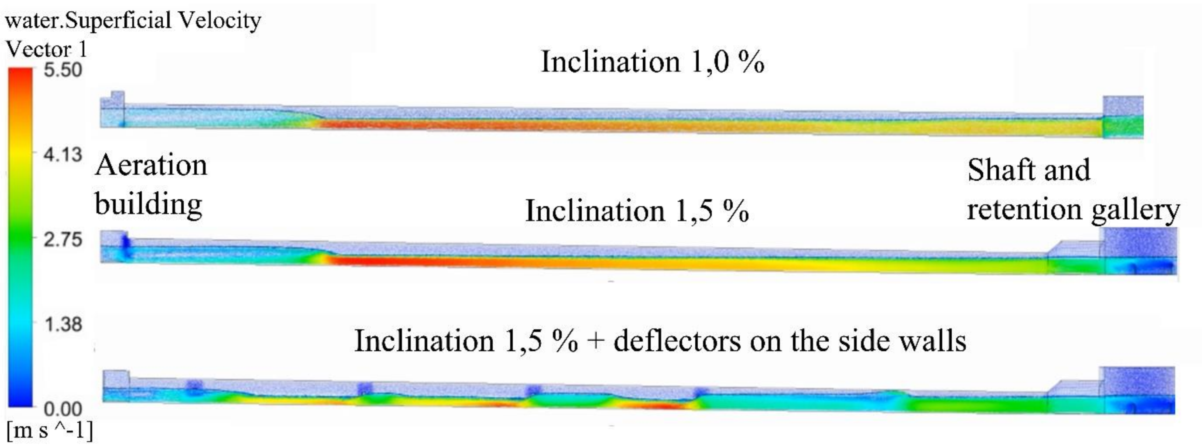


Figure 2: Filling of long upper chamber with the occurrence of a surface wave for three different design variants (Source: Wolfgang Richter)

In cases where waterfalls occur in the surge tank, the power plant operation that create the worst-case waterfall needs to be determined. This operation may differ from the general design operation for the rest of the surge tank. The most unfavorable situation for air intrusion can be evaluated by 1D numerical simulations tools that are able to accurately capture the free surface wave in the upper chamber. To prevent dangerous deep intrusion of air for the Krespa surge tank, a waterfall damping device was proposed and tested [7].

4 Long Lower Chamber Behavior

A challenging situation for design of lower chambers is the change between pressurized flow and free surface flow. The transition from pressurized flow to free surface flow during the downsurge results in a surface wave in the lower chamber.

During the upsurge, the lower chamber is filled, but the deaerating of the tunnel may not occur immediately. Lower chambers are either designed as flow-through tunnels or as dead-end tunnels. Model tests show that lower chambers designed as dead-end tunnels have a sufficient degasing behavior if the crown inclination is 2 %. A criterion for good filling behavior is the absence of large blowouts of air. **Table 2** present the advantages and disadvantages of constructing the lower chamber as a dead-end tunnel or as a flow-through tunnel.

For a long lower chamber with dead-end arrangement, the filling and emptying process produce more problems compared to shorter chambers, and the chamber will not contribute to any additional safety against air bubble intrusion. In a flow-through chamber, the main disadvantage is the increased inertia. This results in both a massive surface wave during the transition from pressurized flow to free surface flow regime, and a delayed water hammer reflection at low water levels in the main shaft. However, for the flow-through arrangement, the length will increase the security against air intrusion into the pressure tunnel.

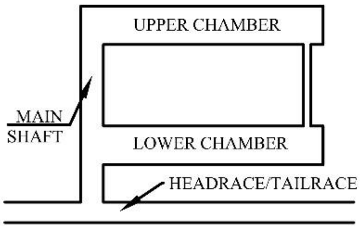
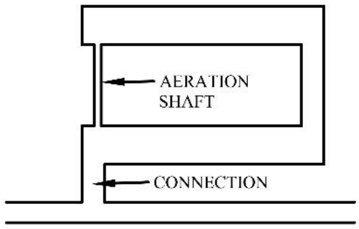
Scheme	Dead-end	Flow-through
Principle layout		
Advantages	• Fast water hammer reflection	• High degassing of air
Disadvantages	• No degassing of waterfall • Slower degassing during filling	• Slower water hammer reflection • Potential surface wave

Table 2: Comparison of the dead-end and the flow-through arrangement

The height of the gravity center of the lower chamber is the governing factor for the acceleration of the mass oscillation during downswing. Subsequently a higher upward inclination of the lower chamber invert increases the volume demand. The invert inclination is necessary in order to enable dewatering during inspections, while the crown inclination is necessary to ensure degassing. The optimal inclination of the two has to be determined individually. In case of high discharge rates, multiple lower chambers are seen to be beneficial compared to a single lower chamber.

5 The Air Cushion Surge Tank

5.1 Benefits

The main benefits of the ACST compared to the TCST are:

- Reduced water hammer
- Enables more flexible and faster operation
- Enables tunneling directly from power house to reservoir
- Reduction of necessary steel lining is possible
- Reduced risk of underpressure near the surge tank
- No surface access required

Tunneling in a straight line from the reservoir to the power house is made possible by the ACST since it does not require a separate surface access [4]. The direct tunneling might be less expensive compared to horizontal headrace tunnel and pressure shaft, but may differ regarding the specifics of a certain project. The direct tunneling and deep position of the

ACST also avoids potential problems regarding topography. A topography with too high or too low overburden in the position of the surge tank has been the main reason for selecting the ACST in many of the Norwegian hydropower plants [8].

In addition, recent refurbishments and replacements of steel lined pressure shafts (steel ageing) in Austria and Norway are showing that the pressure shaft lifetime is significantly lower compared to the overall lifetime of the hydropower plant (Kaunertal power plant ~ 50 years, Kaprun power plant ~ 60 years, and Suldal I power plant ~ 45 years). In comparison, steel lining may be reduced for deep tunneling due to higher rock stress, which protect against hydraulic jacking.

ACSTs are constructed without surface access, reducing the excavated volume and the environmental impact on the surface. Hydropower projects are often developed in areas of natural beauty where reduced environmental impact is of high value. Construction works and transport on challenging terrain during construction of the surface access is also avoided.

The sum of the benefits provided by the ACST could in some cases make this solution more economic and environmentally favorable compared to the TCST with adit tunnels.

5.2 Challenges in the Alpine Region

There are several challenges concerning the use of an ACST in the alpine region, such as [12]:

- Secure and economic progress of deep tunneling
- Requirement to rock quality and strength parameters
- Minimum principle rock stress must be higher than air pressure
- Stability of the excavated rock cavern
- Control of air leakage
- Higher demand of monitoring and maintenance
- Time consumption of air filling procedure

Use of the ACST requires that the minimum principle stress ($\sigma_3 > \sigma_w$) in the rock is higher than the static air pressure, in order to avoid hydraulic fracturing of the rock. It should be noted that the weakest point of the cavern, and not the average should be considered. The Norwegian geology is known to have relatively high horizontal stresses due to tectonic movements in the past, and this reduces the required rock cover in order to gain satisfactory stress levels [9]. In general, construction of an ACST in the Alps will require a deeper placement in the rock, and the site-specific geological conditions needs to be studied in order to evaluate optimal placement of these facilities. Final placement of the ACST needs to be decided based on hydraulic jacking tests in the tunnel during excavation.

A common misconception is that use of the ACST requires high rock strength and quality, while it is the minimum principle stress that is important. An example is the ACST for Brattset power plant, which successfully is constructed in graphitic phyllite rock [8].

To ensure stability of the excavated rock cavern, more use of rock support is expected in the Alps compared to Norway due to the rock mass quality. However, the application of the ACST in China [5] proves that the solution is not exclusive for Norwegian geology. Common measures to increase rock mass stability should be sufficient to enable the use of ACST in some regions of the Alps. However, in areas with very poor rock mass quality, grouting may be used as an extended measure. For small ACSTs, the use of steel tanks is also possible, as applied in the alpine PSP Kops II in Austria. Steel tanks should however be avoided for larger caverns due to the high costs compared to common support measures such as sprayed concrete and rock bolting. The air leakage is dependent on rock mass permeability, which increases with the number of cracks and joints in the rock. Hard rock is known to have higher permeability compared to softer rocks due to rougher transitions in joints and cracks. Air tightness may however be ensured by a water curtain as described in [4]. The water curtain consist of boreholes drilled in the rock above the ACST, which are filled with pressurized water in order to increase the groundwater pressure. The pressurized water have higher pressure compared to the air in the ACST resulting in water leakage into the ACST, instead of air leakage out. Water curtains have been applied for hydropower, compressed air energy storage and LPG storage in several countries successfully [8]. After construction, the ACST requires monitoring in order to ensure that the air pressure and water level is within limited boundaries. A redundant and robust monitoring scheme is necessary.

For large ACSTs the filling time of the air pocket needs to be considered. The filling time of Kvilldal ACST (80 000 m^3 of air with 40 bar pressure) is several weeks, which may result in water losses given high inflow and high reservoir water level. The experience from existing ACST show that higher investment in air compressor capacity and piping connection is valuable in order to reduce stop-time of the power plant during tunnel emptying.

6 Comparison

In order to compare the ACST against the TCST, a generic hydropower scheme is evaluated. A principle drawing of the two alternatives is seen in Figure 1, while **Table 3** presents the properties of the schemes. The TCST scheme is designed with a horizontal headrace tunnel, and a pressure shaft. The ACST scheme incorporates a direct inclined tunnel without pressure shaft. Similar properties for both schemes are head of 600 m, discharge of 100 m^3/s, tunnel cross section area of 60 m^2, and shaft diameter of 6 m. The comparison is made on excavated rock volume, exposed rock surface in the tunnel system, and design pressure.

One should note that 5 % increased tunnel length is assumed in the TCST scheme due to the possibility of a more direct aligned tunnel in the ACST scheme. The shaft of the TCST has a minimum area of 45 m^2 given from Thoma [3], while the upper and lower chambers have 500 m^2 each. The ACST is designed with the minimum volume occurring to the Svee [10] criteria. Both schemes include a throttle with headloss factor 1:5 in upswing and downswing direction respectively. For calculation of the thermodynamic behavior of the air, the adiabatic exponent of 1.4 is applied [4].

	TCST	ACST
Headrace length (m)	10 500	10 000
Pressure shaft length (m)	600	x
Pressure tunnel length (m)	500	500
Surface access tunnels (adits)(m)	1 000	x
Surge tank volume (m^3)	16 000	75 000
Resulting design pressure (mWC)	680	670
Rock surface area surge chamber (m^2)	7 500	12 300
Reflection time of water hammer (s)	1.8	1.0
Water inertia time constant (s)	0.6	0.3
Total amount of rock surface area (m^2)	350 000	301 000
Total amount of excavated volume (m3)	744 000	711 000

Table 3: Comparison of the air cushion and the throttled chamber surge tank schemes

As shown in Table 3, both the total amount of excavated rock volume and resulting exposed rock surface is higher for the TCST scheme compared to the ACST scheme. Less exposed rock surface for the ACST scheme indicates that there is less need for rock support and lining.

It should however be noted that when considered isolated, the volume of the ACST is larger than the volume of the TCST. This implies that for hydropower projects where the headrace length of the two alternatives are more similar, the TCST scheme will be more beneficial.

The numbers for design pressure is obtained through 1D numerical simulation with the software LVTRANS. A resonance load case with succeeding shut-down and start up is applied, and the resulting pressure transients upstream the turbine, and water fluctuation in the surge tank are shown in **Figure 3**.

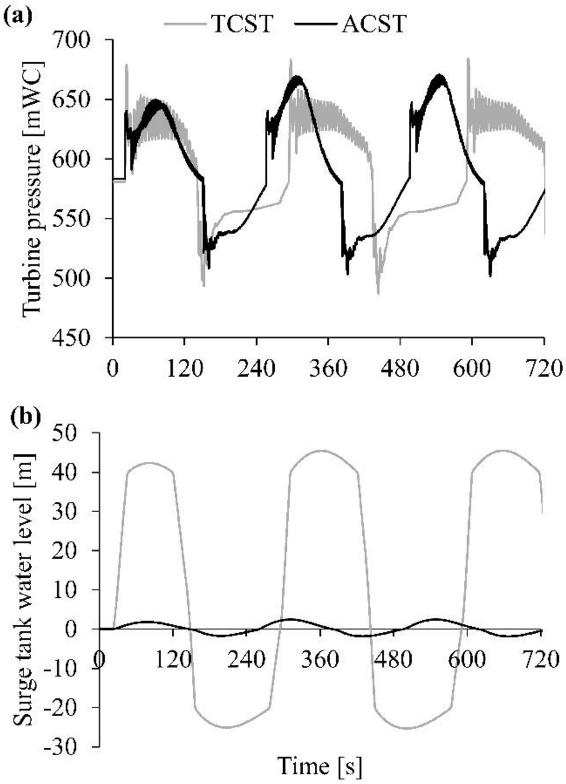


Figure 3: Comparison turbine pressure and surge tank water level

As can be seen from Figure 3a, the water hammer is stronger (due to higher kinetic energy in the longer shaft), and has a lower frequency in the traditional scheme due to longer distance between the turbine and the free water surface. The mass oscillation amplitude is very similar, but the period is longer for the ACST scheme due to different behavior of pressurized and atmospheric air. From Figure 3b we can see that the water level fluctuation in the TCST is large, mainly limited by the upper and lower chamber. The water level fluctuation in the ACST is small in comparison.

The comparison between a TCST, and a ACST scheme show that both excavated rock volume, and resulting exposed rock surface in the tunnels may be reduced when applying the ACST. It is seen that when considered isolated, the ACST requires more rock excavation than the traditional surge tank, but that the benefits of direct inclined tunneling in sum result in a less expensive scheme. The ACST scheme has the additional benefits of reduced design pressure, reduced reaction time of water masses, and less environmental impact on the surface due to fewer surface access tunnels. However, site-specific variation in topography will always have key influence to which solution is most beneficial.

7 Conclusion

Modern pumped storage plants with increasing water discharge request increasingly larger surge tank systems. Simple scaling of available schemes lead to increased challenges in terms of water hammer reflection, air intrusion, and filling and emptying of chambers. To mitigate negative effects, measures such as multiple chamber design, waterfall damping devices, steps and beams, optimized chamber inclination, and aeration shafts are seen to improve the hydraulic behavior significantly.

From the experience of several physical model studies at TU Graz, it is concluded that the hybrid modelling approach is necessary in order to detect and accurately capture all the different hydraulic phenomena occurring in new complex surge tanks to allow highest flexibility during operation.

A review of the benefits of the ACST compared to the TCST shows that the ACST might be more beneficial for certain hydropower projects, and especially for problematic topographies. The limitation for application in alpine projects has so far been the uncertainty regarding geology. It is concluded that application of ACST in the alpine region may be possible with modern rock engineering technology, but should be selected for projects where the benefits are high. For projects where the benefits of the ACST is not high, the TCST scheme with a long low head tunnel and pressure shaft should be selected. This is to better cope with uncertainties regarding geology, and the operational challenges of storing pressurized air in the tunnel system.

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Literature

[1] Heigert, G.: Drossel – und – Differential – Wasserschlösser von Regelkraftwerken mit Freier Betriebsführung. Dissertation, Technische Hochschule Wien, 1970.

[2] Johnson, R: The Surge Tank in Water Power Plants. In: Trans. ASME 30 (1908), P. 443-474.

[3] Thoma, D: Zur Theorie des Wasserschlosses bei selbsttätig geregelten Turbinenanlagen. Dissertation, Technische Hochschule München: R.Oldenburg, 1910.

[4] Goodal, D.C.; Kjørholt, H.; Tekle, T.; Broch, E.: Air Cushion Surge Chambers for Underground Hydropower Plants. In: Water Power and Dam Construction (1988), Issue 11, P. 29-34.

[5] Hu, J.; Zhang, J.; Suo, L.; Fang, J.: Advance in Research on Air Cushion Surge Chamber in Hydropower Plant, In: Proceedings of IMECE2007 (2007), P. 11-15.

[6] Larcher, M.; Knoblauch, H.; Heigerth, G.; Wagner E.; Stering, P.: Instationäre Füll- und Entleervorgänge bei der Auslegung der Oberkammer des Wasserschlosses Limberg II, Wasserwirtschaft Nr.4 (2010), P. 107-109.

[7] Richter, W.; Schneider, J.; Zenz, G.; Innerhofer, G.: Hybrid Modelling and Development of a long Upper Chamber in a Surge Tank, In: Proceedings of Hydro Congress (2013), Innsbruck.

[8] Kjørholt, H.; Dahlø, T.: Geotechnical Design of Air Cushion Surge Chambers, In: Hydropower'92, Balkema, Rotterdam, 1992.

[9] Nilsen, B.; Thidemann, A.: Hydropower Development - Rock Engineering, Trondheim, Tapir Press, 1993.

[10] Svee, R.: Surge Chamber with Enclosed Compressed Air Cushion. Proc. 1st. Int. Conf. on Pressure Surges (1972), British Hydromechanics Research Association, Bedford, P. 15-24.

[11] Richter W.; Schneider J.; Knoblauch H.; Zenz G.: Behavior of Long Chambers in Surge Tanks. Proc. of 18th International Seminar on Hydropower plants (2014), Vienna.

[12] Vereide, K.; Leif, L.; Richter, W.: Benefits of the Air Cushion Chamber for Alpine Hydropower Plants. Proc. of 18th International Seminar on Hydropower plants (2014), Vienna.