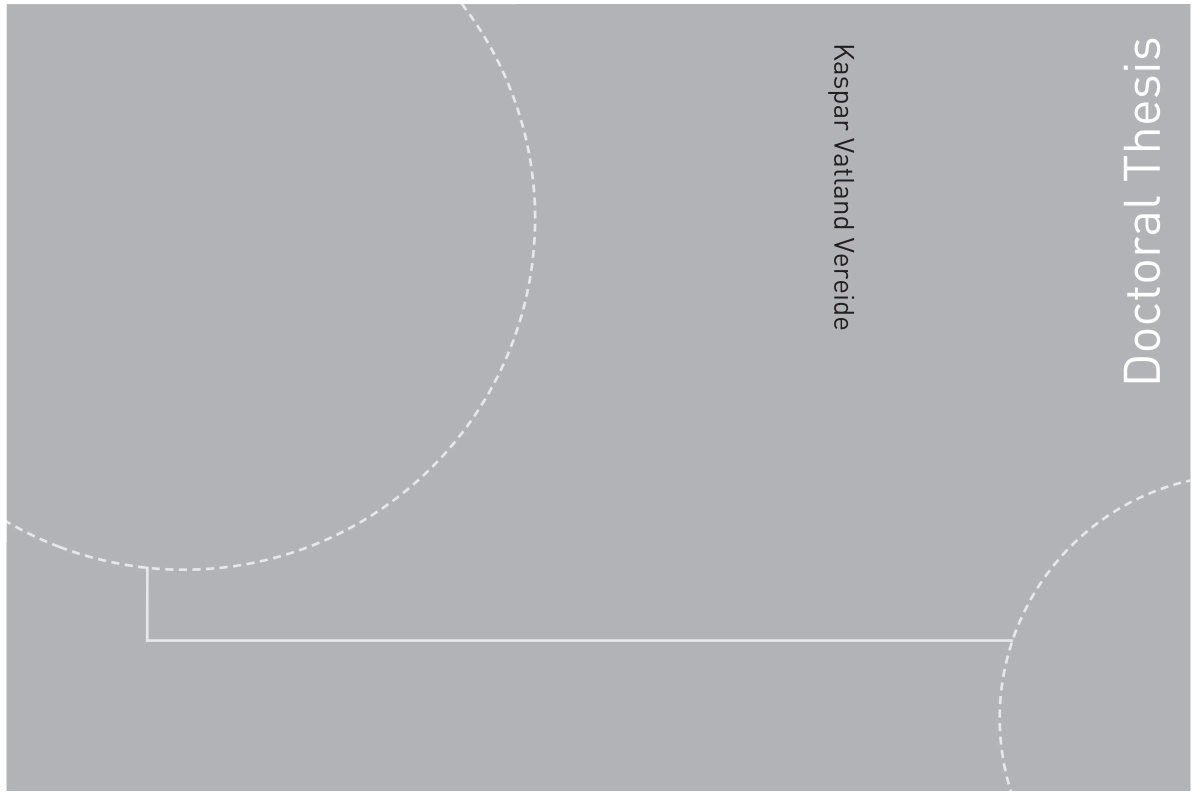
ISBN 978-82-326-1386-1 (printed version).
ISBN 978-82-326-1387-8 (electronic version)
ISSN 1503-8181


Kaspar Vatland Vereide

Doctoral Thesis

Doctoral theses at NTNU, 2016:20

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Norwegian University of
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Hydraulics and Thermodynamics of Closed Surge Tanks for Hydropower Plants

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Norwegian University of
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Hydraulics and Thermodynamics of Closed Surge Tanks for Hydropower Plants

Thesis for the degree of Philosophiae Doctor

Trondheim, January 2016

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Printed by Skipnes Kommunikasjon as

Fides, Spes et Caritas

Faith, Hope and Love

The essentials during a PhD work

Abstract

This thesis presents the work on the hydraulics and thermodynamics of closed surge tanks that resulted in four scientific papers. It describes the context under which the work was conducted, and the methods that were applied. An introduction to closed surge tanks is provided, and the motivation for the work is outlined. A historical review is presented to enable the reader to place the current work in a historical context, and to follow the development of closed surge tank technology over time. Two research objectives and two hypotheses from the work are formulated and answered in this thesis. Finally, the papers and contributions are presented. The work presents six contributions (C) novel to the research field of closed surge tanks:

C1: An overview of the benefits and challenges of the closed surge tank compared with the open surge tank.
C2: A new approach for scaling hydropower tunnels with closed surge tanks for hydraulic scale model tests.
C3: An assessment of the accuracy of a hydraulic scale model of a hydropower headrace tunnel with a closed surge tank.
C4: A modified rational heat transfer (MRHT) method for calculating the thermodynamic behavior in closed surge tanks.
C5: A methodology for evaluating the effect of surge tank throttling on governor stability and performance in hydropower plants.
C6: An evaluation of the effect of surge tank throttling on governor stability and performance in a hydropower plant with a closed surge tank.

It is concluded that improvements to the theory and understanding of closed surge tanks are provided, but that a significant potential remains for further development. Suggestions for future work are described in this thesis.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfilment of the requirements for the degree of Philosophiae Doctor (PhD).

The work was conducted at the Department of Hydraulic and Environmental Engineering, NTNU, Trondheim, with Professor Leif Lia as main supervisor. Professor Torbjørn Kristian Nielsen from the Department of Energy and Process Engineering, NTNU, Trondheim, was co-supervisor.

The work in this thesis was financed through a 4-year PhD position at the Department of Hydraulic and Environmental Engineering. The PhD position was allocated to 25% teaching and 75% research. The teaching has included supervising nine master students, and assisting with lecturing and organization of the courses TVM4116 Hydromechanics and TVM4165 Hydropower Structures.

Funding for a hydraulic scale model was granted by the Centre for Environmental Design of Renewable Energy (CEDREN) through the Norwegian Research Council project number 193818. The work was conducted as a part of the HydroPEAK project in CEDREN. Additional funding for field measurements was granted by Energi Norge.

In accordance with the guidelines of the Faculty of Engineering Science and Technology, this thesis comprises an introduction to the research that has resulted in four scientific papers.

Acknowledgements

My heartfelt appreciation for the assistance and guidance during this work goes to my supervisor Leif Lia. Your passion for hydropower technology and research is extremely inspiring and contagious and has resulted in great joy during this work. Your efforts to assist developing countries are especially admirable, and I hope to follow in your footsteps. Similar appreciation is given to my co-supervisor Torbjørn Kristian Nielsen, who has made the entry into the world of mechanical engineers fun and rewarding. Our theoretical discussions, which often border on the irrelevant, broaden my understanding and fuel my interest in this multidisciplinary science.

Thanks to my family and friends who have contributed with mental therapy during this work. My dear fellow PhD candidates and colleagues at the Department have created the perfect atmosphere for conducting PhD work. Thanks for all your advice and support.

Thanks to Ånund Killingtveit, the head of the HydroPeak program within CEDREN, for believing in and funding the hydraulic scale model test. The close cooperation with Sira-Kvina Kraftselskap, and especially Rolv Guddal, has been greatly appreciated. The friendly and accommodating atmosphere in Tonstad has allowed for several master theses on Tonstad and Duge power plants. Thanks to all master students who have endured my supervision.

Thanks to Bjørnar Svingen, Torbjørn Tekle and Gerald Zenz for assistance and brilliant cooperation. Finally, the quality of this work would not have been the same without the new friendship with Wolfgang Richter at the Graz Technical University. Our shared enthusiasm for surge tank research has elevated my understanding and knowledge through countless hours of enjoyable discussions.

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List of Publications

Selected Papers

1. Kaspar Vereide, Wolfgang Richter, Gerald Zenz and Leif Lia (2015). “Surge Tank Research in Austria and Norway.” Journal Wasserwirtschaft, 105(1), 58-62. Available: http://www.meinfachwissen.de/free-magazine/WAWIextra/index.html#58 (Open Access).

2. Kaspar Vereide, Leif Lia and Torbjørn Kristian Nielsen (2015). “Hydraulic Scale Modelling and Thermodynamics of Closed Surge Tanks.” Journal of Hydraulic Research, 53(4), 519-524, DOI: 10.1080/00221686.2015.1050077 (Open Access).

3. Kaspar Vereide, Torbjørn Tekle and Torbjørn Kristian Nielsen (2015). “Thermodynamic Behavior and Heat Transfer in Closed Surge Tanks for Hydropower Plants.” Journal of Hydraulic Engineering, 141(6), 06015002, 1-5, DOI: 10.1061/(ASCE)HY.1943-7900.0000995 (Open Access).

4. Kaspar Vereide, Bjørnar Svingen, Torbjørn Kristian Nielsen and Leif Lia (2016). “The Effect of Surge Tank Throttling on Governing Stability and Performance in Hydropower Plants.” In Review: IEEE Transactions on Energy Conversion.

Secondary Papers

1. Kaspar Vereide, Leif Lia and Lars Ødegård (2013). “Monte Carlo Simulation for Economic Analysis of Hydropower Pumped Storage Projects in Nepal.” Hydro Nepal Journal of Water, Energy and Environment, 12, 39-44, DOI: dx.doi.org/10.3126/hn.v12i0.9031 (Open Access).

2. Kaspar Vereide, Leif Lia and Torbjørn Nielsen (2014). “Physical Modelling of Hydropower Waterway with Air Cushion Surge Chamber.” In: Hubert Chanson and Luke Toombes, Hydraulic Structures and Society - Engineering Challenges and Extremes. 5th IAHR International Symposium on Hydraulic Structures, Brisbane, Australia, 25-27 June 2014, DOI: 10.14264/uql.2014.28 (Open Access).

3. Kaspar Vereide, Leif Lia and Wolfgang Richter (2014). “Benefits of the Air Cushion Surge Chamber for Alpine Hydropower Plants.” In: Christian Bauer and Eduard Doujak, Innovation and Development Needs for a Sustainable Growth of Hydropower (823-832). 18th International Seminar on Hydropower Plants, Vienna, Austria, 26-28 November 2014.

4. Wolfgang Richter, Kaspar Vereide, Josef Schneider, Helmut Knoblauch, Leif Lia and Gerald Zenz (2014). “Druckluftwasserschlösser für alpine

Hochdruckwasserkraftanlagen." In: Robert Boes, Internationales Symposium Wasser- und Flussbau im Alpenraum, Band 1 (109-120). Internationales Symposium Wasser- und Flussbau im Alpenraum 2014, Zürich, Switzerland, 25-27 June 2014.

5. Wolfgang Richter, Kaspar Vereide, Gerald Zenz (2015). "Hydraulic Design and Modelling of Large Surge Tanks." In: Arris S. Tjisseling, Pressure Surges 2015 (417-424). 12th International Conference on Pressure Surges, Fluid Transients and Water hammer, Dublin, Ireland, 18-20 November 2015.

6. Kaspar Vereide, Bjørnar Svingen and Rolv Guddal (2015). "Case study: Damaging Effects of Increasing the Installed Capacity in an Existing Hydropower Plant." In: Arris S. Tjisseling, Pressure Surges 2015 (745-759). 12th International Conference on Pressure Surges, Fluid Transients and Water Hammer, Dublin, Ireland, 18-20 November 2015.

Master theses

1. Ann Kristin Tuseth (2013). Numerical Modelling of Closed Surge Tanks. Supervisors Leif Lia and Kaspar Vereide.

2. Ola Haugen Havrevoll (2013). Simulation of a Hydropower Pumped Storage Plant in LVTrans. Supervisors Leif Lia and Kaspar Vereide.

3. Britt Rasten (2014). The Effect of Hydraulic Transients on the Intake Gates at Tonstad Hydropower Plant. Supervisors Leif Lia and Kaspar Vereide.

4. Erik Kjøren (2014). Numerical Modelling of Thermodynamic Processes in Closed Surge Tanks. Supervisors Nils Reidar Bøe Olsen and Kaspar Vereide.

5. Daniel Gomsrud (2015). Design of a Surge Tank Throttle for Tonstad Hydropower Plant. Supervisors Leif Lia and Kaspar Vereide.

6. Fredrik Staff Edin (2015). Innovative Surge Tank Solutions for Small Hydro. Supervisors Leif Lia and Kaspar Vereide.

7. Robert Stigen Landskaug (2015). Physical Modelling of Surge Tank Throttling. Supervisors Leif Lia and Kaspar Vereide.

8. Simon Utseth Sandvåg (2016). Surge Tank Atlas for Hydropower Plants. Supervisors Leif Lia and Kaspar Vereide.

9. Eirik Leknes (2016). Comparison of the Svee and Thoma Stability Criteria for Mass Oscillations in Surge Tanks. Supervisors Leif Lia and Kaspar Vereide.

Chapter 1: Introduction

This chapter presents the background, the problem outline, and the scope of work. The context under which the work was conducted is described, and an overview of the research is given. The resulting scientific papers and contributions are introduced.

Background

Surge tanks are applied in hydropower plants with long water conduits to reduce pressure forces during acceleration of the large water mass (Johnson 1908). They are constructed as intermittent water reservoirs close to the turbines, either with open access to atmospheric air or as a closed volume filled with pressurized air. The surge tanks reduce the length of the water column to be accelerated, and thus the resulting pressure forces. This reduction is necessary to limit the design pressure for structural components and to enable speed governing of the turbines (Thoma 1910).

A large pressure transient occurs during fast shutdown from full load in hydropower plants. In hydropower plants without surge tanks, the entire water mass in the conduit decelerates instantly and causes a water hammer with a large pressure rise on the upstream side, and a pressure drop on the downstream side of the turbines (Chaudhry 1987). This water hammer may be acceptable for hydropower plants with short water conduits but is seldom so for long conduits. A long closing time of the turbine can mitigate the problem but is seldom possible. The closing time must be constrained to avoid damaging runaway speeds of the turbines and generators, and to ensure that the specifications in the grid code are fulfilled. The most common means to reduce the water hammer are surge tanks, deflectors and bypass valves (Jaeger 1977).

Speed governing in hydropower plants with long water conduits may be feasible only by means of a surge tank. Speed governing enables hydropower plants to contribute to maintaining a sufficient quality of the frequency in the power grid (IEEE 2007). The frequency in the grid varies according to the ever-changing balance between power production and consumption. To control and limit imbalances, power plants must increase or reduce the power production counteractively to the changes in the grid. Speed governing enables automatic and continuous control, which limits the amplitudes and time-duration of imbalances. Hydropower plants with speed governing, and the ability to change large amounts of produced power within a limited time, are thus highly valuable to the power grid. The main limitation for whether speed governing can be implemented, and the speed at which hydropower plants can change the produced power, is the pressure forces during acceleration of the water are. This can be explained by regarding a situation in which the power plant reduces the power production, and closes the guide vanes or nozzles of the turbine to reduce the water discharge. The closure will result in a pressure rise on the upstream side of the turbine, which in extreme cases may result in an increased power production, in contrast to the desired reduction. To enable speed governing in hydropower plants with long water conduits, surge tanks larger than a minimum size are necessary to reduce the pressure forces (Thoma 1910; Svee 1972).

The acceleration of the water in the hydropower plant causes water level oscillations in the surge tank, which must be controlled. In the case of a surge tank upstream of the turbines, the water level will rise during the closure of the turbine and fall during the turbine opening. The surge tank design must account for these oscillations, which are here called mass oscillations. The maximum mass oscillations in hydropower plants will occur during multiple startup and shutdown operations from full load at resonance (Heigerth 1970). The surge tank design must ensure safety against overflow during water level rise, and air entrainment into the main water conduit during water level fall.

Currently, there is a transition towards more renewable energy sources in Europe. This transition increases the value of flexible hydropower plants to account for the highly variable production from energy sources such as wind and solar (Agora Energiewende 2013). Further, the transition results in the construction of larger hydropower plants, with a higher requirement to perform frequent start-stop operations compared with the present situation. When the size of the power plants increases, the surge tank design becomes more important owing to larger water masses and pressure forces. More frequent start-stop operations further increases the importance of the surge tank, and surge tank research is necessary to prepare for future challenges.

Problem Outline and Scope of Work

Construction and operation of increasingly large hydropower plants with a higher demand for flexibility requires improved surge tank design. Simple upscaling of existing design results in high construction costs and is potentially dangerous, and new development is necessary. This work seeks to gain more understanding and improve the design of closed surge tanks for hydropower plants. More specifically, the work in this thesis answers two research objectives (O) and tests two hypotheses (H):

O1: Determine the state-of-the-art and compare the benefits and challenges of the open surge tank and the closed surge tank.
O2: Test whether hydraulic scale modelling can be applied to model mass oscillations in closed surge tanks for hydropower plants.

H1: "Heat transfer influences the thermodynamic behavior of closed surge tanks."
H2: "Throttling of closed surge tanks has a positive effect on the governing stability and performance in hydropower plants."

The first research objective is to obtain an overview and understanding of surge tank design and the relevant design parameters and processes. Surge tank design is multidisciplinary and influences many aspects of hydropower plants. The state-of-the-art design of both open and closed surge tanks will be described and compared.

The second research objective is to test a potential research method that may be applied to study closed surge tanks. Hydraulic scale modelling is a recognized research and design method in hydraulic engineering, but the literature has revealed only one previous attempt to apply this method to a closed surge tank for a hydropower plant (Larcher et al. 2006). No previous attempts have been made to assess the accuracy of such modelling through comparison with the prototype. The hydraulics and thermodynamics cause the design loads and conditions in closed surge tanks, and hydraulic scale modelling may prove to be a useful tool for the design and studies of such structures.

The first hypothesis is formulated based on a literature study that revealed uncertainty regarding the thermodynamic behavior and heat transfer in closed surge tanks. The standard polytrophic model for calculation of the thermodynamics simplifies heat transfer, even though several studies indicate that heat transfer may have a significant influence (Graze 1968). Accurate calculation of the thermodynamics is important for the design of closed surge tanks, and the theoretical models have potential for improvements. Work was undertaken to investigate the accuracy of different theoretical models.

The second hypothesis is formulated to investigate a potential improvement of the design of closed surge tanks. Hydraulic throttles are known to improve the hydraulic design of open surge tanks and have been applied for this purpose in Austria since the 1960s. In Norway, throttles have never been constructed in closed surge tanks owing among other reasons to uncertainty regarding the effect on the governor stability and performance. Norway currently draws approximately 96% of its total electricity production from hydropower (NVE 2013), and the governor stability and performance is therefore important. The scope of testing this hypothesis is to evaluate the effect of throttling on governor stability and performance, in order to enable more use of such components to improve the design of surge tanks.

Research Context

Surge tank research at NTNU has a long history. The very first doctoral dissertation written at NTNU was entitled “Calculation and Construction of Surge Tanks” by Fredrik Vogt (1923). Research from this university later enabled the first construction of closed surge tanks constructed as underground rock caverns. This thesis presents the first doctoral study on surge tanks from NTNU in more than a decade. The previous study was undertaken by Kjørholt (1991) on air leakage and engineering geology of closed surge tanks. Surge tank research has been limited in recent years owing to a large reduction in the construction of new hydropower plants with surge tanks in Norway. Parts of the motivation of this thesis was to revitalize surge tank knowledge.

This work has benefited from cooperating with domestic and international partners. A cooperation was formed with the Graz Technical University to exchange knowledge and experience of surge tank research. A research stay was realized at the Graz Technical University in March 2013. A cooperation was also formed with Norwegian hydropower companies that operate closed surge tanks to conduct field measurements. No formal restrictions have been imposed by the funders or cooperation partners. The author and supervisors decided the research topics and methods. A wide approach was selected owing to the long time since the last study of closed surge tanks at NTNU.

Research Overview

The connections among the problem outline, research objectives, hypotheses, and resulting papers and contributions are illustrated in Fig. 1. The research methods applied in the individual papers are indicated, and the resulting papers and contributions are presented in the forthcoming sections.

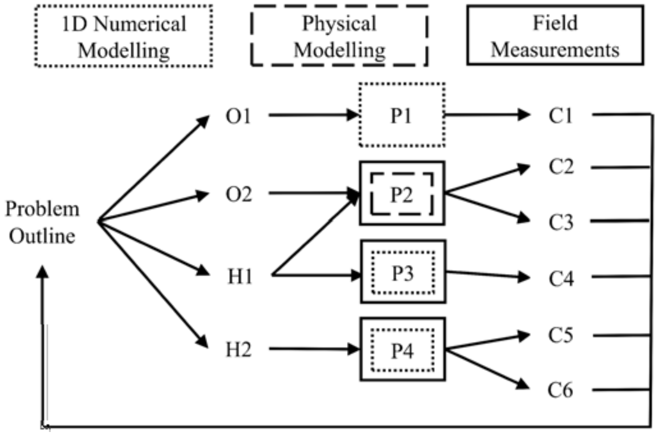

Fig. 1. Overview of the connection among problem outline, research objectives (O), hypotheses (H), papers (P) and contributions (C)

Papers

This section presents the selected papers with a full bibliography. A summary of their relevance to the thesis is given. Detailed descriptions of the methods and the results are presented in later chapters, and the full papers are given in the appendix.

P1 Kaspar Vereide, Wolfgang Richter, Gerald Zenz and Leif Lia (2015). “Surge Tank Research in Austria and Norway.” Wasserwirtschaft, 105(1), 58-62.
Relevance to this thesis: This paper presents work that answers the first research objective. The state-of-the-art surge tank design is presented, and a comparison of the closed surge tank and the open surge tank is conducted. The benefits and challenges of both solutions for a generic hydropower plant are outlined, and an overview of the parameters that are influenced by the surge tank design is given.

P2 Kaspar Vereide, Leif Lia and Torbjørn Kristian Nielsen (2015). “Hydraulic Scale Modelling and Thermodynamics of Closed Surge Tanks.” Journal of Hydraulic Research, 53(4), 519-524, DOI: 10.1080/00221686.2015.1050077.
Relevance to this thesis: This paper presents work to answer the second research objective and parts of the work to tests the first hypothesis. Hydraulic scale modelling is frequently used as a research method in hydraulic engineering. However, the literature reveals no previous attempt to quantify the accuracy of this method for closed surge tanks in hydropower plants. This paper presents an evaluation of whether hydraulic scale models are able to recreate the hydraulics and thermodynamics of closed surge tanks. A new approach for scaling closed surge tanks is proposed, and a hydraulic scale model is constructed. A comparison of field measurements from an existing power plant and the corresponding measurements from the hydraulic scale model is conducted, and the results are used to quantify the accuracy. The scope of this work was to develop and tests a tool for future research and design of closed surge tanks.

P3 Kaspar Vereide, Torbjørn Tekle and Torbjørn Kristian Nielsen (2015). “Thermodynamic Behavior and Heat Transfer in Closed Surge Tanks for Hydropower Plants.” Journal of Hydraulic Engineering, 141(6), 06015002, 1-5, DOI: 10.1061/(ASCE)HY.1943-7900.0000995.
Relevance to this thesis: This paper presents work to test the first hypothesis. The thermodynamics govern both the surge tank behavior and the resulting design, and a thorough understanding is necessary. Heat transfer from closed surge tanks is normally simplified or neglected, and this paper presents field measurements in which heat transfer has a significant effect on the system. Different thermodynamic models for calculation of the thermodynamics are compared with the field measurements to determine the accuracy. A modified version of an existing model that includes the heat transfer is proposed and shown to provide high accuracy. The results indicate that heat transfer is a slow process and confirms previous studies stating that normal transients, such as mass oscillations and the water hammer, will have approximately adiabatic behavior without significant influence from heat transfer. However, for slow transients or transients in which the start and end conditions differ, heat transfer should be considered.

P4 Kaspar Vereide, Bjørnar Svingen, Torbjørn Kristian Nielsen and Leif Lia (2016). “The Effect of Surge Tank Throttling on Governing Stability and Performance in Hydropower Plants.” In Review: IEEE Transactions on Energy Conversion.
Relevance to this thesis: This paper presents work to tests the second hypothesis. Throttling is known to reduce the necessary size of surge tanks. However, throttling has never been applied in closed surge tanks in Norway, partly owing to uncertainty regarding the effect on the governor system. This paper presents a quantification of the throttle effect on governor stability and performance. A methodology for this purpose is introduced and was applied to

an example hydropower plant with a closed surge tank. It is shown that a throttle improved both the governor stability and performance.

Contributions

The main contributions presented in the scientific papers are identified and listed below. These contributions are novel to the research field of closed surge tanks, and a detailed description of each is given in the result chapter.

C1: An overview of the benefits and challenges of the closed surge tank compared with the open surge tank, presented in P1.
C2: A new approach for scaling hydropower tunnels with closed surge tanks for hydraulic scale model tests, presented in P2.
C3: An assessment of the accuracy of a hydraulic scale model of a hydropower tunnel with a closed surge tank, presented in P2.
C4: A modified rational heat transfer (MRHT) method for calculating the thermodynamic behavior in closed surge tanks, presented in P3.
C5: A methodology for evaluating the effect of surge tank throttling on governor stability and performance in hydropower plants, presented in P4.
C6: An evaluation of the effect of surge tank throttling on governor stability and performance in a hydropower plant with a closed surge tank, presented in P4.

Thesis Structure

Chapter 1 has given an introduction to the work. A historical review of closed surge tank research is presented in Chapter 2, and the research methodology is outlined in Chapter 3. The results are presented in Chapter 4, and the application, limitations and uncertainties are discussed in Chapter 5. Chapter 6 presents the conclusions. The full selected papers of this work are given in Appendix A, whereas the bibliographies and abstracts of the secondary papers are given in Appendix B. Appendix C holds the co-author statements for publishing of this thesis.

Chapter 2: Historical Review

An overview of the most significant scientific publications with research on closed surge tanks for hydropower plants is provided in this chapter. Relevant contributions from works on open surge tanks and water supply systems are included.

The first modern scientific description of the closed surge tank known by the author was presented by Michaud (1878). Michaud presented a closed surge tank constructed as a metal tank for reducing the problem of water hammer in water supply pipes. Johnson (1908) was the first to present the closed surge tank as a means to enable speed governing in hydropower plants. Johnson writes that the early hydropower plants were usually run on isolated grids as the single power source, and the frequency in the grid was directly linked to the rotational speed of the generator. To control the rotational speed and thus the grid frequency, surge tanks were often necessary to reduce the water inertia and the water hammer. Johnson demonstrated the possibility of a closed surge tank through a theoretical study. Thoma (1910) showed that surge tanks for hydropower plants required a minimum water surface area to enable speed governing. If the surge tank is too small, the speed regulation will amplify the mass oscillations in the surge tank and cause dangerous water levels. Thoma derived an equation for this minimum area, known today as the Thoma area. This work was conducted for open surge tanks but has provided the foundation for later works on closed surge tanks.

De Sparre (1911) investigated the optimal sizing of closed surge tanks and introduced the concept of throttling. De Sparre stated that the use of closed surge tanks had been generally abandoned for use in hydropower plants owing to the large required volume. Bypass valves were in this period the preferred solution for the reduction and control of the water hammer. To renew the interest in closed surge tanks, De Sparre showed how the required volume of the closed surge tank could be reduced by restricting the flow into the tank by means of throttling. De Sparre, similar to Michaud and Johnson, assumed isothermal behavior of the air in the closed surge tank. Camichel (1918) was the first to conduct an experimental investigation of the thermodynamics of closed surge tanks. Camichel stated that some experiments revealed isothermal behavior whereas others revealed adiabatic behavior, and that the thermodynamics were influenced by the size and construction material of the closed surge tank. Camichel's work is still relevant today as engineers still struggle to determine the correct thermodynamic behavior of closed surge tanks. Foch (1920) further developed a theoretical framework for calculating the thermodynamic behavior of closed surge tanks for adiabatic and isothermal conditions.

In the following years, several engineers and researchers worked on the topic of closed surge tanks; hereafter, only the most influential works are discussed. Evangelisti (1935; 1938) and Allievi (1937) developed a theoretical framework for the calculation of hydraulic transients in systems with closed surge tanks, considering the elasticity of water. Bergeron (1937) introduced the graphical method for calculating the water hammer and mass oscillations in surge tanks. This method rapidly became the preferred solution of hydraulic engineers, and was frequently in use until the modern computer became available. Jaeger (1949) and Frank (1957) wrote textbooks on hydraulics and included descriptions of closed surge tanks. Jaeger (1954; 1958; 1960) also evaluated the stability criterion proposed by Thoma (1910) and suggested a security factor owing to limitations in the original assumptions; Thoma did not consider the influence of factors such as the friction and water inertia in the pressure shaft, the velocity head, and the varying turbine efficiency. Numerous works on design charts for closed surge tanks were developed, including Combes and Borot (1952), Lupton (1953), Parmakian (1963), and Wood (1970).

The thermodynamics of closed surge tanks were a returning topic. Graze (1968) was the first to suggest a thermodynamic model that directly included the heat transfer in the calculation of closed surge tanks. He developed the Rational Heat Transfer (RHT) method and conducted experiments that demonstrated accurate results. However, the RHT method did not gain much popularity owing to limited validation, time-consuming calculation, and its dependency on an empirical constant. Graze continued to work on the thermodynamics of closed surge tanks and presented many publications (Graze 1972; Graze and Forrest 1974; Graze et al. 1976; Graze et al. 1977; Graze and Horlarcher 1982; 1986; 1989). Owing to the development of computing capabilities and more validation, the RHT method is now becoming more frequently applied.

In the 1970s, a large number of hydropower plants were under construction in Norway. Some of the projects were infeasible with conventional open surge tanks owing to challenging topography, and there was a renewed interest in closed surge tanks. Svee (1972) developed a stability criterion for mass oscillations in hydropower systems with closed surge tanks. Svee also reviewed the stability criterion suggested by Thoma (1910) and expanded the theory to include the influence of velocity head and varying turbine efficiency. Simultaneously, Brekke (1972) developed a numerical method with Laplace-transforms for testing the governor stability in systems with closed surge tanks. Rathe (1975) presented the design of the first hydropower plant with a closed surge tank constructed as an underground rock cavern, namely the 140 MW Driva hydropower plant. Jaeger (1977) discussed the possibility of closed surge tanks in his textbook on hydro-electric transients. Goodall et al. (1988) presented the experience of operating ten large hydropower plants with closed surge tanks constructed as underground rock caverns and summarized the existing state-of-the-art for such structures. The construction of new, large closed surge tanks for hydropower plants triggered more research on governor stability. Chaudhry et al. (1985) analyzed the stability of mass oscillations in closed surge tanks with the phase-plane method, which allowed for the evaluation of non-linear effects, and developed a new stability criterion. Chaudhry (1987) also wrote a textbook on applied hydraulic transients with a description of the closed surge tank. Li and Brekke (1989) presented an evaluation of the governor stability for large-amplitude water level oscillation in throttled closed surge tanks. Mader (1990) investigated the possibility of combining the open and closed surge tanks. Yang and Kung (1992), and Yang et al. (1992) continued the work of analyzing the stability of mass oscillations in closed surge tanks. The experience from constructing closed surge tanks as underground rock caverns also allowed for research on the engineering geology design. Kjørholt et al. (1992), and Kjørholt and Broch (1992) investigated the engineering geology design of closed surge tanks and introduced the water curtain technology for preventing air leakage.

Modern textbooks that describe closed surge tanks include Wylie and Streeter (1993) and Thorley (2004). The former demonstrate how closed surge tanks can be included in numerical models with the Method of Characteristics (MOC). This book has had a large impact in the field of numerical modelling of hydraulic transients including closed surge tanks. Recent contributions on closed surge tanks include works from Stephenson (2002) and De Martino and Fontana (2012) on optimal sizing. Larcher et al. (2006) applied hydraulic scale model testing to design a tailrace tunnel with a closed surge tank for a hydropower pumped storage plant. Recent contributions on the thermodynamic behavior of air in hydraulic systems are presented by Zhou et al. (2013a; b). This concludes the historical review. The list is not complete, but it gives a representative overview of previous publications on closed surge tanks for hydropower plants.

Chapter 3: Research Methods

Three different research methods were applied in this work; one-dimensional (1D) numerical simulations, hydraulic scale modelling, and field measurements. Each has different benefits and challenges, and a combination is often necessary to ensure reliable and accurate results. The methods and their individual benefits and challenges for research on closed surge tanks are introduced in the following sections. The hydraulic scale modelling is presented in more detail because less information on this method is provided in the papers. A brief comparison of the three methods for an example hydropower plant is conducted, and references for more in-depth information on the methods are provided at the end of each description.

One-Dimensional Numerical Simulations

One-dimensional (1D) numerical simulation enables transparent and time-effective analyses of hydropower plants with closed surge tanks. Several different numerical methods are available, and in this work, the Method of Characteristics (MOC) as described by Wylie and Streeter (1993) were applied. The MOC is based on the equation of continuity and the equation of motion, respectively described below:

$$\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial x} + \rho a^2 \frac{\partial v}{\partial x} = 0 \tag{1}$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\theta + f\frac{v|v|}{2D} = 0 \tag{2}$$

where p is the pressure (N/m^2), t is the time (s), v is the velocity (m/s), x is the position on the length axis (m), ρ is the mass density (kg/m^3), g is the gravitational acceleration (m/s^2), θ is the angle to the horizontal (^{0}), f is the friction factor (-), and D is the conduit diameter (m). This pair of partial differential equations is combined and transformed into an ordinary differential equation, which allows calculation of the next time-step (t+1) from the current time-step (t). The MOC enables the numerical solution of Eqs. (1) and (2) based on a set of assumptions. The assumptions include neglecting the convective acceleration terms, which is acceptable for slightly compressible, low Mach number flows (Wylie and Streeter 1993).

There are three main error sources in 1D numerical simulations; the cross-sectional averaging, the inability to model phenomena such as vortexes and air intrusion, and inaccuracy and insufficient detail of the input data. The cross-sectional averaging removes effects caused by spatial variations in parameters such as velocity and pressure. An example is energy dissipation due to friction or singular losses, which is dependent on internal shear forces in the flow. To allow for the cross-sectional averaging, empirical models that require calibration are applied. The empirical models are known to yield high accuracy for steady-state flow, whereas transient flow is more challenging. For example, the Darcy-Weisbach equation was derived for steady-state conditions (Moody 1944) and cannot properly represent transient friction. Models for the transient friction during water hammer are available but have not become standard in application (Storli 2011). Models for the transient friction during mass oscillations is seldom necessary and published version are not known by the author. The second error source is the inability to model phenomena such as vortexes and air intrusion, which are highly dependent on 3D flow. Some aspects of the phenomena, such as transported air volume or energy dissipation, may be approximated. The third error source is inaccuracy and insufficient detail of the input parameters. Parameters such as friction factors, conduit length, conduit area, and water hammer speed are seldom accurately described in drawings and technical data from hydropower plants. Field measurements are often necessary to confirm the true parameters of the system.

In spite of the challenges of 1D numerical simulations, they still provide results with sufficient accuracy with limited time and effort. It may also be the only feasible method when evaluating large hydraulic systems, owing to the higher time-consumption of 2D and 3D numerical modelling, and hydraulic scale modelling. A comprehensive overview of the MOC can be found in Wylie and Streeter (1993).

The simulations in this work were conducted with the freeware LVTrans 1.7.11 (2013). This freeware was selected because of available in-house expertise and validation for hydropower systems. New theoretical models were tested and new elements were programmed. The selection of this software was therefore invaluable for access to the source code and support during programming. Detailed information on the freeware LVTrans can be found in Svingen (2007). A new module for simulating closed surge tanks was developed in this work, and the applied theory is presented in P3. Additional information on 1D numerical simulations conducted in this work is found in P1 and P4.

Hydraulic Scale Modelling

Hydraulic scale modelling is regarded as a more reliable method compared with 1D numerical simulations, owing to the representation of 3D flow without empirical models and fewer error sources inherited from the programming of the physics. However, this does not mean that the accuracy of hydraulic scale models are always superior to other methods. The accuracy is dependent on several factors including the scaling law, scaling factor, simplifications of the system, construction materials, and the flow boundary conditions. A general challenge of hydraulic scale models is the time-consuming and expensive construction, which results in less possibility for calibration and testing of different designs compared with 1D numerical simulations.

The accuracy of hydraulic scale models for hydropower plants with closed surge tanks had not previously been assessed, and literature revealed only one previous attempt to construct such a model (Larcher et al. 2006). Hydraulic scale models are normally applied in the design process of hydropower plants before or during construction. In this work, the method was applied to model an already existing power plant to assess the accuracy. For studies of closed surge tanks, hydraulic scale modelling offers the additional benefit of observing and measuring parameters and events that would not be possible in the prototype. Closed surge tanks are by nature inaccessible because they are submerged and pressurized during normal operation. Further, hydraulic scale models enable simulation of extreme operation of the hydropower plant, which the power plant operator will not allow in the prototype power plant. Compared with numerical methods, the main benefit is the possibility of observing and studying the flow in the physical world.

Scaling in this work was performed by Buckingham's (1914) π-theorem. Buckingham regarded all systems in the dimensions length, mass, and time, and the principle of scaling is to preserve the relation between all parameters in the model and the prototype. The similarity of model and prototype can be separated into three different types; geometric, kinematic, and dynamic. Geometric similarity is achieved if the geometric shape is scaled correctly. Kinematic similarity usually requires geometric similitude and is achieved if time, velocities and accelerations are scaled correctly. Dynamic similarity usually requires geometric and kinematic similitude, and is achieved if the ratios between different forces are scaled correctly. The ratio between different forces yield dimensionless numbers that reflect the properties of the investigated system. For hydraulic scale models of closed surge tanks, dynamic similitude is desired. However, it is impossible to scale all the forces in hydraulic scale models correctly at the same time, and one has to choose the ratios where similarity is preserved (Kobus 1978). For closed surge tanks, the thermodynamics present additional challenges for scaling, owing to additional processes and forces where the ratio must be preserved.

The systems investigated in this study have pressurized flow, and the Euler number is chosen as the basis for the scaling. The Euler number represents the ratio of pressure forces to inertia forces, which are the two dominant forces in pressurized pipe flow. It is also possible to use the Froude number, which represents the ratio of inertia forces to gravity forces, as basis for scaling the pressurized flow. The Froude and Euler numbers yield equal scaling factor for hydraulic scale models, if the water is regarded as an incompressible fluid. This can be demonstrated by inserting the pressure head ($H = p/\rho g$) as characteristic length (L) in the Froude number. The Euler and Froude numbers become inverse functions, yielding equal scaling factor. For scaling of closed surge tanks, the Euler scaling law is regarded as appropriate, while the Froude scaling law is regarded as more correct for scaling of open surge tanks with significant influence from free surface flow conditions. Table 1 presents relevant dimensionless numbers for scaling of closed surge tanks:

Table 1 . Dimensionless numbers for hydraulic scale modelling of closed surge tanks

Dimensionless Numbers	Forces or Processes	Expression
Froude number	Inertia/Gravity forces	$\frac{v}{\sqrt{gL}}$
Euler number	Pressure/Inertia forces	$\frac{p}{\rho v^2}$
Reynolds number	Viscous/Inertia forces	$\frac{vD}{\nu}$
Weber number	Inertia/Surface tension forces	$\frac{\rho v^2 L}{\sigma}$
Cauchy number	Inertia/Compressibility forces	$\frac{\rho v^2}{B}$
Mach number	Velocity/Speed of sound	$\frac{v}{c}$
Prantl number	Viscous/Thermal diffusion	$\frac{c_p \mu}{k}$
Nusselt number	Convective/Conductive heat transfer	$\frac{hL}{k}$
Grashoff number	Bouyancy/Viscous forces	$\frac{g(T-T_0)L^3}{T\nu^2}$

where ν is the kinematic viscosity (m^2/s), L is a characteristic length (m), σ is the surface tension (N/m), B is the bulk modulus of elasticity (N/m^2), c_p is the specific heat (J/kgK), μ is the dynamic viscosity (Ns/m^2), k is the thermal conductivity (J/smK), h is the convective heat transfer coefficient (W/m^2K), T is the surface temperature (K), and T_0 is the bulk temperature (K).

The Reynolds, Cauchy, and Mach numbers will not be scaled correctly at the same time as the Euler and Froude numbers. This means that the viscous forces, compressibility forces, and water hammer will not be scaled correctly in the model. However, the error owing to wrong scaling of the viscous forces is known to be limited if the flow is turbulent in both model and prototype (Hughes 1993). The compressibility forces and ratio of the water velocity to the speed of sound influence the water hammer, which will not be scaled correctly in the model. In this work, the mass oscillations were of primary interest as they cause the design loads on the surge tanks. The water hammer does not influence the mass oscillations to a high degree, and the effect of reduced water hammer is assumed negligible.

Scaling of the thermodynamics is highly dependent on the heat transfer. Heat transfer is dependent on the Prantl, Grashof, and Nusselt numbers (Bejan 1993), which are not practically possible to scale correctly simultaneously with the Euler number. It is therefore impossible to scale the heat transfer correctly at the same time as the mass oscillations. However, for isothermal or adiabatic conditions, the thermodynamics may still be scaled correctly. For adiabatic conditions, no heat transfer occurs, and the Euler scaling preserves correct thermodynamic behavior. Based on Goodal et al. (1988) it was seen that closed surge tanks constructed as underground rock caverns for hydropower plants have approximately adiabatic behavior during mass oscillations. The hydraulic scale modelling in this work is therefore conducted under the assumption of adiabatic conditions.

Another special challenge of modelling closed surge tanks is to obtain the correct boundary conditions for pressure. Scaling of closed surge tanks requires a correct relationship between the ambient atmospheric air pressure and the absolute pressure and water level inside the surge tank. Three methods currently exists; (1) manipulate the geodetic height of the closed surge tank, (2) scale and control the air pressure at all points of contact between water and air, or (3) account for the atmospheric air pressure by increasing the volume of the closed surge tank. The first option sacrifices the geometric similitude in parts of the water conduit, but was selected in this work owing to lower cost and complexity, and to preserve the geometry of the closed surge tank. In comparison, the second option is more expensive and technically challenging, whereas the third option sacrifices the correct geometry of the closed surge tank. The selected method had not been described in earlier literature and is now outlined in the results chapter and in P2. The advantages and disadvantages of the different methods are further discussed under contribution C2 in the results chapter.

Validation of hydraulic scale models is possible trough comparison with the prototype. In this work, pressure and volume measurements are taken from the closed surge tanks in the model and prototype during a power plant shutdown from full load. Temperature measurements would have given an additional parameter for comparison, but have not been possible in this work. Temperature measurements from the prototype were impossible, as equipment could not be installed owing to the water-filled tunnels. Temperature measurements from the model were attempted but unsuccessful, owing to condensation on the available temperature sensor. In addition, the reaction time of the available temperature sensor was too slow to measure the correct instantaneous temperatures during the mass oscillations. Further details of the hydraulic scale model constructed as a part of this work is presented in P2. For additional information on theories and application of hydraulic scale modelling, one may consult the works of Buckingham (1914), Kobus (1978), and Hughes (1993).

Field Measurements

Field measurements are the only way to verify the true behavior of hydraulic systems. Methods such as numerical modelling and hydraulic scale modelling are approximate replications of the real system. However, it is challenging to obtain field measurements. The challenges include accessing the components of interest, calibration of the measurement equipment, resolution of the measurement equipment, software, wrong installation of equipment, signal noise and disturbances. The main challenge for field measurements in closed surge tanks in hydropower plants is the access. The closed surge tanks are submerged and pressurized during normal operation and are seldom drained. Furthermore, it is the extreme operation of the power plants that is most interesting and relevant for measurements, and the power plant operator may refrain from such operation. In this work, field measurements are used to calibrate and validate theoretical models, 1D numerical models, and the hydraulic scale model.

Measurements from two hydropower plants with closed surge tanks are presented in this work. The field measurements from Jukla power plant include air pressure and water level in the closed surge tank, and the reservoir water levels. These measurements were taken during a switch between two upper reservoirs at different elevations, which resulted in a doubling of the air pressure in the surge tank during 40 min. The power plant was not operated during this event, and the process was controlled by opening and closing the intake gates at the two reservoirs. These measurements are presented in P2, and offer a unique possibility to study the thermodynamics of slow and large transients in the closed surge tank. The field measurements from Torpa power plant included the pressure in front of the turbine, air pressure and water level in the closed surge tank, power plant production, and water level in the reservoirs. The measurements were taken during an emergency shutdown from full load. These measurements are presented in P2 and P4 and offer the possibility to study the mass oscillation in closed surge tanks.

Five recommendations are given to those who may attempt to take field measurements in closed surge tanks in hydropower plants in the future: (1) use two independent sensors to measure each individual parameter to allow for control and redundancy of the measuring equipment; (2) be specific in describing the desired power plant operation to the power plant operator, and disable the turbine speed governor and run the power plant locally with manual servo control if possible; (3) given that some parameters are measured by the power plant with permanently installed equipment, enquire about the maximum sample rate and whether this is activated. The sample rate is often reduced relative to the maximum for permanently installed equipment owing to computer storage capacity. The time period since the last calibration should be considered. The two last recommendations are; (4) obtain controlled drawings of the power plant to know the elevation at which the measuring equipment is positioned; and to (5) complete general preparations such as visual inspection and installation of necessary equipment prior to the day of measurement.

Comparison of the Methods

A comparison of results from 1D numerical simulations, hydraulic scale modelling, and field measurements is presented in this section. The comparison was conducted with the field measurements of the emergency shutdown from full load in Torpa hydropower plant. It should be noted that the hydraulic scale model has a lower initial pressure due to higher velocity head at the point of measurement, but the sum of velocity and pressure head is equal in the three methods. The field measurements have a different sampling rate upstream the turbine and in the closed surge tank, owing to different measuring equipment. The different advantages and disadvantages of the methods are outlined in the previous sections. For selection of the appropriate research method, a holistic consideration is necessary, and a combination may be required. Graphs with the comparison are presented in Fig. 2.

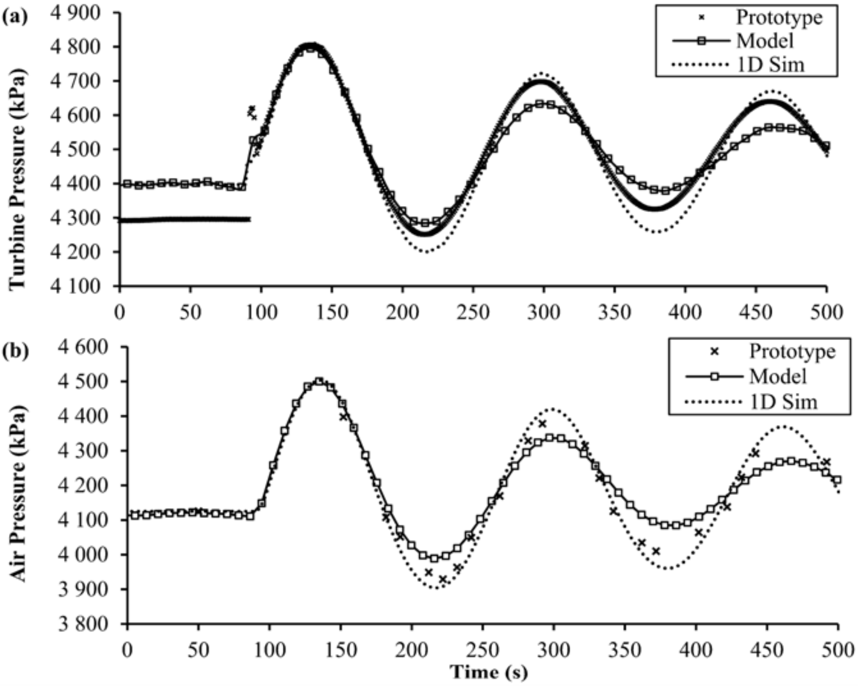

Fig. 2. Comparison of field measurements, hydraulic scale model and 1D numerical simulations for (a) pressure upstream the turbine, and (b) air pressure in the closed surge tank

Within the field measurements it was not possible to capture the water hammer propagation owing to limited sampling rate. However, parts of the maximum water hammer amplitude were captured, and it is seen that the water hammer was not accurately modelled in either the hydraulic scale modelling or the 1D numerical simulations. The hydraulic scale model was not able to scale water hammer at the same time as mass oscillations owing to different scaling of the Mach number and the Euler number. The 1D numerical simulations would have been able to simulate the water hammer with higher accuracy, but the water conduit was not modelled in sufficient detail in the present example.

The field measurements have an error estimate of less than 0.1% for the mass oscillations, and it is seen that the first amplitude is captured with high accuracy in both the 1D numerical simulations and the hydraulic scale model. For subsequent amplitudes, the 1D numerical simulations have a lower dampening, and the hydraulic scale model has a higher dampening compared with the field measurements. The lower dampening in the 1D numerical simulations is caused by either underestimation of the singular losses in the surge tank, air pockets in the prototype water conduit, or the use of steady-state friction models for transient flow. The higher dampening in the hydraulic scale model may be caused by air bubbles in the model pipes, varying water level in the upper reservoir, underestimation of the heat transfer, or overestimation of singular losses in the surge tank. The error sources of the hydraulic scale model is further discussed under contribution C3 in the results chapter.

The present comparison is for a case-study hydropower plant. In contrast to the present example, hydraulic scale models may underestimate, and 1D numerical simulations may overestimate the dampening of mass oscillations in other power plants. The theory for the 1D numerical simulations is given in P3 and P4. The parameters of the power plant and the hydraulic scale model are presented in P2. The field measurements presented in this comparison are found in P2 and P4.

Chapter 4: Results

This chapter presents the results. Summaries of the four selected scientific papers are presented, focusing on the findings relevant for closed surge tanks. Thereafter, detailed descriptions of the contributions novel to the research field of closed surge tanks are given. The full version of the selected papers are provided in Appendix A.

Selected Papers in Summary

P1: Surge Tank Research in Austria and Norway

This paper presents a comparison of the state-of-the-art surge tank design in Austria and Norway. The designs are in this paper referred to as the open throttled chamber surge tank (TCST) and the closed air cushion surge tank (ACST) respectively. A list of comparison parameters for surge tank design is provided and applied to compare the two solutions. A generic example power plant including reservoir, a tunnel system, surge tanks, a turbine and a power house is developed for the comparison of hydraulic properties and rock excavation volumes. 1D numerical simulations are applied to compare the hydraulics of the two different schemes.

The comparison reveals that the ACST requires a larger excavation volume than the TCST. However, the complete scheme with the ACST requires less excavated volume because the water conduit between the reservoir and the power house may have a more direct alignment, resulting in a shorter length. In addition, the costly and time-consuming construction of a pressure shaft can be avoided. The ACST scheme does not require a surface access for the surge tank, and has a reduced risk of negative pressures in the water conduit. Compared with the alternative solutions where the water conduit is located closed to the surface, the ACST scheme has a reduced risk of conduit collapse with resulting flooding on the surface, which in extreme cases have caused loss of human lives. The hydraulic comparison reveals that the ACST scheme has a reduced water hammer amplitude but an increased mass oscillation amplitude. Furthermore, the water inertia time constant is significantly lower in the ACST scheme and enables more flexible operation of the power plant. The negative aspects of the ACST scheme have a high influence on decision-making. These include a higher risk owing to geological challenges of deeper underground construction works, requirements of air tightness, and long filling time of the closed surge tank. In spite of the arguments above, it is concluded that the decision on preferable design is predominantly dependent on site-specific geological conditions, topography and operational requirements.

P2: Hydraulic Scale Modelling of Mass Oscillations in Closed Surge Tanks

Hydraulic scale modelling is an important tool for studies of hydropower hydraulics. However, literature revealed only one previous attempt to model a closed surge tank in a hydropower plant, and the accuracy had never been assessed. The main scope is to test the applicability and accuracy of hydraulic scale modelling of mass oscillations in closed surge tanks. A new method for scaling of the closed surge tank is developed and tested by constructing a hydraulic scale model of an existing hydropower plant. The accuracy of the modelling is determined by comparison with field measurements from the prototype. The atmospheric air pressure poses a challenge for scaling of mass oscillations in closed surge tanks. The behavior of closed surge tanks depends on the absolute pressure, resulting in an influence from the atmospheric air pressure. The new scaling method manipulates the geodetic height of the closed surge tank to obtain the correct relation between absolute air pressure, volume and water level. Another challenge was the scaling of the thermodynamics, which are influenced by the heat transfer. Heat transfer cannot be scaled at the same time as mass oscillations, and physically correct scaling is therefore possible only under adiabatic or isothermal conditions. Goodal et al. (1988) and the author’s own experience from field measurements indicated that the thermodynamic behavior during mass oscillations in closed surge tanks constructed as large underground rock caverns is approximately adiabatic. The hydraulic scale model was therefore scaled under this assumption.

The hydraulic scale model provided accurate representation of the maximum (first) amplitude, with a relative error of less than 4%. The period of the mass oscillations has a relative error of less than 1%. The model had a higher dampening of the oscillations compared with the prototype, resulting in 20% relative error of the second amplitude. It was observed that the prototype had adiabatic behavior in the closed surge tank, which confirms the observations from Goodal et al. (1988). The hydraulic scale model had an unexplained higher dampening of the pressure oscillations. The higher dampening could have been caused by various error sources outlined in the paper, and future investigations should be undertaken to determine the cause. Regardless, it is concluded that the first (maximum) and most important pressure peak can be modelled with reasonable accuracy.

P3: Thermodynamic Behavior and Heat Transfer in Closed Surge Tanks for Hydropower Plants

This paper presents an investigation of the thermodynamic behavior and heat transfer in closed surge tanks. A unique dataset with field measurements from a power plant with a closed surge tank provided an opportunity to compare different theoretical models for 1D numerical simulations of the thermodynamics. The measurements were collected during a transition from a low-lying upper reservoir to a higher-lying upper reservoir, which resulted in a doubling of the air pressure in the surge tank over a period of 40 min. The measured transient is slow compared with normal transients such as water hammer and mass oscillations. A numerical model of the hydropower plant was developed in the 1D simulation software LVTrans, and different thermodynamic models were tested. The polytrophic equation yielded inaccurate results, and it was concluded that there was a significant influence of heat transfer, which is not accurately represented by this model. The Rational Heat Transfer (RHT) method presented by

Graze (1968) was applied, yielding improved results. Finally, a modified RHT (MRHT) method developed by the authors yielded the highest accuracy.

The improvements in the MRHT method compared with the RHT method is a separation of the heat transfer to air and water and calculation of the heat propagation in the rock. The MRHT accounts for variable temperature in the rock and provides more accurate boundary conditions for the heat transfer. It is concluded that there was a significant heat transfer which influenced the thermodynamics during this event, and that the MRHT was able to capture this process. Further, it is observed that the heat transfer is a slow process, not significant until after 20 min of the transient. This indicates that the thermodynamics can be regarded as adiabatic for normal transients such as water hammer and mass oscillations in large closed surge tanks constructed as underground rock caverns.

P4: Effect of Surge Tank Throttling on Governing Stability and Performance

Surge tank throttles are applied to reduce the mass oscillations and the necessary size of surge tanks. Throttles introduce a singular loss during water flow in the surge tank and are usually constructed as steel orifices. The scope of this paper is to investigate the throttle impact on governor stability and performance in a hydropower plant with a closed surge tank. Throttles have never been applied in closed surge tanks for hydropower plants in Norway, partly owing to uncertainties regarding the effect on the governor system. A methodology for evaluating the throttle effect is proposed and applied to an example hydropower plant. The example is the 150 MW Torpa hydropower plant, which is constructed with a non-throttled closed surge tank. Field measurements of an emergency shutdown from full load are used to validate a numerical model, which in turn is applied for evaluation of the throttle effect.

The proposed methodology includes the effects of non-linearities and a non-ideal discrete-time implemented governor system. The basic principle is to establish a 1D numerical model and evaluate the governor stability through frequency-response test, and the governing performance through step-response tests. Governing stability is evaluated for a governing system with speed feedback exclusively. Governing performance is evaluated with two different governor systems; (1) with combined speed and power feedback, and (2) with speed feedback exclusively. The results show that the throttle has no significant impact on the governor stability, because normal disturbances in the grid frequency result only in limited water flow through the throttle. For governor performance, the results show that the produced power may be controlled more accurately when a throttle is installed. The produced power also reaches the desired steady-state faster in systems with a throttled surge tank. All tests show that the installation of a throttle will result in reduced mass oscillations and increased water hammer pressure amplitudes.

Contributions

C1: An overview of the benefits and challenges of the closed surge tank compared with the open surge tank (P1).

The overview of the benefits and challenges of the closed surge tank compared with the open surge tank provides a reference that will assist hydropower engineers in selecting a surge tank type for new projects. Surge tank design is a multi-disciplinary task, in which both civil and mechanical engineering challenges must be considered. A generic hydropower project is used to benchmark the state-of-the-art hydropower design from Austria and Norway with open and closed surge tanks respectively. Fig. 3 presents a drawing of the two different designs.

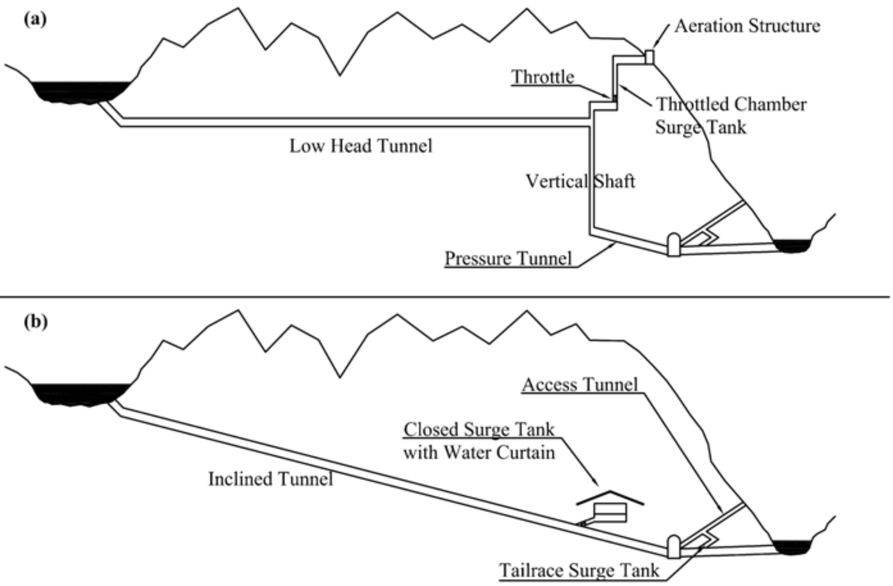

Fig. 3. Comparison of hydropower plant design with (a) open and (b) closed surge tanks

The selection of surge tank type has a strong influence on the design of the entire hydropower scheme, including the possibilities for how to construct and align the water conduit. An effort is made to identify and describe all the effects of the different surge tank types on hydropower projects. The most important factors are site-specific such as topography, rock properties, and operational requirements of the power plant. The overview of benefits and challenges of the different surge tank designs is given in P1.

C2: A new approach for scaling hydropower plants with closed surge tanks for hydraulic scale model tests (P2).

A new approach for scaling hydropower plants with closed surge tanks has been developed to improve hydraulic scale modelling of such systems. There are two main challenges in scaling of closed surge tanks. The first challenge is scaling of the thermodynamics, previously discussed in the method chapter. Scaling of closed surge tanks is possible only if the thermodynamic behavior is either adiabatic or isothermal.

The second challenge is that scaling must be conducted in terms of the absolute pressure to preserve the validity of the perfect gas law. For hydraulic scale modelling of open surge tanks it is sufficient to scale the relative pressure, owing to constant atmospheric air pressure in all points of contact between water and air. For scaling of closed surge tanks, the air pressure inside the tank is a variable and differs from the atmospheric air pressure. The new approach developed in this work manipulates the geodetic height of the closed surge tank relative to the upper water reservoir to acquire the correct relation between pressure, volume and temperature in the closed surge tank. Fig. 4 shows a comparison of a hydraulic scale model and a prototype hydropower plant.

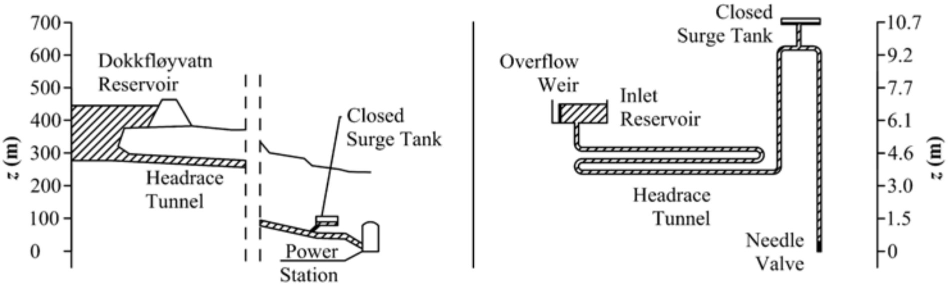

Fig. 4. Comparison of the prototype and the hydraulic scale model.

There are four negative aspects of the proposed approach. The water pressure, in the parts of the model where the geodetic height has been manipulated, will be wrong compared with the prototype. However, the sum of geodetic height and pressure is still similar in the model and prototype, preserving the similarity of the energy line. The second negative aspect is the necessity of a longer distance between the surge tank and the turbine in the model compared with the prototype, which influences the water hammer in the system. As described in the method chapter, this error is assumed insignificant when scaling mass oscillations. The third negative aspect is that the geometric manipulation reduces the visual similitude between the hydraulic model and the prototype. Parts of the visual benefits of a hydraulic scale model are therefore lost. The fourth negative aspect is that the scaling factor must be low enough to avoid a practically challenging geodetic height of the closed surge tank. However, low scaling factors will also reduce the various scaling effects in general. In spite of the negative aspects, the approach is seen to yield acceptable results for modelling of the maximum pressure amplitude presented in P2.

Two alternative methods with different advantages and disadvantages are known. The first alternative is to scale the air pressure over the inlet and outlet water reservoirs with pressure tanks, and the second alternative is to increase the volume of the closed surge tank to account for the relatively higher atmospheric air pressure. The first alternative has not been tested in available literature, and was disregarded in this work owing to the cost and complexity of the necessary pressure tanks. These pressure tanks would require an advanced control system to ensure constant pressures during variable water inflow and outflow. In addition, with the scaling factor applied in this work (1:65), the low pressure in these tanks would become challenging. The second alternative was applied by Larcher et al. (2006) to scale an air chamber in the tailrace tunnel for the pumped storage plant Kops II in Austria. This approach increases the air volume in the closed surge tank relative to the prototype to account for the relatively higher atmospheric air pressure. The approach has been shown to be mathematically acceptable, but sacrifices the geometric similitude of the closed surge tank. Compared with the two alternative approached, the advantages of the new method include the lower cost and complexity, and the preservation of the geometry of the closed surge tank. It is concluded that the new method involves serious manipulations at the cost of the geometric similitude of the water conduit geodetic height. However, under these circumstances, the similitude of the hydraulics and the thermodynamics is preserved, and the approach is feasible for scaling closed surge tanks.

C3: An evaluation of the accuracy of a hydraulic scale model of a hydropower plant with a closed surge tanks (P2)

A hydraulic scale model of an existing hydropower plant with a closed surge tank was constructed and applied to determine the accuracy by comparing the results with field measurements from the prototype. Hydraulic scale models are usually constructed for the design of new hydropower plants, and the accuracy is rarely quantified. The main reasons for this include differences between the actual constructed prototype and the hydraulic scale model, and dismantling of the model before the prototype is constructed to clear laboratory space for new models. The accuracy was tested with field measurements from the prototype during an emergency shutdown from full load. The prototype is the 150 MW Torpa hydropower plant in southern Norway, and technical data of the power plant and the measurements are found in P2 and P4. Fig. 5 presents a comparison of the measured pressure in front of the turbine in the hydraulic scale model and in the prototype.

As can be seen from the comparison, the pressure in front of the turbine in the model and the prototype is different during the steady-state operation in the first 100 s. The reason is different velocity heads owing to the fact that the bifurcation pipe of the prototype has not been included in the model. However, the sum of the velocity head, pressure and geodetic height is equal. The comparison of the results from the hydraulic scale model and field measurements show a deviation of approximately 4% in the first (maximum) pressure amplitude, and a deviation of less than 1% for the oscillation period. There is a significantly higher dampening of the oscillations in the hydraulic scale model compared with the prototype, resulting in a 20% deviation for the second amplitude.

The deviations of both the first and subsequent amplitudes may be caused by one or several of the following reasons; heat transfer in the closed surge tank, errors in the power plant drawings, scaling errors, scaling effects, construction errors, and measurement errors. The author believes that one of the following four error sources are most likely; a limited capacity of the overflow weir in the upper reservoir, lingering air bubbles in the water pipes, simplification of frictional losses by the means of singular losses through valves, or the thermodynamics of the air. Regarding the overflow weir in the upper reservoir, the water discharge and level is varying due to the alternating flow direction in the headrace tunnel during the mass oscillations. The variable water level in the upper reservoir may thus have increased the dampening of the mass oscillations, but this has not been confirmed at the time of writing. Regarding the air bubbles in the pipes, flushing of air was necessary to obtain the presented results. The flushing was

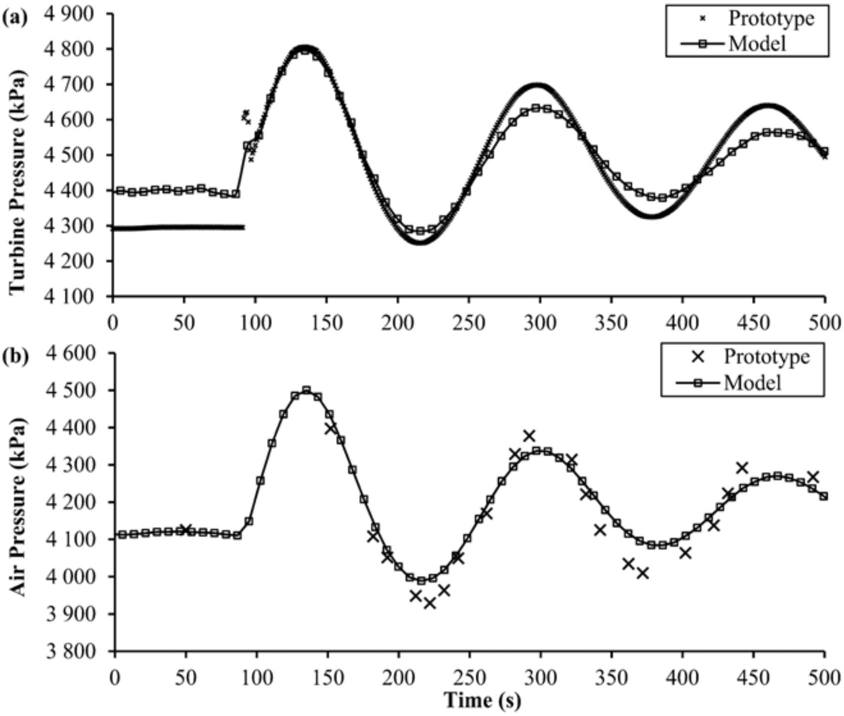

Fig. 5. Comparison of (a) pressure upstream the turbine and (b) air pressure in the closed surge tank in the prototype and the hydraulic scale model

conducted by running the maximum possible water velocity through the pipes (0.4 m/s) for 8 h. Additional flushing time did not result in improvements, but it is possible that the maximum velocity was insufficient to flush all air in the system. Air in the system is a known problem in hydraulic scale modelling of closed conduit flow and explains a higher dampening. Regarding the frictional losses, these were simplified with singular losses through valves in the model, to enable easier control of the head loss. This approach was accurate for steady-state conditions, but may have yielded higher energy dissipation during transients. Regarding the thermodynamic behavior, this may not have been fully adiabatic. Hydraulic scale modelling of closed surge tanks was only possible by assuming adiabatic behavior, and heat transfer out of the closed surge tank may have enhanced the energy dissipation during the mass oscillations.

For the design of closed surge tanks, it is the first (maximum) amplitude that is of highest importance. This amplitude will determine the design pressure and water levels in the surge tank. Accuracy of 4% is regarded as acceptable, and it is concluded that hydraulic scale models can be applied to the evaluation of the important first (maximum) amplitude. The 20% deviation in the subsequent amplitudes is too high to recommend hydraulic scale modelling to determine anything other than the first (maximum) amplitude. It is possible that future studies will identify and mitigate the error sources and enable hydraulic scale modelling with higher accuracy.

C4: A modified rational heat transfer (MRHT) method for calculating the thermodynamic behavior in closed surge tanks (P3).

A modified rational heat transfer (MRHT) method was developed to calculate the thermodynamic behavior in closed surge tanks for 1D numerical simulations. This method is regarded as more accurate than the standard approach, which is to use the polytrophic model as described in Eq. (3):

$$pV^n = C \tag{3}$$

where n is the polytrophic factor ranging from 1.0 to 1.4 (-) for isothermal to adiabatic condition respectively, and C is a constant (N/m). The polytrophic model simplifies the heat transfer process, and a literature review revealed inaccuracy when it is applied to closed surge tank with significant influence from heat transfer. Graze (1968) proposed a Rational Heat Transfer (RHT) method that improves the modelling of thermodynamic behavior with heat transfer. However, this method did not receive wide application owing to limited validation, higher complexity, and the introduction of an additional empirical constant. Eqs. (4) and (5) presents the equations for calculation of the thermodynamics in the RHT method:

$$dp = \frac{1}{V}[-\kappa p dV + (\kappa - 1)dQ] \tag{4}$$

$$dQ = 0.92 \, |T_a - T_r|^{\frac{1}{3}} \, A(T_a - T_r)dt \tag{5}$$

where κ is the adiabatic constant set to 1.4 (-), dQ is the heat transfer (Nm), T_a is the air temperature (K), T_r is the rock temperature (K), A is the area of heat transfer surface (m^2), and dt is an increment of time (s). The constant 0.92 has been converted to SI units ($N/mK^{4/3}s$) from the imperial units ($B.Th.U/ft^2F^{4/3}s$) of the original work. The derivation of the RHT method is presented in P3. Fig. 6 present the thermodynamic parameters during water inflow in a closed surge tank.

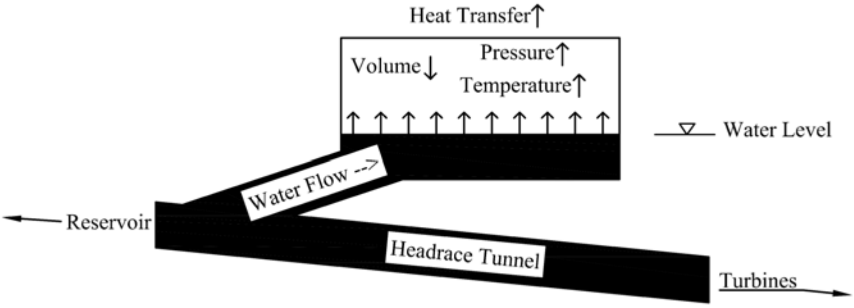

Fig. 6. Closed surge tank parameters during water inflow

The MRHT method is a modification of the original RHT method. The MRHT method also applies Eq. (4), but modifies the calculation of the heat transfer (dQ). Eqs. (6) to (8) present the calculation of the heat transfer in the MRHT method:

$$dQ = \frac{Nu_w \lambda_a}{L_w} A_w (T_a - T_w) dt + \frac{1}{\frac{L_r}{Nu_r \lambda_a} + R_r} A_r (T_a - T_w) dt \tag{6}$$

$$dQ_i = \frac{\lambda_r A_r (T_i - T_{i+1})}{l} dt \tag{7}$$

$$dT_i = \frac{dQ_i - dQ_{i+1}}{A_r l c_p \rho} \tag{8}$$

where subscripts a, w, r, l and i indicate air, water, rock, layer and index respectively, λ is the thermal conductivity (N/Ks), L is a characteristic length over which heat transfer occurs (m), R is the heat transfer resistance (N/mKs), l is the thickness of rock layers (m) over which heat transfer is calculated, and c_p is the specific heat capacity (Nm/K) of the rock. Nu is the dimensionless Nusselt number (-) derived as the ratio between heat transfer from convection and conduction, and the value can be estimated from empirical equations (Incropera and Dewitt 2007). Eq. (6) is used to calculate the amount of heat transfer from the air to the water and rock. Eqs. (7) and (8) are used to calculate the heat transfer internally in the rock. In the MRHT method, the rock is regarded as a finite number of 1D layers. After a sufficient amount of layers, found by trial and error, dT becomes zero and the rock temperature reaches steady state. This steady-state is applied as the boundary conditions for the rock temperature.

The main improvements of the MRHT method include separating the heat transfer to rock and water and accounting for the effect of the temperature change in the rock. The three different methods for calculating the thermodynamic behavior are tested in a case-study of the 40 MW Jukla power plant. Field measurements of water level and pressure in the closed surge tank were collected during a switch between two upper reservoir. The switch occurred during a period of 40 min, over which the air pressure in the closed surge tank was approximately doubled. Fig. 7 presents a comparison of the field measurements and simulations of the water level in the closed surge tank. The simulation with the polytrophic model were conducted with the polytrophic constant equal to 1.0 (isothermal), 1.2 (intermittent) and 1.4 (adiabatic).

The comparison shows that the polytrophic equation is not able to properly represent the thermodynamic behavior in this case. The RHT method is more accurate, whereas the highest accuracy was obtained with the MRHT method. However, these results are subject to the limitations of a case-study, and the RHT and MRHT methods are dependent on empirical constants to calculate the heat transfer. The simulated transient is slow and large which gives the heat transfer time to influence the system. For normal hydraulic transients in closed surge tanks, such as water hammer and mass oscillations, the heat transfer is too slow to have significant influence on the system. Goodall et al. (1988) and P2 show that the thermodynamics for mass oscillations in closed surge tanks

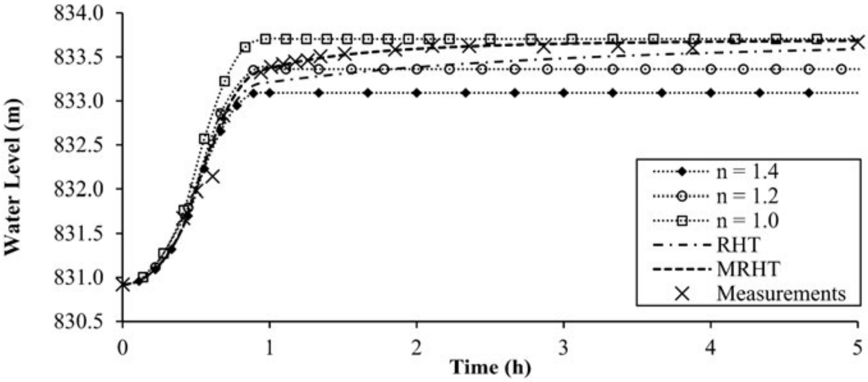

Fig. 7. Comparison of water level simulations and measurements

constructed as underground rock caverns are approximately adiabatic and may be represented by the polytrophic model. The more advanced methods are necessary only for calculation of slow transients or transients in which the start and end conditions differ. In such cases, the heat transfer will influence the system and must be considered.

It should be noted that the calibrated MRHT method is expected to yield correct results also for normal mass oscillations and water hammer in Jukla power plant. The magnitude of dQ is small and results in approximately adiabatic conditions during mass oscillations and water hammer. This be seen from the equations, where the MRHT method transforms into the derivate of the polytrophic equation for adiabatic conditions, if dQ in Eq. (4) goes to zero. Hence, the MRHT method is versatile and able to represent the thermodynamic behavior for a wide range of transients. However, the implementation is more complex and calibration is necessary. Additional information on the MRHT method is found in P3.

C5: A methodology for evaluating the effect of surge tank throttling on governor stability and performance in hydropower plants (P4).

A methodology for evaluating the throttle effect on governor stability and performance with 1D numerical simulations is proposed. The methodology was developed in this work to test the effect of throttling on closed surge tanks, but is also applicable for hydropower plants with open surge tanks. Throttles are applied the surge tank to reduce the necessary volume and improve the hydraulics of the power plant. The impact on governor stability has been investigated previously (Li and Brekke 1989; Yang and Kung 1992) but not in combination with the impact on the performance. The governor performance is in this work defined as the ability to produce the exact power requested by the power plant operator during a load change, and the ability to return the system to a steady-state within a limited time. A drawing of a surge tank throttle is presented in Fig. 8.

The methodology for evaluating the throttle effect improves the existing practice by considering non-linearities and implementing a non-ideal time-discrete governor system. Conventionally, the stability is evaluated in the frequency domain by linearizing

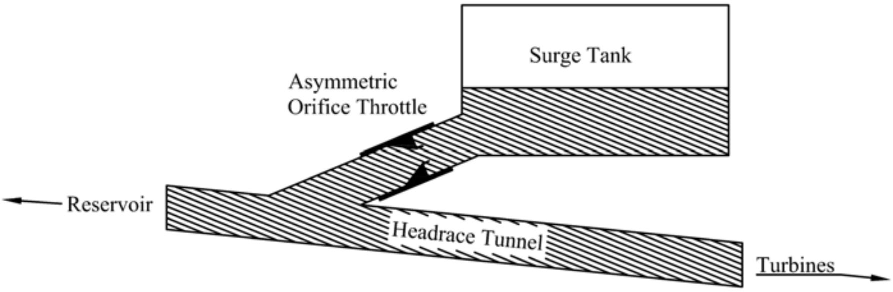

Fig. 8. Closed surge tank with an asymmetric orifice throttle

the governing equations and transforming them with the Laplace transform. In the proposed methodology, the governing equations are solved without linearization in the time domain, and the resulting time-series are evaluated in Bode-plots (Bode 1945) via Fast-Fourier transform. By avoiding linearization and solving in the time-domain, the stability analysis becomes more accurate and transparent. In addition, the methodology includes step-response tests to determine the governor performance.

The basic principle of the proposed methodology is to develop a 1D numerical model of the hydropower plant, and evaluate the governor stability through frequency-response tests, and the governor performance through step-response tests. The frequency-response tests are performed by calculating the hydraulic response of the system during disturbances in the grid frequency. The tests are run with the power plant operating with speed governing in an isolated grid. The frequency-response tests are analyzed in Bode plots where the stability is quantified with the phase margin and the gain margin (Nyquist 1932; Bode 1945). The step-response tests are performed by calculating time-series of the produced power and the pressure upstream the turbine during a change of the set-point for power. The tests are run with the power plant operating on a large interconnected grid with a governor of choice. The step-response tests are run as a load acceptance from 0% to 100% with a ramping time of 100 s. The performance is quantified with the time until a new steady state is obtained, and the amplitude of the produced power overshoot and turbine pressure undershoot. A short time until steady state is obtained, and low amplitudes of the over- and undershoots equals high performance. To ascertain accurate results with the proposed methodology, validation of the numerical model with field measurements is recommended if possible. The governor system is electronic and can be modelled with high accuracy, but it is more challenging to obtain an accurate model of the hydraulic components a priori.

The proposed methodology is regarded as flexible with few negative aspects compared with the alternatives. The main challenge is to obtain accurate input data of the system in sufficient detail. The methodology allows for testing of most types of governor systems and hydraulic layouts. By considering non-linearities and calculating in the time-domain, accurate and transparent results are obtained.

C6: An evaluation of the effect of surge tank throttling on governor stability and performance in a hydropower plant with a closed surge tank (P4).

The effect of surge tank throttling on governor stability and performance in a hydropower plant with a closed surge tank was evaluated. A 1D numerical model of Torpa hydropower plant was established, and the hydraulic and thermodynamic behavior was validated with field measurements. The methodology described in C5 was applied, and the results show that the throttle improved both the governing stability and performance in this power plant.

Three different configurations with different throttle headloss (h_l) were tested; no throttle (ζ=60), medium throttle (ζ=300), and strong throttle (ζ=1 200) configurations, where ζ (-) is the throttle loss factor given as $h_l = \zeta v^2/2g$. The velocity (v) is defined to be in the connection tunnel after the throttle, to allow comparison of the loss factor independent of the throttle geometry. The results show that the throttle effect on governor stability is positive but negligible for practical purposes, because the frequency response tests reveal equal phase margin (ψ) and gain margin ($\angle h$) for all configurations. There is however a minor improvement in both the phase angle and the gain amplitude at the mass oscillation resonance frequency, owing to the throttles reduction of the mass oscillations. The step-response tests shows that the throttle enables a more accurate control of the output power and a reduced time until steady state conditions occur. Fig. 9 presents the resulting Bode plots from a frequency-response test of the governor stability. Fig. 10 presents the results from a step-response test for the governor performance during a load acceptance from zero to 150 MW.

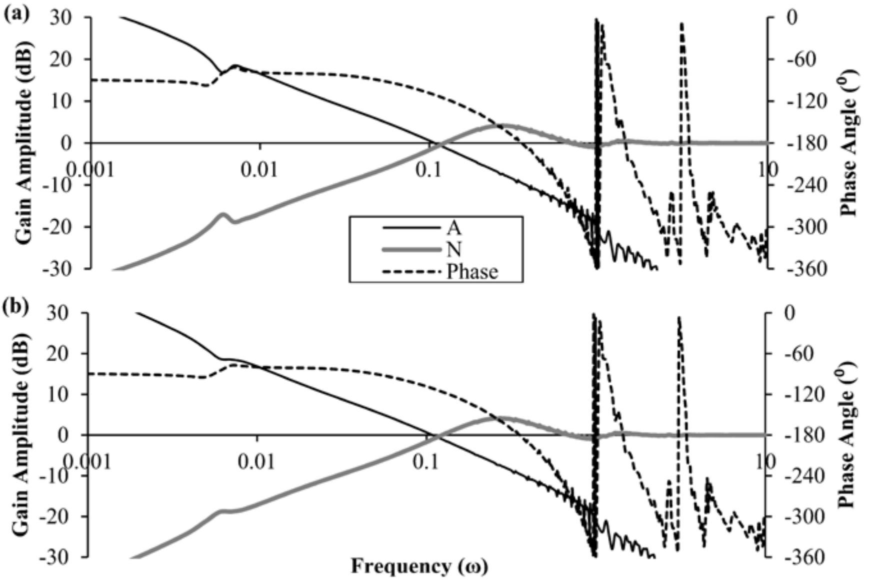

Fig. 9. Comparison of Bode plots for the system with (a) the no throttle and (b) the strong throttle configurations where A is the gain amplitude without speed feedback and N is the gain with speed feedback

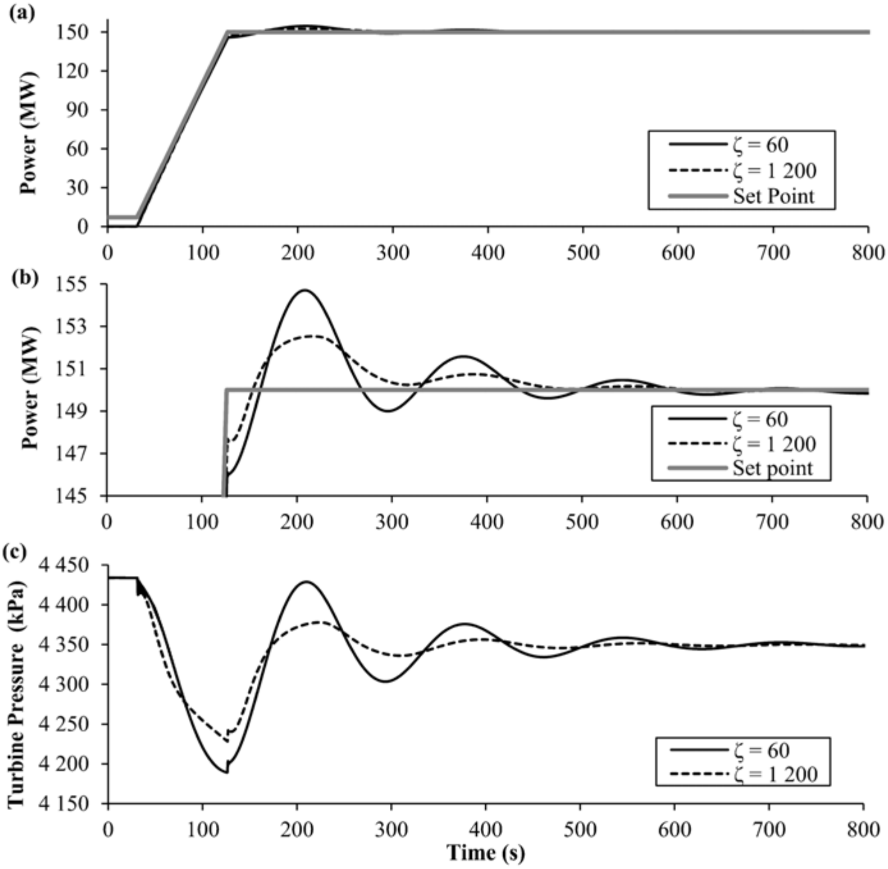

Fig. 10. Comparison of the step-response tests for a system with the no throttle (ζ=60) and the strong throttle (ζ=1 200) configurations where (a) shows the change in power set-point, (b) shows a close-up of the produced power, and (c) shows the resulting pressure oscillations upstream of the turbine

The results are specific for Torpa hydropower plant, but the throttle is believed to have a positive impact for a range of different power plants. It is suggested to include throttles in future design of closed surge tanks, and to test the effect on governor stability and performance with the methodology outlined in P4. The main purpose of the throttle is to reduce the necessary size of the surge tank, but this study demonstrates additional benefits. It should be noted that there is a limit to the strength of throttling that can be implemented before the water hammer increases too rapidly. Excessive throttling may result in hydraulic decoupling of the surge tank and must be avoided. Additional information on the throttle effect on governor stability and performance is given in P4.

Chapter 5: Discussion

This chapter discusses the potential application and the limitations of this work. The main uncertainties of the work are presented. The following research objectives and hypotheses were presented in the introduction:

O1: Determine the state-of-the-art and compare the benefits and challenges of the open surge tank and the closed surge tank.
O2: Test whether hydraulic scale modelling can be applied to model mass oscillations in closed surge tanks for hydropower plants.

H1: "Heat transfer influences the thermodynamic behavior of closed surge tanks."
H2: "Throttling of closed surge tanks has a positive effect on the governing stability and performance in hydropower plants."

Application and Limitations of the Work

The work on the first research objective has resulted in a description of the state-of-the-art and an overview of the benefits and challenges of open and closed surge tanks (C1). These results can be applied as a starting point for hydropower design engineers for new surge tank projects. The comparison presented in this work was conducted for a high-head hydropower scheme, but the parameters are valid also for low-head hydropower schemes. It should be noted that one might experience different importance of the different parameters for low-head hydropower compared with high-head hydropower. The main limitation of this work is that the final design of surge tanks are highly dependent on site and project-specific conditions.

The work on the second research objective has resulted in a new scaling approach and an assessment of the accuracy of a hydraulic scale model of a hydropower plant with a closed surge tank. The new scaling approach (C2) can be applied to scale a wide range of hydropower plants with closed surge tanks. The main limitation is which scaling factors are practically possible. When the scaling factor increases, the closed surge tank must be lifted higher above the upper reservoir, and may yield problems with available height in the laboratory. In addition, the resulting pressure in the model closed surge tank may become low and yield practical problems. In this work, a scaling factor of 1:65 was applied and proven feasible. This scaling factor is relatively high for hydropower systems, and indicates that other scaling effects may impose stricter limitations compared with the presented scaling method. The assessment of the accuracy of the presented hydraulic scale model (C3) can be applied as a benchmark for future hydraulic scale models. The main limitation is how different the new scale models are compared with the presented one. It should also be noted that a higher dampening of the mass oscillations was observed in the hydraulic scale model compared with the prototype, for which the cause has not be determined. However, if either of the alternatives suggested in the results chapter have caused the higher dampening, the accuracy of future models may yield a higher accuracy compared with the present. Another limitation is the lack of temperature measurements. Attempts to measure the temperature in both model and prototype were unsuccessful for reasons outlined in the method chapter. Temperature measurements would have enabled an additional comparison of the model and prototype for assessing the accuracy of the modelling. However, the pressure and volume are more important than the temperature for design and operation of closed surge tank, and the present validation is sufficient for practical purposes.

The work on the first hypothesis has proven that heat transfer has a significant influence on the thermodynamics under certain conditions, and should be considered for design and calculation of closed surge tanks. This work has not investigated the limits for when heat transfer has a significant influence, and this topic is suggested for future work. However, it has been shown that the thermodynamic behavior of the mass oscillations in Torpa hydropower plant is adiabatic, providing additional validation of the work presented in Goodall et al. (1988). This implies that closed surge tanks with similar properties as the ten closed surge tanks for hydropower plants in Norway can be assumed to have adiabatic behavior. For closed surge tanks with significant influence from heat transfer, the modified rational heat transfer (MRHT) method (C4) has been proven to enable accurate representation of the thermodynamics. The main limitation of the MRHT method is the dependency on calibration. The Nusselt number is not known a priori and must either be calibrated, or estimated from empirical relationships (Incropera and Dewitt 2007). For calculation of adiabatic conditions in closed surge tanks, the simpler polytrophic equation can be applied, or the dQ in the MRHT method can be set to zero.

The work on the second hypothesis has resulted in a method to determine the throttle effect on governor stability and performance (C5), which has been applied to show that the throttle may have a positive impact on the governor stability and performance (C6). The latter strengthens the arguments to implement throttles in both new and existing surge tanks. The main limitation of this results is the confinement to a case study, resulting in the need to evaluate the throttle effect for future hydropower plants to ascertain the positive effects. However, the proposed method is available for this purpose. The method can be applied to all types of hydropower plants independent of the implementation of a throttle. The main limitation of the method is the need for accurate and detailed input for the 1D numerical simulations.

Uncertainties of the Work

This section identifies and discusses the main uncertainties that comprise threats to the validity of the results presented in this thesis. The measures taken to mitigate and control the uncertainties are outlined. The major uncertainties include the following:

- Software errors in the 1D numerical simulations.
- Theoretical errors in the 1D numerical simulations.
- Human errors in the 1D numerical simulations.
- Scaling errors in the hydraulic scale modelling.
- Construction errors in the hydraulic scale modelling.
- Human errors in the hydraulic scale modelling.
- System errors in the field measurements.
- Human errors in the field measurements.

The possible errors in the 1D numerical simulations are separated in software errors, theoretical errors, and human errors. Software errors are not considered to be likely because the applied software has been validated with field measurements, and through several previous studies (Svingen 2007). However, an extension to the default program has been programmed as a part of this work to enable simulation of systems with closed surge tanks. This extension does not have validation from previous studies and rely fully on the validation from the field measurements presented in this work. Theoretical errors in 1D numerical simulations are related to the applied theoretical models and assumptions. The theory applied in this work is basic and has been validated through numerous studies (Chaudhry 1987; Wylie and Streeter 1993). An exception include the RHT and MRHT theory for which less validation exists. These methods should thus be regarded with some uncertainty until additional validation is available. In addition, there is some unquantified uncertainty in modelling of the turbine governor in P4, owing to simplification of details such as time constants of minor electronics and mechanic actuators. Human errors in the 1D numerical simulations include program operation, typing errors, data interpretation, and conversion. Field measurements are used to validate 1D numerical simulation results in this work, and there should not exist any such error.

The possible errors in the hydraulic scale modelling include scaling errors, construction errors, measurement errors, and human errors. The scaling errors are inherited from the selected scaling law and simplifications of the system. It is impossible to make a perfect hydraulic scale model that preserves the similitude of all the forces and processes, and the errors sources owing to scaling were described and discussed in the method chapter. Construction errors in hydraulic scale modelling may occur in the construction phase. The position and lengths of the structural components must be exact, or the results will be compromised. Periodic controls and measurements during construction was carried out and no major errors are known. The uncertainty of the elevations of the overflow weirs in the upper and lower reservoirs is estimated to ± 1 cm, and the uncertainty of the water conduit length is estimated to ± 10 cm. The uncertainty of the diameter of pipes, valves and other steel components are ± 1 mm. The measuring errors in the hydraulic scale model are of similar type as for the field measurements, and similar precautions were implemented as described in the next section. Human errors are related to wrong operation of the hydraulic scale model. Operation errors were mitigated through control with field measurements and repetition of tests.

The results presented in this thesis rely on validation through field measurements. The possible errors in the field measurements are separated in systematic and human errors. Systematic errors include measuring equipment calibration errors, installation errors, external noise and disturbances. Human errors include signal interpretation, data conversion, and equipment setup. To reduce these uncertainties in this work, several parameters were measured simultaneously and are used for mutual control. In addition, calculation results from simplified equations for periods and amplitudes are compared with the measurements as a secondary control. Based on the controls there is no reason to believe that any major error exists in the field measurements presented in this work. Minor errors and uncertainties may still be present, and these are evaluated in P2 and P3.

Chapter 6: Conclusions

This chapter presents the conclusions to the research objectives and hypotheses. Suggestions for future research on closed surge tanks, and the concluding remarks are given. The research objectives and hypotheses of this work were as follows:

O1: Determine the state-of-the-art and compare the benefits and challenges of the open surge tank and the closed surge tank.
O2: Test whether hydraulic scale modelling can be applied to model mass oscillations in closed surge tanks for hydropower plants.

H1: "Heat transfer influences the thermodynamic behavior of closed surge tanks."
H2: "Throttling of closed surge tanks has a positive effect on the governing stability and performance in hydropower plants."

Research Objectives and Hypotheses

The first research objective is fulfilled. State-of-the-art design for open and closed surge tanks have been presented and an overview of the relevant parameters for comparison has been provided. However, a general conclusion to which surge tank design is superior is impossible owing to the large variability in site-specific conditions. It is concluded that the selection of surge tank solution is predominantly dependent on topography, geology, and operational requirements. For projects where both open and closed surge tanks are possible, the overview of the benefits and challenges can be applied to assist the decision-making.

The second research objective is fulfilled. A hydraulic scale model of an existing hydropower plant has been constructed to assess the accuracy. It is concluded that the hydraulic scale modelling provided acceptable accuracy for modelling of the mass oscillation period and the first (maximum) amplitude. The method is currently not recommended for modelling of the subsequent amplitudes, as a higher dampening of the oscillations was observed in the model compared with the prototype. The accuracy of the hydraulic scale modelling can possibly be improved by measures suggested in this work. A new approach for scaling of hydropower plants with closed surge tanks has been developed and described.

The first hypothesis is true under specific conditions. The heat transfer has a significant impact on the thermodynamic behavior of closed surge tanks for hydropower plants under two conditions; (1) slow transients with period longer than 20 minutes, and (2) transients where the start and end conditions differ. In both these situations, the heat transfer has time to occur in a significant magnitude and will influence the system. However, for the closed surge tanks studied in this work, the heat transfer process is too slow to have a significant influence on normal transients such as mass oscillations. The closed surge tanks studied in this work have large volumes and high pressures compared with the mass oscillation amplitude. From the historical review, it is known that heat transfer has a higher influence for lower volumes and pressures compared with the mass oscillation amplitude. Further work is necessary to determine the limit before heat transfer has a significant influence.

The second hypothesis is true under certain conditions. Surge tank throttling had a positive impact on governing stability and performance in a case-study hydropower system. The throttle had an insignificant positive impact on the governing stability, and a significant positive impact on the governing performance. The throttle resulted in a more accurate control of the output power, and a reduced time until steady state conditions occurred in the system. However, it was observed that the throttle increases the water hammer pressure in the system, and that excessively strong throttling must be avoided. This work has only studied one hydropower plant and a general conclusion on the throttle effect for other hydropower plants cannot be given. However, the author believes the results may be valid for a range of other hydropower plants. To determine the throttle effect on governor stability and performance in other hydropower plants, a methodology has been developed and described.

Suggestions for Future Work

There is a large potential for future development of the theory and design of closed surge tanks. Several research topics are regarded as feasible for further work:

1. Investigate the limits of different air volumes, air pressures, geometries, construction materials, mass oscillation amplitudes and periods before the heat transfer has a significant impact on the thermodynamic behavior of closed surge tanks.
2. Investigate the validity of the MRHT method for different closed surge tanks, and derive charts to determine the empirical constants a priori.
3. Investigate the error sources that caused the higher dampening of the mass oscillations in the hydraulic scale model compared with the prototype, and determine whether the accuracy of the modelling can be improved.
4. Improve theories and methods to design the optimal hydraulic throttle for surge tanks.
5. Develop an air-sealing valve for closed surge tanks, to allow for emptying of the water in the tunnel system without emptying the compressed air.
6. Improve the technology for ensuring air tightness in closed surge tanks constructed in rock with high permeability without steel lining.

The first suggestion involves collection of field measurements from surge tanks with different design volumes and pressures, to find the limits before heat transfer has a significant influence on the thermodynamics. This work could result in improvements of the thermodynamic models and enable a priori calculation and design of new surge tanks. Especially valuable in such work will be accurate measurements of temperature during mass oscillations in the closed surge tanks. Attempts to conduct temperature measurements were unsuccessful in this work.

The second suggestion is related to the first, where the field measurements from different types of closed surge tank can be applied to enable the MRHT method to perform a priori calculation. Charts similar to the Moody's diagram for friction factors could possibly be derived for the Nusselt number in the MRHT method.

The third suggestion is to test the possible measures described in this thesis to improve the accuracy of hydraulic scale modelling of closed surge tanks. In addition, the three different methods for scaling closed surge tanks could be benchmarked on a case-study. Further, it will be interesting to know how much the accuracy improves or reduces when the scaling factor is reduced or increased.

The fourth suggestion is to improve the theory and methods for calculating the optimal hydraulic throttle for surge tanks. Such work has not been within the scope of this thesis, but may enable improved and easier design of such components. The design must consider the effect on the governor stability and performance when governors are implemented.

The fifth suggestion is to develop an air-sealing valve, to reduce the downtime of power plants with closed surge tanks. The air-sealing valve may allow drainage of the water in the tunnel system while still preserving the air in the closed surge tank. The valve can be constructed as an integral part of the throttle arrangement, resulting in a multipurpose structure. Presently, large air volumes and high pressures pose a challenge for commercially available compressors during filling of the closed surge tank. As an example, the 1 240 MW Kvilldal hydropower plant uses over one month to fill the closed surge tank of 80 000 m^3 at a pressure of 4 100 kPa. This closed surge tank is currently the largest in the world, and the filling time is significantly lower for smaller tank. However, the development of an air-sealing valve may prove economically viable.

The sixth suggestion is to improve the technology for air tightness of underground caverns without steel lining. The requirements for air tightness is the crucial factor for implementation of closed surge tanks in hydropower projects in many regions. The existing designs of closed surge tanks in the Alps include steel lining to ensure air tightness, which renders most projects economically unfeasible. If alternative technologies can ensure air tightness without steel lining, the closed surge tank would become a more attractive option. The currently existing alternative is the water curtain technology, which has successfully been employed in several closed surge tanks (Kjørholt and Broch 1992), but requires specific geological conditions.

Concluding Remarks

This work has studied the hydraulic and thermodynamic behavior of closed surge tanks for hydropower plants. Two research objectives and two hypotheses have been answered, and four selected papers including six novel contributions are presented. Additional results that are not presented in this thesis include six secondary papers. A bibliography and summary of the secondary papers are provided in Appendix B. This work has spanned a wide range of topics, and more in-depth analyses in the future will be beneficial to further validate and utilize the results provided in this work.

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Appendix A: Selected Papers

The full versions of the selected papers presented in this thesis are presented in the following. The original formatting is preserved and does not conform to the general formatting of the thesis.

Paper 1

Surge Tank Research in Austria and Norway

Kaspar Vereide, Wolfgang Richter, Gerald Zenz and Leif Lia (2015)

Journal Wasserwirtschaft, 105(1), 58-62 (Open Access).

Kaspar Vereide, Wolfgang Richter, Gerald Zenz and Leif Lia

Surge Tank Research in Austria and Norway

Modern high-head hydropower plants, and in particular 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 are given special attention.

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 reduces 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 behaviour of the lower chamber.

The authors from Graz University of Technology (TU) have recently conducted several physical scale-model tests of new surge tanks, including pumped storage hydropower plant (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 behaviour 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.

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

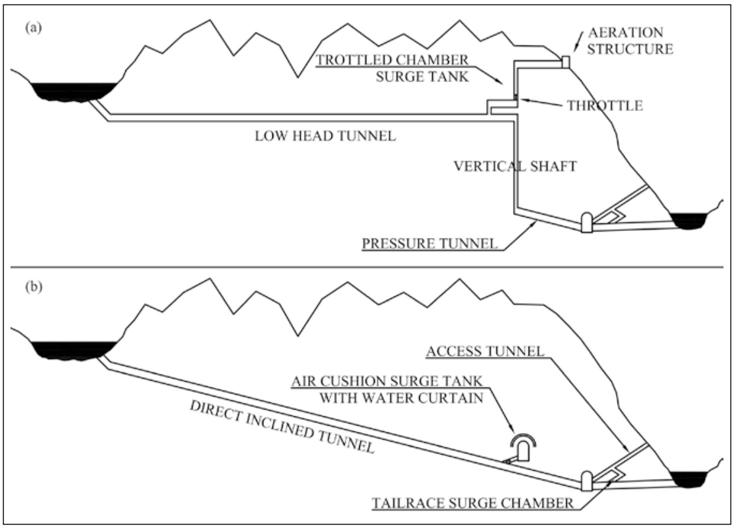


Figure 1: Throttled chamber surge tank (a) and air cushion surge tank (b) (Source: Kaspar Vereide)

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.

Table 1: Surge tank investigation tools

Investigation tools	Advantages	Disadvantages
Physical scale-model test	▪ Visualization of overall hydraulic behaviour ▪ Detection of possible problems such as swirl flows or waterfalls ▪ Proofing the safety against outflow from aeration structure ▪ Measurement of throttle loss	▪ No similitude for air behaviour ▪ 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 behaviour 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

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 Behaviour

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 m and a diameter of 7 m, and is filled with about 210 m^3/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 behaviour has to be safely reflected at the aeration building.

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 unfavourable 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].

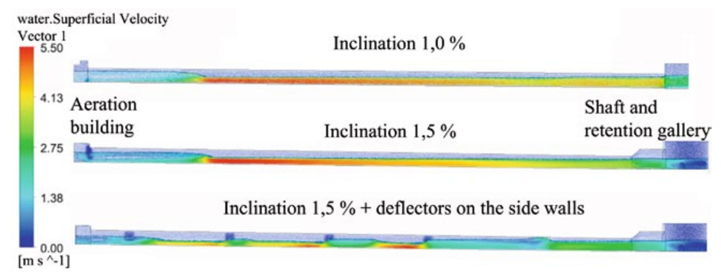


Figure 2: Filling of long upper chamber with the occurrence of a surface wave for three different design variants (Source: Wolfgang Richter)

4 Long Lower Chamber Behaviour

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 behaviour if the crown inclination is 2%. A criterion for good filling behaviour is the absence of large blowouts of air. **Table 2** presents 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.

The height of the gravity centre 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

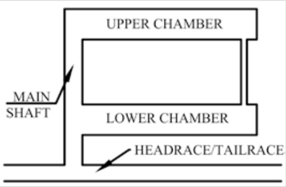
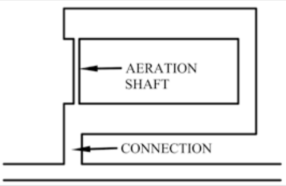
5.1 Benefits

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

- Reduced water hammer,
- Enables more flexible and faster operation,
- Enables tunnelling 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.

Tunnelling 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 tunnelling might be less expensive compared to horizontal headrace tunnel and pressure shaft, but may differ regarding the specifics of a certain project. The direct tunnelling 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].

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

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

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 tunnelling due to higher rock stress.

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 favourable 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 tunnelling,
- 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 poor rock mass quality, grouting may be used as an extended measure. For small ACST, 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]. 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 ACST the filling time of the air pocket needs to be considered. The filling time of Kvilldal ACST (80 000 m³ of air with 40 bar pressure) is several weeks, which may result in economical losses. 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 m³/s, tunnel cross section area of 60 m², and shaft diameter of 6 m. The comparison is made on excavated rock volume, exposed rock surface in the tunnel system, and design pressure.

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

	TCST	ACST
Headrace length (m)	10 500	10 000
Pressure shaft length (m)	600	x
Surface access tunnels (adits)(m)	1 000	x
Surge tank volume (m³)	16 000	75 000
Resulting design pressure (mWC)	680	670
Rock surface area surge chamber (m²)	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 excavated volume (m³)	744 000	711 000

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 m² given from Thoma [3], while the upper and lower chambers have 500 m² 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 behaviour of the air, the adiabatic exponent of 1.4 is applied [4].

As shown in Table 3, the total amount of excavated rock volume is higher for the TCST scheme compared to the ACST scheme.

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 is 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.

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 behaviour 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 tunnelling 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 topography will always have key influence to which solution is most beneficial.

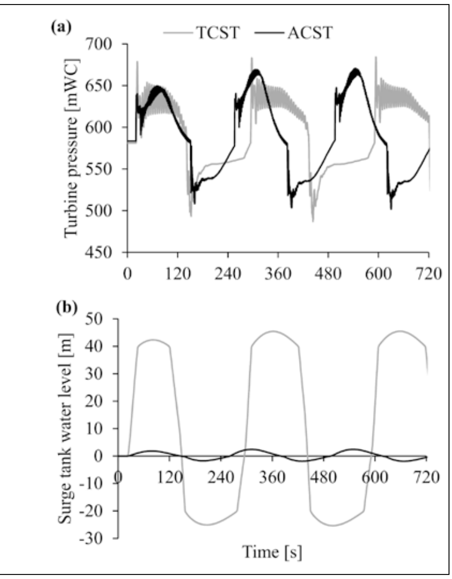


Figure 3: Comparison turbine pressure and surge tank water level (Source: Kaspar Vereide)

7 Conclusion

Modern pumped storage plants with increasing water discharge request increasingly larger surge tank systems. Simple scaling of available schemes leads 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 behaviour 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.

Acknowledgements

Vorarlberger Illwerke AG supported the investigation of a long upper chamber. The authors are very thankful for the valuable process and friendly-constructive communication. Ass. Prof. Helmut Knoblauch and Ass. Prof. Josef Schneider for great leading of the high head model tests at TU Graz. The Centre for Environmental Design of Renewable Energy (CEDREN) have given economical support.

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Kaspar Vereide, Wolfgang Richter, Gerald Zenz und Leif Lia

Wasserschlossforschung in Österreich und Norwegen

Moderne Hochdruck-Wasserkraftanlagen, darunter insbesondere Pumpspeicherkraftwerke, werden zunehmend mit höheren Ausbaudurchflüsse 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.

Paper 2

Hydraulic Scale Modelling and Thermodynamics of Mass Oscillations in Closed Surge Tanks

Kaspar Vereide, Leif Lia and Torbjørn Kristian Nielsen (2015)

Journal of Hydraulic Research, 53(4), 519-524, DOI: 10.1080/00221686.2015.1050077 (OpenAccess).

Journal of Hydraulic Research Vol. 53, No. 4 (2015), pp. 519–524
http://dx.doi.org/10.1080/00221686.2015.1050077

Technical note

Hydraulic scale modelling and thermodynamics of mass oscillations in closed surge tanks

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ABSTRACT

The design and results from a hydraulic scale model of mass oscillations in a hydropower plant with a closed surge tank constructed as an underground rock cavern are presented. The results from the model test of an existing hydropower plant at scale 1:65 are compared with field measurements. The main contributions of this work include (1) an assessment of whether hydraulic models may be applied to evaluate hydropower tunnels with closed surge tanks, (2) a novel approach to scale atmospheric air pressure, and (3) an evaluation of the thermodynamic behaviour in the model and prototype. The hydraulic model is shown to provide an accurate representation of the maximum (first) amplitude, with a relative error of less than 4%. An estimate of the period of the oscillations has a relative error of less than 1%. The model has higher dampening compared with the prototype, resulting in the 20% relative error of the second amplitude. Both the model and prototype reveal approximately adiabatic behaviour of the closed surge tank.

Keywords: Closed surge tanks; field studies; hydraulic models; mass oscillations; thermodynamics

1 Introduction

Mass oscillations in hydropower tunnels with closed surge tanks cause large pressure amplitudes, and need to be understood by engineers for control of the hydraulic pressure in the power plants. Mass oscillations are hydraulic transients caused by a change of turbine flow and the inertia of the water mass in the tunnel. In the case of a load rejection in a hydropower plant, the turbine flow is reduced and the water in the headrace tunnel is forced to flow into the surge tank. The water inflow initiates mass oscillations in the tunnel between the surge tank and the upstream reservoir.

The closed surge tank was first introduced by Michaud (1878) as a means to mitigate water hammer in pipes. Johnson (1908) further shows that the closed surge tank may be applied to obtain regulation stability in hydropower plants. Closed surge tanks for hydropower plants may be constructed as rock caverns or steel tanks filled with pressurized air, and are applied where the topography or other factors render them more feasible than open surge tanks connected to atmospheric air.

The thermodynamic behaviour of the closed surge tank is described with the perfect gas law as shown in Eq. (1):

$$pV = mRT \tag{1}$$

where p is air pressure, V is air volume, T is air temperature, m is air mass, R is the specific gas constant for air. However, the exact behaviour is difficult to calculate analytically due to the three unknowns (pressure, volume, and temperature) and the influence of heat transfer. From a literature review, it is seen that several different theories have been applied, varying from isothermal to adiabatic. The earliest researchers on closed surge tanks (De Sparre, 1911; Johnson, 1908; Michaud,

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Received 3 December 2014; accepted 7 May 2015/Open for discussion until 29 February 2016.

ISSN 0022-1686 print/ISSN 1814-2079 online
http://www.tandfonline.com

1878) assume isothermal behaviour. Camichel (1918) presented several experiments with some showing adiabatic behaviour and others revealing isothermal behaviour. Camichel (1918) noted that the behaviour depends on the period of the oscillations and the construction material of the closed surge tank. Graze (1968) reported new experiments observing that the heat transfer to the surrounding environment influences the thermodynamic behaviour appearing between of adiabatic and isothermal regimes. Graze (1968) furthermore showed that the polytrophic Eq. (2):

$$pV^n = k \tag{2}$$

is not accurate for closed surge tanks, unless the thermodynamic behaviour is either isothermal or adiabatic (n is the polytrophic constant ranging from 1.0 to 1.4 for isothermal and adiabatic conditions, respectively, and k is a constant). However, in engineering applications the thermodynamics are usually simplified, and the polytrophic equation is assumed to be valid (Thorley, 2004; Wylie & Streeter, 1993). The thermodynamic behaviour of air in hydraulic systems is still an important research topic, with recent results presented in Zhou, Liu, Karney, & Wang (2013) and Vereide, Tekle, & Nielsen (2015).

The present work investigates whether hydraulic scale models may be applied for evaluation of mass oscillations in hydropower plants with closed surge tanks constructed as underground rock caverns. To the best of our knowledge, no previous attempts at hydraulic scale modelling of such systems are reported in the literature. One of the main challenges is scaling of the atmospheric air pressure, and a novel approach in addressing this issue is proposed in this Note. Furthermore, measurements from both a full-scale existing closed surge tank and the hydraulic scale model are used to evaluate the thermodynamic behaviour.

The hydraulic scale model is constructed in the hydraulic laboratory of the Norwegian University of Science and Technology in Trondheim. The prototype is the 150 MW Torpa hydropower plant in southern Norway. Field measurements are conducted in the closed surge tank during an emergency shutdown from full load. The surge tank is constructed as an underground rock cavern with 13,000 m^3 of air at pressure 4.1 MPa.

2 Theoretical background

Transient water flow in closed conduits is described with the continuity and momentum equations (Wylie & Streeter, 1993):

$$v\frac{\partial p}{\partial x} + \frac{\partial p}{\partial t} + \rho a^2 \frac{\partial v}{\partial x} = 0 \tag{3}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial x} + v\frac{\partial v}{\partial x} + \frac{\partial v}{\partial t} + g\sin\varphi + f\frac{v|v|}{2D} = 0 \tag{4}$$

where v is the water velocity, p is the water pressure, x is the longitudinal coordinate, t is the time, φ is the conduit angle, ρ is the water density, a is the wave celerity, f is the Darcy-Weisbach friction factor, and D is the conduit internal diameter.

For a hydropower headrace system, the boundary conditions for these differential equations are the upper reservoir, the closed surge tank, and the turbine. The upper reservoir is represented by a fixed water level providing a constant pressure. During an emergency shutdown from the full load, the turbine in the currently investigated system closes in ten seconds with a linear closing law. The flow through the turbine is described as:

$$Q = \alpha A(2gH)^{1/2} \tag{5}$$

where Q is the water discharge, α is the percentage opening, A is the water flow cross section during full opening, g is gravity acceleration, and $H = p/(\rho g)$ is the piezometric head.

For calculation of the thermodynamic behaviour during mass oscillations in the specific type of closed surge tanks presently considered, Goodall, Kjørholt, Tekle, & Broch (1988) have shown that the assumption of adiabatic conditions yields accurate results. Based on these studies, the working hypothesis has been that the thermodynamic behaviour of the closed surge tank is adiabatic and may be described with Eq. (2) and the adiabatic exponent equal to 1.4.

3 Dimensional analysis

A dimensional analysis of the hydropower system is conducted with Buckingham's (1914) π-theorem to determine the scaling of the hydraulic model. The physical behaviour of the system then depends on 12 parameters: pressure (p), density of water (ρ), water velocity (v), tunnel diameter (D), dynamic viscosity of water (μ), tunnel length (L), tunnel friction (f), gravity (g), air volume (V), the adiabatic constant for air (κ), the wave celerity in water (a), and the tunnel slope ($\sin\varphi$). By selecting ρ, v and D as independent units one derives the π-terms shown in Table 1. It is seen from the dimensional analysis that the system is characterized by the Euler, Reynolds, Froude, and Mach numbers. To scale the mass oscillations of the system correctly, the Euler scaling law is selected to preserve the effects of the pressure and inertial forces. For the present hydraulic system, the Reynolds and Mach numbers cannot be scaled correctly at the same time as the Euler number, due to physical restrictions of the laboratory environment.

Scaling effects due to the different Reynolds numbers of the model and prototype are known to be limited if the flow is turbulent (Hughes, 1993). The scaling factors are therefore selected to ensure that the flow is in the turbulent regime in the hydraulic scale model. The Mach number characterizes the compressibility and the water hammer effects in fluid flow. However, the selection of the Euler scaling law causes the water hammer effects in the hydraulic scale model to reduce compared with the prototype. For most hydropower schemes, the water hammer effects do not significantly influence the mass oscillations.

Table 1 Derived π-terms for the hydraulic system

Name	Similarity number
Euler number	$p/(\rho v^2)$
Reynolds number	$vD\rho/\mu$
Froude number*	$v^2/(gD)$
Mach number	v/a
Length factor	L/D
Volume factor	V/D^3
Adiabatic constant	κ
Friction factor	f
Pipe slope	$\sin\varphi$

*Given for completeness even if the current system is pressurized flow

Table 2 Scaled dimensions

Parameter	Prototype	Model
Turbine level (m)	0	0
Upper reservoir level (m)	451	6.9
Surge tank water level (m)	36.2	10.71
Headrace length (m)	9,600	147
Headrace diameter (m)	6.56	0.1
Headrace headloss (m)	4.5	0.07
Shaft length (m)	300	11.2
Shaft headloss (m)	2.5	0.04
Surge tank volume (m^3)	17,000	0.062
Air volume (m^3)	13,000	0.047
Air pressure (Pa)	4,110	63.2
Water velocity (m s^{-1})	1.0	0.124
Approx. wave celerity (m s^{-1})	1,200	800
Discharge (m^3 s^{-1})	35	0.001
Time (s)	1	0.124
Air temperature (K)	283	283
Euler number (–)	4.11	4.11
Froude number (–)	0.015	0.015
Reynolds number (–)	6,560,000	12,400
Mach number (–)	0.00083	0.00016

The presence of such influence in the current hydraulic scale model and the prototype is evaluated in the later discussion.

The Euler model law results in the scaling factors L_r for length, $v_r = L_r^{1/2}$ for velocity, $t_r = L_r/v_r = L_r^{1/2}$ for time, and $p_r = v_r^2 = L_r$ for pressure. Water density, gravity, viscosity, adiabatic constant, friction factor, and temperature are the same for the model and prototype. The wave celerity is smaller in the scale model compared with the prototype owing to the higher elasticity of the conduit, which is beneficial for obtaining a better scaling of the Mach number. The difference, however, is small and the improvement is limited. The tunnel slope is different in the model and prototype to allow for scaling of the atmospheric air pressure, as described in the next section. As the slope terms in Eqs (3) and (4) are commonly disregarded for practical purposes, their effect is assumed negligible.

4 Hydraulic scale model design and operation

The prototype for the hydraulic model is the headrace tunnel of the 150 MW Torpa power plant in southern Norway. The power plant was commissioned in 1989 and is owned by Eidsiva Vannkraft AS. The nominal head of the power plant is 445 m, and the nominal discharge is 35 m^3 s^{-1}. The headrace length is 9.6 km, the diameter is 6.56 m, and the tunnel is inclined directly between the reservoir and the power station without a pressure shaft. Figure 1 shows a principle diagram of the power plant.

The closed surge tank of the power plant is constructed as an unlined rock cavern, with a total volume of 17,000 m^3. During normal operation, the water depth in the surge tank is 2 m, giving 13,000 m^3 of air at pressure of 4.1 MPa. The surge tank is located 300 m upstream of the turbine. The scale of 1:65 is selected based on available laboratory space, and the resulting dimensions of the hydraulic scale model are shown in Table 2.

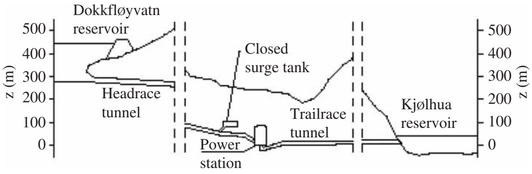

Figure 1 Schematic diagram of the Torpa power plant

Some practical considerations are necessary to account for atmospheric air pressure. For most hydraulic scale models only the relative air pressure needs to be considered, as there are no thermodynamic processes. However, for scaling of closed surge tanks the absolute air pressure must be scaled to obtain the correct thermodynamics. In the present work, a novel method has been developed. The method involves placing the closed surge tank at a higher elevation in the model compared with the prototype, to obtain the correct relation between the volume and pressure in the surge tank, while allowing free atmospheric pressure at the inlet reservoir and the outlet. An alternative is to use pressure tanks to scale the atmospheric pressure at the inlet reservoir and the outlet, but this approach was regarded as unfeasible due to higher cost and complexity. The main error introduced by the proposed technique is the need for a longer shaft between the surge tank and the turbine in the model, due to the required height difference between the closed surge tank and the outlet. This will, however, influence a water hammer effect only, as the water mass in the shaft does not oscillate between the surge tank and the upper reservoir.

Another practical consideration relates to the diameter of the pipes close to the turbine. In the prototype, the last 130 m of the headrace has a reduced diameter, leading to a bifurcation pipe that splits the water flow for the two turbines. This detail is not included in the hydraulic scale model due to the added complexity. The main error introduced by this manipulation is the reduced water hammer effect and water velocity close to the

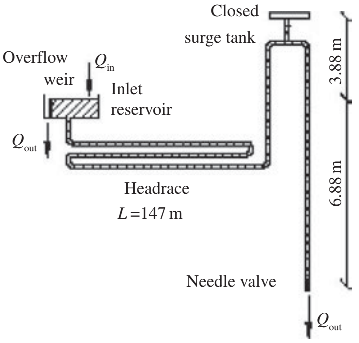

Figure 2 Hydraulic scale model layout

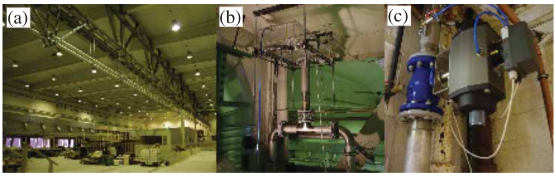

Figure 3 Pictures of (a) the headrace pipe, (b) the closed surge tank, and (c) the needle valve and pneumatic actuator

turbine, which is considered to have a negligible effect on the mass oscillations and thermodynamics of the closed surge tank.

The resulting layout of the hydraulic model is presented in Fig. 2, and pictures of the headrace pipes, the closed surge tank, and the closing valve are shown in Fig. 3. As can be seen from Fig. 2, the novel approach to account for the atmospheric air pressure requires the closed surge tank to be placed 3.83 m above the water level in the upper reservoir to gain the correct relation between the pressure and the water level.

The model is constructed with welded AISI304 stainless steel pipes with internal diameter of 100 mm, and wall thickness of 3 mm. The model rig is fixed by clamping in the flow direction and perpendicular to the flow direction. The closed surge tank is constructed as an acrylic glass box with an air volume of 64.5 dm^3 and wall thickness of 10 mm. A vacuum pump is used to set the initial air pressure. The inlet reservoir is a wooden box with a volume of 0.48 m^3, with an overflow weir to control the water level. Water inflow is supplied from the water mains. The lumped frictional and singular losses in the pipes are controlled by butterfly valves situated between the inlet reservoir and the closed surge tank, and between the closed surge tank and the outlet. Water flow and shutdown in the model is controlled with a pneumatic-controlled needle valve, which closes from full opening in one second.

The model is equipped with two absolute pressure transducers (GE Druck PTX-1400) with an error of less than 0.15% of full scale 0.6 MPa. One transducer is placed in the surge tank, and one is placed immediately upstream of the outlet needle valve. Water discharge in the pipes is measured with an electromagnetic flow sensor (SITRANS F M 5100 W) with an error of less than 0.4% of full scale 10 m s^{-1}.

Field measurements have been collected from Torpa power plant during an emergency shutdown in ten seconds from the full load. Pressure measurements are collected in front of the turbine with a PARO scientific DIQ 73 K sensor with an error of less than 0.04% of full scale of 20 MPa, and from the air pocket in the closed surge with a PARO scientific 8DP000-S sensor with an error of less than 0.01% of full scale of 6 MPa.

The authors collected the measurements upstream of the turbine, while the power plant owner collected the measurements from the closed surge tank. The measurements upstream of the turbine are sampled at 1 Hz. The measurements from the closed surge tank are sampled with lower and unstable frequency, as the measurement system collects samples based on thresholds of water level movement. Table 3 presents the initial ($t = 0$ s) and the end ($t = 3{,}600$ s) steady state conditions of the mass oscillations measured in the prototype. The headrace velocity is calculated based on produced power (MW), and efficiency curves provided by the power plant operator. The resulting time-series of the measured shutdown are presented in the next section.

5 Results and discussion

The measured shutdown situation at Torpa power plant is recreated in the hydraulic scale model for comparison. The initial parameters are set according to Table 3, and a comparison of the prototype and the model turbine pressure at up-scaled values is presented in Fig. 4a. The comparison of measured and modelled air pressure in the closed surge tank is presented in Fig. 4b.

Note that the initial pressure upstream of the turbine is different in the model and the prototype due to different velocity heads in front of the turbines, as described in the previous section. The sum of the pressure head and velocity head is, however, equal in the model and the prototype. The Nash-Sutcliffe efficiency coefficient is 0.90 for the presented turbine pressure time-series, and 0.84 for the closed surge tank air pressure. The relative error of the first amplitude (design pressure) of the turbine pressure is 4%, while the relative error in the second amplitude is 20%. The relative error in the oscillation period is 1%. The repeatability of the experiments is high: the standard deviation of the maximum

Table 3 Initial and end conditions

Parameter	Initial	End
Produced power (MW)	142	0
Upper reservoir level (m)	451	451
Surge tank water level (m)	36.2	36.3
Air pressure (kPa)	4,110	4,168
Turbine inlet pressure (kPa)	4,296	4,429
Turbine velocity head (kPa)	54	0
Headrace velocity (m s^{-1})	1.0	0.0
Headrace headloss (m)	7.4	0.0
Shaft headloss (m)	1.8	0.0

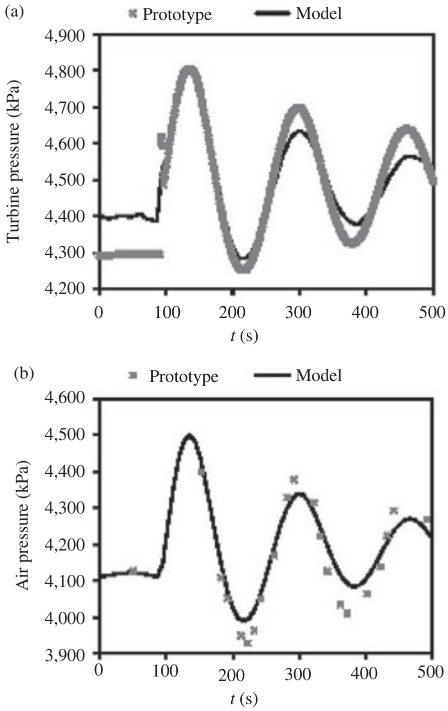

Figure 4 Comparison of (a) pressure upstream of the turbine, and (b) the air pressure in the closed surge tank

amplitude from four experiments conducted over two separate days is 7.3 kPa, while the standard deviation of the period is 1.2 s.

The results presented above show that the hydraulic scale modelling of hydropower tunnels with closed surge tanks is possible within a reasonable error. The main error is the dampening of the oscillations, which may be caused by unscaled roughness (headloss is adjusted with valves), air bubbles in the flow, insufficient fixation of the model rig, limited overflow capacity in the upper reservoir, and minor heat transfer occurring over time. It has also been confirmed that the novel approach to account for atmospheric air pressure is fairly suitable. However, this approach raises the elevation of the pipes in parts of the model, which may have a minor effect on the results.

The water hammer effect is not scalable if the focus is on mass oscillations in hydraulic scale models. In addition, Amara, Achour, & Berreksi (2013) showed that in specific cases the water hammer and mass oscillation may occur with harmonic frequencies, and thus may affect each other. In this study, one can see in Fig. 4a at $t = 100$ s that water hammer occurs immediately after shutdown in both prototype and model, but the influence on the mass oscillations is in this case seen to be limited for practical purposes.

The field measurements reveal that the thermodynamic behaviour of this specific closed surge tank is approximately adiabatic during the mass oscillations. The hydraulic scale model also exhibits adiabatic behaviour despite the different construction material and size of the surge tank. By comparing the present results with previous studies, it is seen that different thermodynamic behaviour should be expected for different types of surge tanks depending on size, construction material, and period of the mass oscillations. Future studies involving both laboratory and field experiments are necessary to gain better understanding of the thermodynamics in different types of closed surge tanks.

Acknowledgements

The authors thank Eidsiva Vannkraft AS for access to the Torpa power plant, the supply of necessary drawings, and the logistical support during the field measurements. The research was conducted as a part of the Centre for Environmental Design of Renewable Energy (CEDREN).

Disclosure statement

No potential conflict of interest was reported by the authors.

Notation

α = percentage turbine opening (–)
κ = adiabatic constant (–)
ρ = mass density (kg m^{-3})
D = tunnel diameter (m)
g = acceleration by gravity (m s^{-2})
H = piezometric head (m)
k = constant (–)
L = tunnel length (m)
m = air mass (kg)
n = polytrophic exponent (–)
p = pressure (kg m^{-1} s^{-2})
Q = turbine water flow (m^3 s^{-1})
R = specific gas constant (J kg^{-1} K^{-1})
t = time (s)
T = temperature (K)
v = velocity (m s^{-1})
V = volume (m^3)

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Paper 3

Thermodynamic Behavior and Heat Transfer in Closed Surge Tanks for Hydropower Plants

Kaspar Vereide, Torbjørn Tekle and Torbjørn Kristian Nielsen (2015)

Journal of Hydraulic Engineering, 141(6), 06015002, 1-5, DOI:
10.1061/(ASCE)HY.1943-7900.0000995 (Open Access).

Technical Note

Thermodynamic Behavior and Heat Transfer in Closed Surge Tanks for Hydropower Plants

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Abstract: A numerical model of a hydraulic system with a closed surge tank is developed for evaluating the thermodynamic behavior during slow transients in the air pocket. The numerical model is used to evaluate the polytrophic equation against a Modified Rational Heat Transfer (MRHT) method, and the results are compared to field observations. The original RHT method considers heat transfer to walls and water as a lumped quantity, and the method is modified in this work to evaluate these two processes separately. The field observation dataset contains pressure and water level measurements from a 3,050 m^3 closed surge tank during a pressure increase from 805 to 1543 kPa over 40 min, thus providing a unique opportunity to investigate the thermodynamic behavior during slow transients. This paper will show how the accuracy of modeling slow transient events in a closed surge tank may be improved by applying the MRHT method, which accounts for heat transfer to enclosing media. **DOI: 10.1061/(ASCE)HY.1943-7900.0000995.**

Author keywords: Closed surge tanks; Thermodynamics; Field measurements; Numerical simulations; Slow transients; Heat transfer; Hydro power.

Introduction

Thermodynamic behavior in closed surge tanks is traditionally modeled with the polytrophic equation (Wylie and Streeter 1993; Thorley 2004)

$$pV^n = \text{constant} \tag{1}$$

where P = absolute gas pressure; V = gas volume; and n = polytrophic exponent. The polytrophic equation is derived by assuming heat transfer linearly dependent to the work done by the air (Moran et al. 2012). For fast transients, field observations and experiments show that n is approximately 1.4 in closed air pockets, and that the thermodynamic behavior is close to adiabatic with zero heat transfer (Svee 1972; Goodall et al. 1988; Steward and Borg 1989; Zhou et al. 2013a, b). However, when calculating closed surge tank behavior for slow transients, this work will show that heat transfer has a significant effect on the thermodynamics of the system and that the heat transfer is therefore not properly represented by the polytrophic equation.

An alternative model for calculation of closed surge tank behavior was proposed by Graze (1968), who presented the Rational Heat Transfer (RHT) method. Graze presented accurate results when comparing simulations against experiments, and the authors are interested in the application of the RHT method for calculation of slow transients in large-scale surge tanks for hydropower plants.

Recently a restricted dataset from a Norwegian hydropower plant has been made available for publication. In this paper, relevant theory will be presented and it will be shown how the polytrophic relationship is unsuccessful in modeling a slow transient event, whereas a modified RHT method yields more accurate results.

Thermodynamic Theory

The ideal gas law is applied for calculating thermodynamic behavior in a closed surge tank

$$pV = mRT \tag{2}$$

where p = absolute air pressure; V = air volume; m = air mass; R = specific gas constant; and T = air temperature. By differentiating Eq. (2) and applying the concept of reversibility, Graze (1968) derived an expression for pressure change as a function of volume change and heat transfer

$$dp = \frac{1}{V}[-\kappa p dV + (\kappa - 1)dQ] \tag{3}$$

where $\kappa = 1.4$ = adiabatic constant; and dQ = heat transfer. Eq. (3) may be used to derive the polytrophic equation [Eq. (1)] by assuming heat transfer linear to the work done by the air [$dQ = pdV(\kappa - n)/(\kappa - 1)$].

When compared to Eq. (1), Eq. (3) is expected to give a more accurate representation of the thermodynamic behavior in closed surge tank where heat transfer occurs. The constraints of applying Eq. (3) is the added complexity and limited studies of heat transfer.

Heat Transfer Process

The main types of heat transfer are conduction, convection, radiation, and phase change (Moran et al. 2012). Of these processes,

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Note. This manuscript was submitted on February 18, 2014; approved on December 9, 2014; published online on February 10, 2015. Discussion period open until July 10, 2015; separate discussions must be submitted for individual papers. This technical note is part of the ***Journal of Hydraulic Engineering***, © ASCE, ISSN 0733-9429/06015002(5)/$25.00.

radiation and phase change are assumed to be negligible for calculation of closed surge tank behavior. Heat transfer is assumed to be dominated by the combination of convection in the air and conduction through the enclosing rock and water, and this process is modeled with the Newton's empirical law of cooling [Eqs. (5) and (6)].

The RHT method considers lumped heat transfers through rock and water of the surge tank, and is for this study expanded to separate heat transfer to water (subscript w) and rock (subscript r) separately in order to consider the individual contribution of each (subscript a is used for air).

$$dQ = dQ_r + dQ_w \tag{4}$$

$$dQ_r = -h_r A_r (T_a - T_r)dt \tag{5}$$

$$dQ_w = -h_w A_w (T_a - T_w) \tag{6}$$

where h = heat transfer coefficient; and A = boundary surface. The modified version is in the following referred to as the MRHT method.

Heat transfer through convectionisassumedto be natural. According to Bejan (1993), the relative magnitude of natural versus forced convection may be quantified as the ratio of the Grashof number [$\mathrm{Gr} = g\Delta T L^3/(\upsilon^2 T)$] divided by the Reynolds number ($\mathrm{R} = \mathrm{UL}/\upsilon$) squared, where L is the characteristic length, U is fluid velocity, and υ is kinematic viscosity.From this relationship, it can be shown that the forced convection is negligible compared to the natural convectionfor normal transient in closed surge tanks ($\mathrm{Gr}/\mathrm{R}^2 \gg 1$).

For heat transfer from air to water, it is assumed that the water holds constant a temperature due to circulation. The heat transfer coefficient for natural convection from air to water may then be calculated from Incropera and Dewitt (2007)

$$h_w = \frac{\mathrm{Nu}_w \lambda_a}{L_w} \tag{7}$$

where Nu = Nusselt number; and λ = thermal conductivity for air. For heat transfer from air to rock, it is necessary to account for heat transfer resistance and temperature gradient in the rock. The heat transfer coefficient for air to rock may be calculated from Incropera and Dewitt (2007)

$$h_r = \frac{1}{\frac{1}{h_a} + R_r} \tag{8}$$

$$h_a = \frac{\mathrm{Nu}_r \lambda_a}{L_r} \tag{9}$$

$$R_r = \frac{l}{\lambda_r} \tag{10}$$

where R_r = heat transfer resistance defined in Eq. (10); and l = rock layer thickness. Finally, the resulting model for heat transfer in closed surge tanks in the MRHT method becomes

$$dQ = \frac{\mathrm{Nu}_w \lambda_a}{L_w} A_w (T_a - T_w)dt + \frac{1}{\frac{L_r}{\mathrm{Nu}_r \lambda_a} + R_r} A_r (T_a - T_r)dt \tag{11}$$

The Nusselt number (Nu) is the only unknown and is determined from laboratory experiments, field measurements, or empirical relationships. Incropera and Dewitt (2007) suggest the following empirical relationship for turbulent air flow ($\mathrm{Gr} > 10^8$):

$$\mathrm{Nu} = k\sqrt[3]{\mathrm{PrGr}} \tag{12}$$

where $\mathrm{Pr} = c_p \mu/\lambda$ is the Prantl number; μ is the dynamic viscosity of the fluid; and k is an empirical constant. For large closed surge tanks, the factor k is individual for walls, roof, and floor. Due to the complexity of measuring and calculating each individual surface, the problem may be simplified by assuming lumped factor k for all surfaces.

In order to account for heating and cooling of the rock mass, Eqs. (13) and (14) solve Fourier's law in order to account for the propagation of heat in the rock

$$dQ_l = \frac{\lambda_r A_r (T_0 - T_l)dt}{l} \tag{13}$$

$$dT_l = \frac{dQ_l - dQ_0}{A_r l c_p \rho} \tag{14}$$

Given an infinite amount of layers, dT becomes zero and the rock temperature reaches a steady state. The necessary amount of layers for reaching a steady state is found by trial and error.

For comparison against the MRHT method, the equation for calculating the heat transfer in the RHT method is given in Eq. (15) as follows:

$$dQ = 0.92|T_a - T_r|^{\frac{1}{3}} A(T_a - T_r)dt \tag{15}$$

The expression is converted from imperial to metric units based on the presentation in Graze (1968), which is applied in the benchmark model WHAMO by U.S. Army Corps of Engineers (1998).

Methodology

A numerical model is established for comparing the presented theory with field observations. The Method of Characteristics (MOC) as described by Wylie and Streeter (1993) is applied, and Eqs. (3), (11), and (12) are used for calculating the thermodynamic behavior of the closed surge tank. The numerical model is used to calibrate the factor k and simulate the heat transfer and thermodynamic behavior of the observed event.

Numerical Model

The numerical model is developed with the freeware *LVTrans 1.7.11*, developed by SINTEF research group, which is based on the MOC. This method solves the equations of continuity and motion, and is applied in numerous studies on pipe and tunnel flow (Joung and Karney 2009; De Martino and Fontana 2012; Zhou et al. 2013a, b). For the present study, the software is expanded by including a closed surge tank module, which solves Eqs. (3), (11), and (12) through Newton's iteration method. Air temperature is calculated with the ideal gas law, as presented in Eq. (2), and rock temperature is calculated with Eqs. (13) and (14). The rock is modeled as 1D layers, with the following thicknesses (cm): 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.03, 0.05, 0.10, 0.20, and 0.40. The module calculates air pressure, air volume, air temperature, rock temperature, water level, and water flow in the closed surge tank. Singular loss, gravity, and pressure forces are included, while inertia and friction loss are neglected due to low water velocity. All simulations are performed with a time-step 0.1 s.

The prototype for the numerical model is the power plant Jukla (40 MW) in western Norway, which utilizes runoff from the glacier Folgefonna. The power plant has two upper reservoirs at different geodetic levels and is constructed with a closed surge tank. The

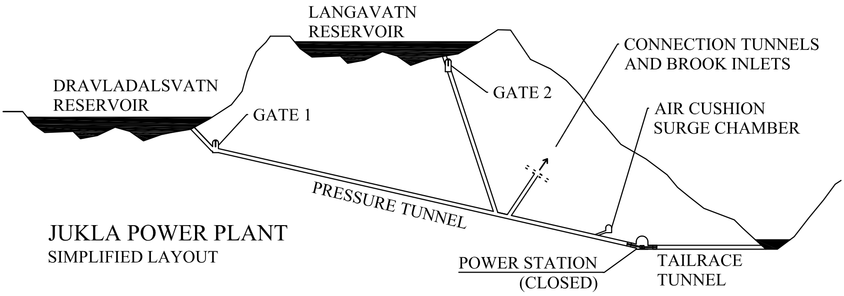

Fig. 1. Jukla power plant layout

Table 1. Key Model Data

Component	Unit	Value
Langavatn reservoir level	masl	980.3
Dravladalsvatn reservoir level	masl	902.3
Surge tank initial water level	masl	830.9
Surge tank end water level	masl	833.7
Surge tank initial air volume	m^3	3,050.0
Surge tank end air volume	m^3	1,760.0
Surge tank initial air pressure	kPa	805.0
Surge tank end air pressure	kPa	1,543.0

surge tank is an unlined rock cavern constructed by conventional drill and blasting. The layout of the power plant as modeled with *LVTrans 1.7.11* is presented in Fig. 1, and key data from the power plant are shown in Table 1.

Statkraft AS is the owner and operator of the power plant, which has been in operation since 1974. The length of the headrace between Dravladalsvatn reservoir and the junction point is 5,804 m, and the length from Langavatn reservoir to the junction point is 3,320 m. The length from the connection point to the turbines is 724 m.

There are numerous brook inlets in the tunnel system, which are added in the numerical model as a lumped volume.

Field Observations

The data set was collected in May 1979 by Statkraft AS. By switching from the lower upstream reservoir to the higher reservoir, the air pressure in the closed surge tank was doubled during 40 min. The duration of the filling process is mainly governed by filling several connection tunnels and brook inlets.

The water level and air pressure measurements from the closed surge tank are presented in the result section. The temperature in air and rock was not measured. The water temperature in the Jukla waterway was 275 K at the time of measurement.

Power Plant Operation during Measurements

The turbines were closed during the entire event. Initially, the water flow in the system was zero, the intake gate to Langavatn reservoir was closed, and the pressure in the waterway was governed by the water level in Dravladalsvatn reservoir. The power plant operation is separated into the following main events: (1) the intake gates for Dravladalsvatn reservoir close, (2) the intake gates for Langavatn reservoir are opened slowly in order to fill the dry connection tunnel, (3) the dry tunnel is filled after 40 min, and (4) the system reaches the steady state after 5 h.

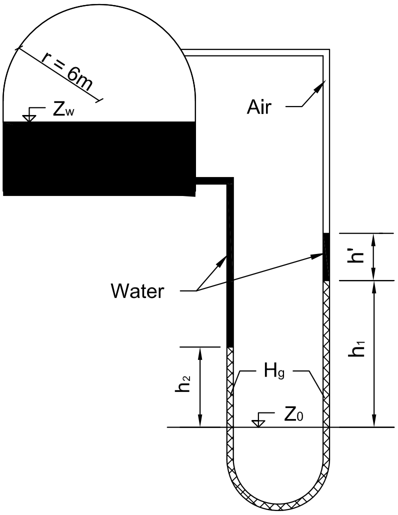

Fig. 2. Measurement principle

Measurement Equipment and Uncertainty

Water level measurements are conducted with a mercury U-pipe system as show in Fig. 2. The U-pipe is connected to two steel pipes with a diameter of 6 mm that lead into the closed surge tank. The elevation of the two pipes in the surge tank is known, and the water level is calculated from the pressure difference.

The rock cavern geometry is known and air pressure is calculated from the pressure balance between upper reservoir, water level in the surge tank, and air pressure.

The uncertainties of the significant parameters are $\Delta h_1 = \pm 0.005$ m, $\Delta h_2 = \pm 0.001$ m, $\Delta \rho_{Hg} = \pm 10\ \mathrm{kg/m^3}$, and $\Delta p_{Z_o} = 1$ kPa. The rest of the parameters have a negligible effect on the uncertainty. The parameter h_1 has a larger uncertainty compared to h_2 due to water evaporation in the U-pipe. The total uncertainty of the water level and air pressure is $\Delta Z_w = \pm 0.08$ m and $\Delta p_{\mathrm{air}} = \pm 0.8$ kPa.

Results

Water Level

Fig. 3 presents the observed and simulated water level in the closed surge tank. For the MRHT method, the empirical factor k is found

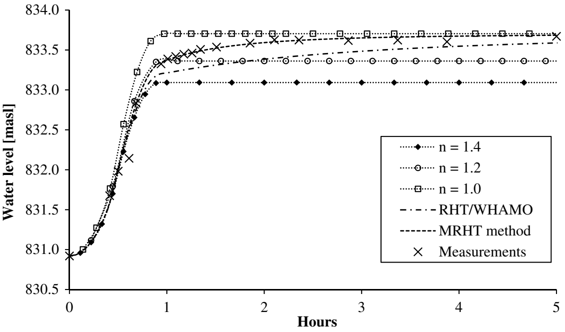

Fig. 3. Comparison of water level simulations and measurements

to be 0.05 (-). For comparison, results obtained with the RHT method as expressed in Eq. (15) are provided. For the polytrophic relationship, simulations are performed with $n = 1.4$ (adiabatic), $n = 1.2$ (intermittent), and $n = 1.0$ (isothermal). The total amount of heat transfer in the MRHT and isothermal simulations is approximately 1.6 GJ. The total amount of heat transferred is 1.4 GJ in the RHT simulation, 0.7 GJ in the intermittent polytrophic simulation, and 0 GJ in the adiabatic simulation.

The gradient of water level rise is high during the filling process and decreases rapidly after the filling process is complete. After completion, the water level increases slowly as heat energy in the air disperses into the enclosing rock and water.

Air Pressure

Fig. 4 presents simulated and observed air pressure in the closed surge tank during the slow transient event. The pressure builds up during the filling process, peaks immediately after the filling is complete, and thereafter declines as heat energy dissipates into the surrounding media. Fig. 4 show that the difference in calculated pressure between the different thermodynamic models is limited, as pressure is governed by the upstream water level. In comparison, the water level simulations show larger differences as it is dependent on both pressure and temperature in the air pocket.

As can be seen, the observed data reveal a peak in the pressure immediately after completing the filling process. The simulations also show a peak in the pressure at this point, but at smaller magnitude. The water level does not indicate such a peak, and the cause of the pressure peak therefore needs to be related to another physical phenomena. This is discussed further in the next section.

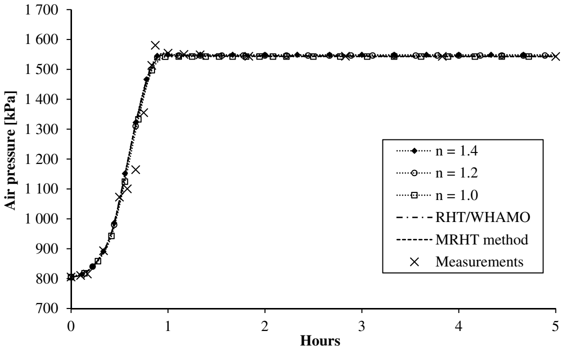

Fig. 4. Comparison of air pressure simulations and measurements

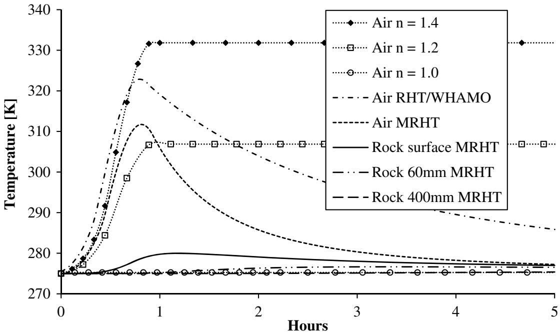

Fig. 5. Simulated temperature in air, rock, and water

Temperature

The simulated air temperatures are compared in Fig. 5. Additionally, rock temperatures at selected depths are presented as calculated with the MRHT method. The air temperatures show a peak at the end of the filling, and thereafter remain constant for the polytrophic simulations. For the RHT and MRHT methods, the air temperature eventually cools down and moves toward equilibrium as heat is transferred to water and rock.

For the polytrophic simulations, the air temperature is highest at the time of the pressure peak (end of the filling process). For the RHT and MRHT simulations, the temperature peaks slightly before, at the time when heat transfer out of the system is equal to heat generation due to work done by the air. The results from the MRHT and adiabatic simulations are approximately equal during the first 20 min. The rock temperature is seen to be affected until 400 mm deep, at which depth the temperature is stable at 275 K during the entire event.

Discussion

As is seen in Fig. 3, the adiabatic, intermittent, and isothermal relationships fail to provide satisfying accuracy compared to the MRHT method. For calculation of slow transients where start and end conditions differ, heat will disperse into the surrounding rock and water, and the system will stabilize at the isothermal state. For such events, the MRHT method is shown to produce more accurate results.

For comparison against the existing RHT/WHAMO method, the equivalent to the constant 0.92 in Eq. (15) is calculated to be the k-value in the range between 0.01 and 0.02 in the MRHT method. The difference is caused by the Nusselt number dependence on geometry, air pressure, and temperature. As is shown, the RHT/WHAMO model underestimates the heat transfer for this particular case-study. This implies that the heat transfer coefficient is not constant but needs calibration for individual surge tanks. It should also be noted that the RHT method does not account for temperature transients in the enclosing media, which in the MRHT method is seen to influence the system.

Although the MRHT method provides higher accuracy compared to the other models, the results still do not fall within the given uncertainty of the observations, and it is possible to further develop the heat transfer model. The main limitation of this study has been the lack of temperature data; such measurements will indeed be crucial for future developments.

Further refinement of the model is also necessary for capturing the pressure peak at the end of the filling process. Fig. 4 reveals that all the models fail to capture this pressure peak. One possible explanation is that the pressure peak may be caused by phase change due to moisture in the air, as this effect is not included in either of the models. Phase change has been observed in enclosed air pockets by Zhou et al. (2013b). To further investigate the cause of the pressure peak, temperature measurements would be of great assistance, and the matter is left for future research when such data are available.

In Fig. 5 it is observed that the MRHT method and adiabatic simulations are approximately equal in the first 20 min, which indicate the time limit before heat transfer needs to be accounted for in this particular case study.

Conclusion

Based on the comparison presented in Figs. 3 and 4, it is concluded that the MRHT method should be preferred to the polytrophic equation for modeling of slow transients in closed surge tanks. The main limitation is uncertainty regarding the empirical *k* factor for calculation of the Nusselt number. For this case-study it is indicated that heat transfer needs to be accounted for after approximately 20 min of pressure rise.

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Paper 4

The Effect of Surge Tank Throttling on Governor Stability and Performance in Hydropower Plants

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In Review: IEEE Transactions on Energy Conversion.

Effect of Surge Tank Throttling on Governor Stability and Performance in Hydropower Plants

Kaspar Vereide, Bjørnar Svingen, Torbjørn Kristian Nielsen and Leif Lia

***Abstract*—This work investigates the effect of surge tank throttling on governor stability and performance in hydropower plants. A new methodology for this purpose is proposed, which includes the effect of non-linarites and the use of a non-ideal discrete-time implemented governor system. Governor stability is analyzed through non-linear frequency-response tests evaluated in Bode plots for power plant operation in an isolated grid, and governor performance is analyzed via step-response tests for operation on large interconnected grids. The methodology is demonstrated through an example hydropower plant, from which field measurements are used to calibrate a numerical model based on the method of characteristics. Two different governor systems are tested; with speed feedback exclusively, and with speed and power feedback combined. The step-response tests are performed with load acceptance from 0 to 100% load. The results from the example hydropower plant show that the throttle has an insignificant positive impact on governor stability for normal disturbances in the grid frequency. For governor performance, the results show that the produced power is controlled more accurately when a throttle is installed. The results indicate that surge tank throttling will have a positive impact on governing stability and performance for a wide range of hydropower plants.**

***Index Terms*—Control systems, hydroelectric power generation, fluid dynamics, stability analysis.**

I. INTRODUCTION

THE ever-changing balance between power input and consumption affects the frequency in the power grid, and there is need for governor systems to ensure control and stability. The governor systems need to consume or produce power counteractively to the variation in the grid, to restore the desired frequency, and this counteraction must occur within restricted time to limit the amplitude and time duration of the imbalance. Hydropower plants are suitable for this task due to their ability to increase or reduce a large amount of produced power within a short time, thereby limiting the amplitude and time duration of imbalances.

The control of grid frequency by hydropower plants is enabled through turbine governors [1–3]. The governor measures the rotational speed and/or produced power of the units and closes or opens the guide vanes or nozzles in order to maintain a set point. The governor may be programed with several variants of speed feedback and power feedback, depending on system stability and grid requirements. When a single turbine unit is operated on an isolated grid, only speed feedback is enabled. When operated on a large interconnected grid, droop is included and power feedback may also be included to improve control of output power.

All governing systems for hydropower are potentially unstable. The main challenges for governor stability are water inertia and elasticity. When the power plant reduces the water flow in order to reduce the produced power, water inertia and elasticity counteracts the desired change as the pressure will increase. Power feedback may increase this effect compared to when only speed feedback is activated. To ensure stability, the appropriate turbine governor has to be selected based on thorough studies. In hydropower plants with long water conduits, restrictions to surge tank water-level amplitudes may require governors to operate exclusively through speed feedback and droop functionality without power feedback.

Implementing a surge tank is often necessary to improve governing when the penstock otherwise would become too long [4–7]. The surge tank introduces a water reservoir with a free water surface close to the turbine, and thereby reduces the water inertia. In addition, the surge tank reduces the magnitude and reflection time of the elastic water hammer [8]. For hydropower plants with long water conduits, the surge tank is often the only feasible measure from which governor stability may be achieved with adequate time constants that fulfill the relevant grid codes. However, the surge tank introduces the problem of mass oscillations, which occur in the form of U-pipe oscillations between the reservoir and the surge tank. The resulting surge tank design is governed by the characteristics of the mass oscillations. Furthermore, these mass oscillations may cause a physical instability in the governor system [5]. The mass oscillations may be reduced by increasing surge tank size or by installing a throttle in the surge tank inlet [9]. The throttle is often constructed as a steel orifice that restricts the water flow in and out of the surge tank.

This work investigates the throttle's effect on governor stability and performance. Previous works on this topic

Manuscript received September 09, 2015; revised February XX; accepted XX. Date of publication XX; date of current version XX.

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include Escande [10] who was among the first to investigate the impact of throttling on governor stability for small oscillations in hydropower plants. Li and Brekke [11] investigated the stability of large amplitude water-level oscillations in throttled surge tanks, and found that the throttle improves governor stability for large oscillations. Yang and Kung [12] investigated governor stability of closed surge tanks with throttles, and confirmed that the throttle has a positive effect on stability. The last two studies were conducted with the phase plane method as described in Chaudhry et al. [13]. These studies assume an ideal governing of power, i.e. the product of pressure, discharge, and unit efficiency is constant. In addition, the effect of surge tank throttling on the governor performance has not been evaluated. In the modern power market, the governor performance is of increasing importance, both to improve the control of the grid frequency and to optimize the production of electrical power and energy. It is therefore useful to have a methodology that includes an evaluation of the performance.

This study introduces a new methodology for evaluating the throttle effect on governor stability and performance, which includes non-linarites and the use of a non-ideal discrete-time implemented governing system. Governor performance is defined as how accurately the produced power may be controlled and is quantified by how fast the system reaches a steady state after a disturbance. The methodology is demonstrated through example hydropower plant, namely the 150 MW Torpa power plant in southern Norway. This power plant is constructed with a closed surge tank, and the throttle effect on governor stability and performance will be quantified. The performance will be evaluated separately for a governor system with speed feedback exclusively, and a governor system with speed and power feedback combined.

Design of surge tank throttling is performed relatively similar for different hydropower plants, and it is assumed that the conclusions on whether the throttle has a positive or negative effect in the example hydropower plant are valid for a wide range of hydropower plants. Section II of this work presents relevant theory for hydraulics and governing systems in hydropower plants. Section III outlines the new methodology for evaluation of the throttles effect, and presents an example hydropower plant on which the method is demonstrated. Section IV gives the results, while Sections V and VI present a discussion and the conclusions.

II. THEORY

The theory section is limited to hydropower plants with pressurized pipe flow and the following boundary conditions: upper and lower reservoirs, turbine units, open surge tank, and closed surge tank. The turbine unit is here defined to include a Francis turbine, a governor, the generator's inertia, and the grid's frequency and power consumption. For theory on additional types of hydropower plants, and boundary conditions, one may consult the work of Chaudhry [2] and Wylie and Streeter [14]. A schematic overview of an example hydropower plant is given in Fig. 1.

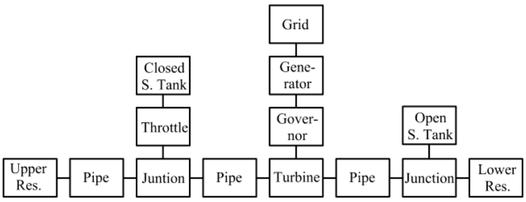

Fig. 1. Schematic overview of an example hydropower plant.

The governing equations for pressurized pipe flow are the equation of continuity (1) and the equation of motion (2):

$$\frac{\partial H}{\partial t}+v\frac{\partial H}{\partial x}+\frac{a^2}{g}\frac{\partial v}{\partial x}=0 \tag{1}$$

$$\frac{\partial v}{\partial t}+g\frac{\partial H}{\partial x}+v\frac{\partial v}{\partial x}+g\sin\varphi+\lambda\frac{v|v|}{2D}=0 \tag{2}$$

where $H = p/(\rho g)$ is the piezometric head, ρ is the water density, g is the acceleration of gravity, v is the water velocity, x is the length coordinate, t is the time, φ is the angle to the horizontal plane, a is the speed of sound in water, λ is the Darcy-Weisbach friction factor, and D is the pipe diameter. For low Mach number flow, and slightly compressible fluids, these two equations may be solved numerically with the method of characteristics (MOC) as described by Wylie and Streeter [14].

Closed surge tanks are usually assumed to have adiabatic thermodynamic behavior, with an adiabatic gas constant of 1.4 for air [15,16]. The adiabatic behavior in closed surge tanks is modelled with the following relationship:

$$pV^{1.4}=k \tag{3}$$

where p is the absolute air pressure, V is the air volume, and k is a constant. Previous studies have however shown that different closed surge tanks may have different thermodynamic behavior based on size and construction material [17], and that closed surge tanks may be influenced by heat transfer [18,19]. Field measurements may be necessary to determine the appropriate thermodynamic model. The throttle is a singular loss described by

$$H_{loss}=\xi\frac{Q^2}{2gA^2} \tag{4}$$

where ζ is the singular loss coefficient, Q is the water discharge through the throttle, and A is the cross-sectional area of the tunnel before and after the throttle. The equations for open surge tanks and reservoirs are described in Wylie and Streeter [14]. The Francis turbine may be calculated via the Euler turbine equation [20], which describes the relation between pressure, flow, and rotational speed of the unit:

$$gH_t=u_1c_{1x}-u_2c_{2x} \tag{5}$$

where H_t is the head utilized by the turbine, $u = \omega r$ is the cross-radial (tangential) velocity, ω is the angular speed, r is the radius of the turbine runner, and c is the absolute velocity.

To aid the derivation of the turbine equations, a velocity diagram for the Francis turbine is shown in Fig. 2, where subscript *z* represents the vertical plane, subscript *x* represents the horizontal plane perpendicular to the generator shaft, and subscripts *1* and *2* represent the turbine inlet and the outlet respectively.

By multiplying the Euler turbine equation with water density and gravitational acceleration, one derives the following relation:

$$\rho Q g H_t = \rho Q(r_1 c_{1x} - r_2 c_{2x})\omega = T\omega \tag{6}$$

The expression to the left denotes the hydraulic power (P_h), and T is the torque transferred from the turbine to the generator. By applying the continuity equation and the trigonometry of the velocity diagrams, the resulting equation for the turbine may be written as

$$P_h = \rho Q(r_1 c_1 \cos\alpha + r_2 A_z c_1 \cot\beta \sin\alpha - r_2^2 \omega \tag{7}$$

where A_z is the inlet area divided by the outlet area of the runner perpendicular to the *z*-axis. Changes in the angular speed is derived from

$$J\omega \frac{d\omega}{dt} = P_h - P_g - P_l \tag{8}$$

where J is the generator's inertia, P_g is the power consumed by the grid, and P_l is the sum of hydraulic and electromechanical losses. The losses can be calculated from Nielsen's work [20]. The generator delivers alternating current to the grid, and the nominal rotational speed is therefore selected to deliver the correct grid frequency:

$$\frac{n_0}{60} = \frac{f_0}{\#} = \frac{\omega}{2\pi} \tag{9}$$

where f_0 is the nominal grid frequency, # is the number of pole pairs on the generator, and n_0 is the generator's nominal rotational speed (rpm). The turbine governor controls the opening degree of the guide vanes in order to maintain a constant rotational speed. In the present case study the governor is a standard Proportional-Integral-Derivative (PID) type as described in the ideal mathematical description below. The last term (y/b_p) is only included when running on a large interconnected grid:

$$\frac{dy}{dt} = -K_P \frac{dn}{dt} + K_I(n_0 - n) + K_D \frac{d^2 n}{dt} - \frac{y}{b_p} \tag{10}$$

where y is the gain, K_P is the proportional constant, K_I is the integral constant, K_D is the derivative constant, n is the turbine's rotational speed, n_0 is the turbine's nominal rotational speed, and b_p is the speed droop constant. A realizable governing system includes several additional functions, which are more clearly illustrated in a block-diagram. Fig. 3 presents an example block diagram for a realizable governor system. The variable s is the complex number frequency, P is the produced power, P_r is the set point for power, T_p is the integral constant for the power feedback, T_s is the anti-windup time constant, and T_a is the time constant of the generator inertia. The *y/P* element represents power control in a governor system without power feedback. It consists of curves that estimate the necessary guide vane opening for different turbine heads. The ramp for the governor gain controls how fast the produced power is increased or decreased when the power set point is changed. The input set point for power can also be ramped directly. The anti-windup loops (T_{s1} and T_{s2}) hinder windup from too much integration (saturation) if the guide vanes reach full opening or closing.

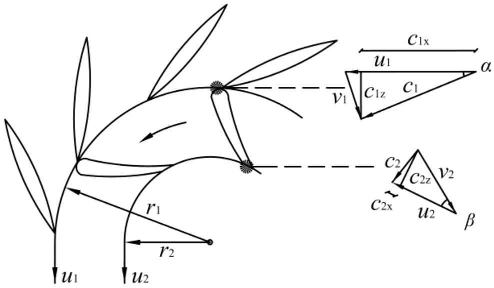

Fig. 2. Velocity diagram for a Francis turbine blade.

III. METHODOLOGY

Governor stability can be tested with frequency-response tests evaluated in Bode plots [21]. Traditionally, the governing equations are linearized to analytically calculate the response function through Laplace transforms. This approach is acceptable for small oscillations around a stationary point but is less accurate for large amplitude oscillations, as the system is influenced by non-linarites [11]. Non-linear methods, such as the phase-plane method [13], or numerical solution of the governing equations are necessary for evaluating the governing capabilities both for small and large oscillations. In the present work, the one-dimensional governing equations are solved with the MOC in the time domain, and transformed into the frequency domain with the Fast Fourier transform. A similar methodology for evaluation of hydropower plant governing is reported by Nicolet et al. [22], who uses a finite difference numerical scheme. In this work, the MOC is selected as it is known to yield accurate results for calculating hydraulic systems with throttles [23]. The frequency-response tests are performed with the following procedure:

1. State an oscillating frequency and amplitude in the reference (f_r) grid frequency.
2. Run simulation until steady-state oscillatory conditions occur.
3. Measure the response (phase and gain) from the system.
4. Repeat with new oscillating frequencies until the desired spectrum is covered.

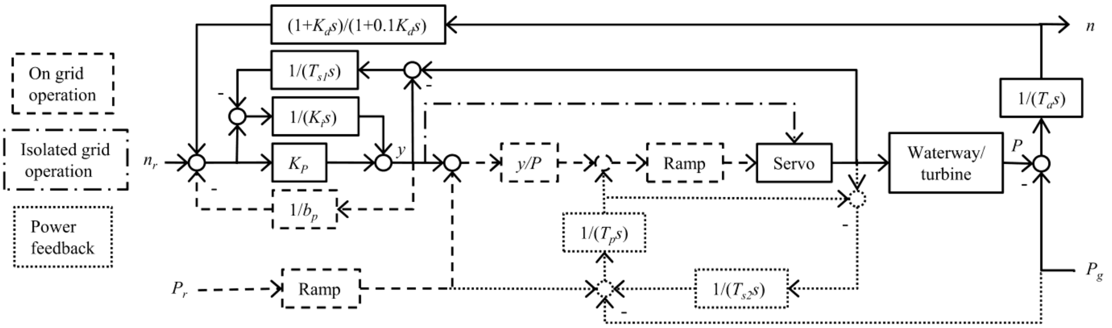

Fig. 3. Block diagram for a realizable PID governor.

An amplitude of 50 ± 0.1 Hz in the reference frequency (f_r) with oscillating frequencies ranging from 0.001 to 10 Hz are suggested. The resulting Bode plot may now be analyzed. The system is regarded as stable if it satisfies the Nyquist stability criterion [24]. The criteria states that the system is stable if the phase angle ($\angle$h) between the impulse and the response is higher than -180^0 at the frequency where the gain amplitude (h) first crosses the 0-line (the cross frequency).

Governor stability may be quantified with the phase margin (ψ) and the gain margin (Δh) [21]. The phase margin is the margin between the actual phase and -180^0 at the cross-frequency. The gain margin is the gain value at the frequency where the phase crosses the -180^0 line. Large margins equal more stable systems, but too large margins also yield slow-acting systems.

Governor performance is evaluated from a step-response test, through diagrams of the produced power and penstock pressure during a load acceptance from 0% to 100% load with a ramping time of 100 s. The system that most accurately follows the specified ramp has superior performance. Performance is quantified with the amplitude of the overshoot of produced power and the undershoot for pressure upstream from the turbine, as well as the time before the system reaches steady state. The steady-state criteria is

$$\sum_{t_1}^{t_2} | q_i | < w \tag{11}$$

where q_i denotes the numbers in the time series between t_1 and t_2, t_1 is the time of steady state, t_2 is the last time step in the time series, and w is a number representing sufficient convergence. Overshoot of unit rotational speed is not considered as the tests are performed for synchronous operation on a large interconnected grid. The effect of throttling may be evaluated with speed feedback exclusively and with speed and power feedback combined.

A. An example hydropower plant

The methodology is tested on an example hydropower plant, namely the 150 MW Torpa hydropower plant located in Nordre Land County in southern Norway. This power plant was commissioned in 1989 and is owned and operated by Eidsiva Vannkraft AS. Fig. 4 shows a principle diagram of the power plant.

Two 75 MW Francis turbines, with a nominal head of 430 m and a nominal discharge of 40 m^3/s are installed. The headrace is 9.6 km long with an unlined cross-sectional area of 35 m^2 and is inclined directly between the reservoir and the power station, without a pressure shaft. A closed surge tank is located 300 m upstream from the turbines and is constructed as an unlined rock cavern filled with 13 000 m^3 of air at pressure 4.1 MPa. The tailrace is 10 km long with an unlined cross-sectional area of 35 m^2 and an open surge tank with 1650 m^2 of water surface area, which is located 100 m downstream of the turbines. The turbine governors are PID-type speed governors, with proportional constant (K_P) equal to 4.0 and integral constant (K_I) equal to 6.0. The turbine's closing time from full opening is 10.0 s. When running on a large grid, the governor has a permanent speed droop (b_p) of 6%. The two generators each have an inertia (J) equal to 114 250 kgm^2 resulting in time constant for the generator inertia (T_a) of approximately 6.0 s. The nominal rotational speed (n_0) is 600 rpm. The existing governors do not have activated power feedback, but for simulations with power feedback in this work the time constant T_p is set to 10.0 s. The derivate constant for the speed feedback (K_D) is set to 0.0 s, while the anti-windup time constant for speed feedback (T_{s1}) is set to 6.0 s, and the anti-windup time constant for power feedback (T_{s2}) is set to 10.0 s. The ramp for both the power set point and the governor gain is set to 100 s.

None of the surge tanks are equipped with throttles in the existing power plant. A numerical model has been established and used to simulate the current situation, and compare to situations where throttles with different head loss are installed in the headrace surge tank.

B. Numerical model and field measurements

The numerical model of the power plant is established with the 1D numerical simulation freeware LVTrans [25]. This program solves the MOC and the governing equations for hydropower plants as described in the theory section. The hydraulic system is simplified by assuming one equivalent turbine instead of two. The simulations were carried out with a time step (dt) of 0.001 s and a length step (dx) of 1.2 m. The singular loss coefficient (ζ) of the T-connection between the

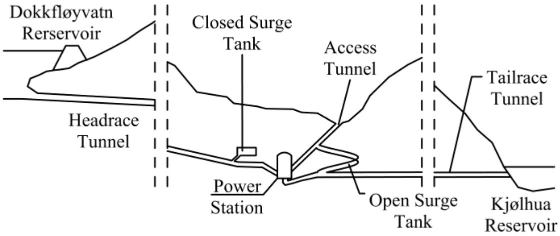

Fig. 4. Principle diagram of Torpa power plant

TABLE I
INPUT DATA FOR THE NUMERICAL MODEL

Parameter	Value
upper reservoir level (m)	707
lower reservoir level (m)	263
closed surge tank water level (m)	292.3
closed surge tank air pressure (kPa)	4125
power production	141
turbine flow (m^3/s)	35
tunnel friction factor (–)	0.07
speed of sound in water (m/s)	1200

headrace tunnel and the surge tank was 60 (–) for the existing power plant, when A in Eq. (4) is 35 m^2. In addition to the existing non-throttled configuration, two different throttles were tested, with $\zeta = 300$ (–) and $\zeta = 1200$ (–). These three different cases are hereby respectively referred to as no throttle, medium throttle, and strong throttle configurations.

To calibrate the numerical model, field measurements were collected from Torpa power plant. The measurements include reservoir water levels, produced power, air pressure, water level in the closed surge tank, and water pressure upstream from the turbine. The measurements were collected during an emergency shutdown from full load, and the initial conditions and input data for the numerical model are given in Table I.

A PARO scientific DIQ 73K pressure sensor with error less than 0.04% of full-scale 20 MPa was used to measure the pressure upstream from the turbine. A PARO scientific 8DP000-S with error less than 0.01% of full-scale 6 MPa was applied to measure the air pressure in the closed surge tank. Measurements of the produced power, the closed surge tank water level, and the reservoir water levels were taken and provided by the power plant owner.

These measurements allow for calibration of the hydraulics of the power plant. The governor system is not calibrated, but assumed to be accurately represented due to equal electronic implementation in both the real power plant and in the simulations. The field measurements were only collected upstream from the turbine and in the closed surge tank, and it is therefore only possible to calibrate the hydraulic behavior of the tailrace tunnel and open surge tank. To account for this, the present study only evaluates the effect of installing a throttle in the closed surge tank in the headrace tunnel. The accuracy of the tailrace modelling is thereby of limited importance for evaluation of the throttling effect.

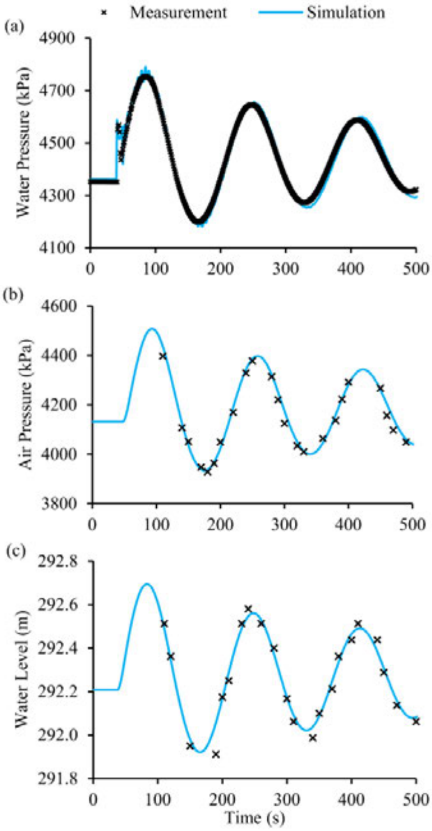

Fig. 5. Comparison of field measurements and simulations of (a) pressure upstream from the turbine, (b) the closed surge tank air pressure, and (c) the closed surge tank water level.

C. *Calibration of the numerical model*

The numerical model is calibrated with the field measurements. A comparison of (a) pressure upstream from the turbine, (b) pressure in the closed surge tank, and (c) water level in the closed surge tank is presented in Fig. 5.

The period of mass oscillations is approximately 164 s in both simulations and measurements. The maximum pressure upstream from the turbine is 4790 kPa and 4753 kPa according to the simulations and the measurements respectively. The coherent minimum pressures are 4181 kPa and 4199 kPa. The maximum water hammer pressure simulated and measured upstream from the turbine is 4584 kPa and 4569 kPa respectively. Due to low sampling frequency, the water hammer period in the measurements is not detectable in the field measurements. The water hammer period for propagation between the turbines and the surge tank is 6 s in the simulations. The mass oscillation period is 163 s for the measurements and 162 s the simulations. The field measurements show that the numerical model is able to simulate the hydropower plant with high accuracy.

IV. RESULTS

The proposed methodology is applied for the example hydropower plant, and this section present the results of the analysis. The governor stability and performance is evaluated for the no throttle medium throttle, and strong throttle configurations

A. Frequency-response tests

Frequency-response tests are conducted with isolated grid operation and with the speed feedback governor system. The amplitude of the grid frequency disturbance is ± 0.1 Hz. The gain amplitude is given in dB = $20\lg|h(j\omega)|$, where $j\omega$ is the complex number frequency (s) and $h(j\omega)$ is the gain amplitude for the given frequency. Fig. 6 presents the resulting Bode plots.

The phase margin (ψ) is 69^0, while the gain margin ($\angle h$) is 10 dB for all configurations. The cross frequency is 0.1 Hz for all the configurations. There is a local amplitude in the phase and gain, due to mass oscillations at frequency 0.006 Hz. The mass oscillation phase angle amplitudes are -97^0, -96^0, and -94^0 for the no throttle, medium throttle, and strong throttle respectively. The equivalent mass oscillation gain amplitude is 17 dB, 17 dB, and 19 dB.

B. Step-response tests

Step-response tests are conducted both with and without power feedback enabled. The governor performance is evaluated by observing which configuration is able to control the produced power most accurately. In addition, the effect on the pressure in front of the turbine is considered. Fig. 7 illustrates the results from simulations of produced power and pressure in front of the turbine. As Fig. 7 depicts, the throttle improves control of the produced power and reduces both the overshoot and the time before the desired steady-state conditions are reached. Furthermore, the undershoot of the pressure upstream from the turbine is reduced when a throttle is installed. The power feedback improves control of the produced power but increases the time before steady-state conditions occur. In addition, the power feedback has a minor negative impact on the turbine pressure and results in increased pressure amplitudes.

The steady-state condition is here defined by (11) where t_2 is 1500 s and w is 3000. Overshoot and undershoot are defined as the maximum deviation from the steady-state value after the load acceptance. Table II lists the time before steady-state conditions occur, the overshoot of produced power, and undershoot of pressure upstream from the turbine. The time before steady-state conditions occur in the system with speed feedback exclusively is reduced by 6% or 25% by installing a medium or strong throttle respectively. The time before steady-state conditions occur in the system with speed and power feedback combined is reduced by 7% or 26% by installing a medium or strong throttle respectively.

The overshoot of the produced power for the governor system with speed feedback is reduced by 12% or 51% by installing the medium or strong throttle respectively. By comparison, the overshoot for the governor system with speed and power feedback combined is reduced by 8% or 24% by installing the medium or strong throttle respectively. Finally, the undershoot of the pressure upstream from the turbine for the governor system with speed feedback is reduced by 5% or 25% by installing the medium or strong throttle respectively. The undershoot for the governor system with speed and power feedback combined is reduced by 4% or 23% by installing the medium or strong throttle respectively.

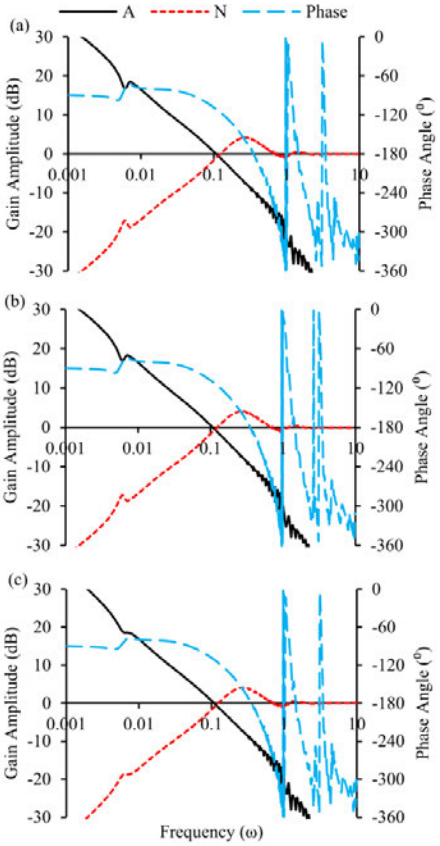

Fig. 6. Frequency-response plot for the system running on isolated grid with (a) no throttle, (b) medium throttle, and (c) strong throttle. A is the gain amplitude without speed feedback, and N is the gain amplitude with speed feedback.

V. DISCUSSION

The proposed methodology enables evaluation of the throttle effect on governing stability and performance. It may be applied to any hydropower plant with surge tank throttling. The methodology is based on well-know theory, and the results are regarded as reliable.

The methodology is demonstrated through an example. The results show that throttling has a positive impact on governor stability and performance, and this conclusion is believed to be valid for a wide range of hydropower plants, except cases of very severe throttling. The results show that the system with

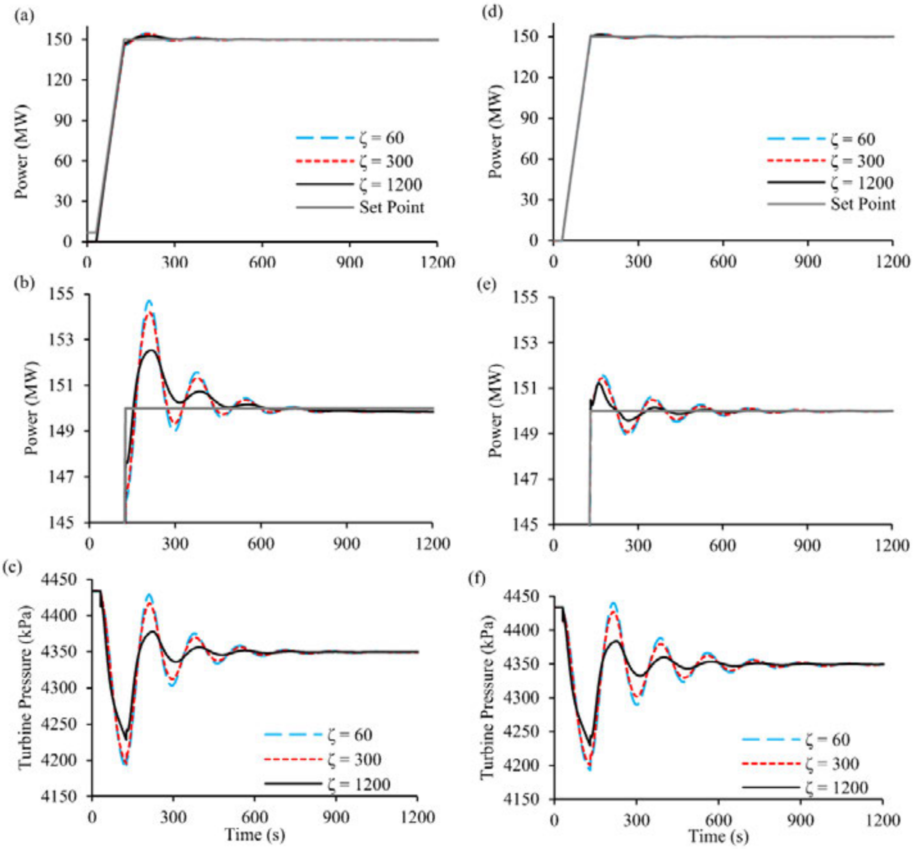

Fig. 7. Step response of produced power and pressure in front of the turbine. Plot (a) shows total range of the load acceptance, (b) shows close-up of the load acceptance, and (c) shows resulting pressure in front of the turbine for the system with speed feedback exclusively. Plots (d), (e), and (f) show the equivalent results for the system with speed and power feedback combined.

TABLE II
RESULTS FROM THE STEP-RESPONSE TESTS

Throttle loss factor (ζ)	60	300	1200	Unit
time before steady state (speed)	720	675	675	s
time before steady state (speed/power)	994	922	681	s
power overshoot (speed)	4.7	4.2	2.5	MW
power overshoot (speed/power)	1.6	1.4	1.2	MW
pressure undershoot (speed)	161	154	122	kPa
pressure undershoot (speed/power)	156	149	120	kPa

a surge tank throttle has an improved governor stability, although the Bode plots reveal that the difference is negligible, except for a small improvement at the mass oscillation frequency. This limited effect was expected as the maximum frequency disturbances in the grid (±0.1 Hz) are relatively small and only result in a limited water flow through the throttle. However, the throttle will have an increased effect if more severe maximum frequency deviations occur in the grid. For the configurations with no throttle, medium throttle, and strong throttle, the maximum water flow through the throttle in the frequency-response tests is 2.8 m^3/s, 2.6 m^3/s, and 1.9 m^3/s respectively, while the equivalent headloss is 0.2 kPa, 0.8 kPa, and 1.8 kPa respectively. These are insignificant magnitudes compared to the total amplitude of the oscillations.

The step-response tests show that the throttle enables more accurate control of the power output and reduces the time before steady-state conditions are restored in the system. This conclusion is valid for systems both with and without power feedback. Power feedback further increases the control of output power. The throttle results in reduced mass oscillation amplitudes but an increased water hammer amplitude. The power feedback further reduces the mass oscillation amplitudes, while the effect on the water hammer is negligible. For the configurations with no throttle, medium throttle, and strong throttle, the maximum water flow through the throttle in the step-response tests without power feedback is 17 m^3/s, 14 m^3/s, and 10 m^3/s, while the equivalent headloss is 8 kPa, 26 kPa, and 94 kPa respectively. The maximum water flow through the throttle in the step-response tests with speed and power feedback combined is 18 m^3/s, 16 m^3/s, and 10 m^3/s, while the equivalent headloss is 8 kPa, 31 kPa, and 94 kPa for configurations with no throttle, medium throttle, and strong throttle respectively. The analysis reveals that the effect of the throttle is stronger for systems with power feedback, as the mass oscillations and water flow through the throttle are increased.

In general, the research shows that a throttle reduces the mass oscillation amplitudes and increases the water hammer amplitudes. Even though the results demonstrate positive impacts of the throttle, there is a limit to how strong the throttling can be before the water hammer increases too much and the surge tank is decoupled from the hydraulic system [9].

VI. CONCLUSIONS

A new methodology for evaluation of the throttling effect on governing stability and performance is presented and demonstrated. The proposed methodology is regarded as an improvement to existing practice as it allows for direct solution of the governing equations without linearization. Furthermore, it allows for implementation of non-ideal discrete-time implemented governor systems, and a more transparent quantification of the throttle effect.

The methodology is demonstrated on an example hydropower plant. Based on frequency-response tests, it is concluded that the power plant gains an improved governor stability when a throttle is installed in the headrace surge tank. The stability increases with stronger throttling. The improvement is, however, insignificant for normal disturbances in the grid frequency, except for an improvement at the mass oscillation frequency.

The step-response tests demonstrate that the governor performance is improved by the throttle, considering control of the output power and the time before the system reaches steady state. This conclusion is valid for both the governor systems with speed feedback and with combined power and speed feedback. The improvement increases with stronger throttling. The mass oscillation amplitudes are reduced, but the water hammer amplitudes in front of the turbine increase with stronger throttling.

The step-response tests also demonstrate that power feedback increases the governor performance with regard to power control. Yet the power feedback does lengthen the time before steady-state conditions occur. The power feedback also has a minor negative effect on amplitudes of pressure in front of the turbine compared to a system with only speed feedback.

Design of surge tank throttling is performed relatively similar for different hydropower plants, and it assumed that surge tank throttling will have a positive impact on governing stability and performance for a wide range of hydropower plants.

ACKNOWLEDGMENTS

This work would not have been possible without the scientific cooperation via the Norwegian Research Center for Environmental Design of Renewable Energy (CEDREN). Wolfgang Richter is acknowledged for assistance during the manuscript preparation.

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Appendix B: Secondary Papers

This appendix presents a journal paper with work outside the main scope of this thesis and five published and presented conference papers. The full bibliographies and abstracts are presented.

SP1 Kaspar Vereide, Leif Lia and Lars Ødegård (2013). "Monte Carlo Simulation for Economic Analysis of Hydropower Pumped Storage Projects in Nepal." Hydro Nepal Journal of Water, Energy and Environment, 12, 39-44, DOI: dx.doi.org/10.3126/hn.v12i0.9031 (Open Access).

Abstract: Investments in hydropower pumped storage projects (PSP) are subjected to a high degree of uncertainty. In addition to normal uncertainties in hydropower schemes, the profit of a pumped storage scheme is dependent on the margin between power prices for buying and selling, which is difficult to predict without a power purchase agreement (PPA). A PSP without a PPA and without known construction costs requires quantification of the uncertainties in order to make qualified decisions before investing in such projects. This article demonstrates the advantages of using Monte Carlo (MC) simulations as a tool in the economic analysis of PSPs. The method has been tested on a case study, namely, the Tamakoshi-3 Hydropower Project (HPP) in Nepal. The MC method is used to calculate the probability distribution of the net present value of installing reversible units in the Tamakoshi-3 HPP. The calculations show that PSPs may be profitable in Nepal, given a beneficial development of the power market. The MC method is considered to be a useful tool for economic analysis of PSPs. In this case study of installing reversible units in the Tamakoshi-3 HPP, there are many uncertainties, which the MC simulation method is able to quantify.

SP2 Kaspar Vereide, Leif Lia and Torbjørn Nielsen (2014). "Physical Modelling of Hydropower Waterway with Air Cushion Surge Chamber." In: Hubert Chanson and Luke Toombes, Hydraulic Structures and Society - Engineering Challenges and Extremes. 5th IAHR International Symposium on Hydraulic Structures, Brisbane, Australia, 25-27 June 2014, DOI: 10.14264/uql.2014.28 (Open Access).

Abstract: The interest for new large hydropower pumped storage plants in Norway is increasing. Such large plants have massive hydraulic transients, and the surge chamber design have crucial impact. The air cushion surge chamber design is the preferred design for large hydropower plants in Norway since the 1970s, and new research is now initiated in order to further investigate the physical properties and optimum design of these constructions. A new physical model of a hydropower waterway with an air cushion surge chamber is currently under construction at the Norwegian University of Science and Technology. The model design is difficult owing to huge impact of atmospheric air pressure. This paper will present the model design, dimensional analysis and a comparison of numerical simulations of the model and field measurements from the prototype in order to test the model design. The model design is found to be feasible, and the construction works are initiated.

SP3 Kaspar Vereide, Leif Lia and Wolfgang Richter (2014). "Benefits of the Air Cushion Surge Chamber for Alpine Hydropower Plants." In: Christian Bauer and Eduard Doujak, Innovation and Development Needs for a Sustainable Growth of Hydropower (823-832). 18th International Seminar on Hydropower Plants, Vienna, Austria, 26-28 November 2014.
Abstract: Modern hydropower pumped storage projects (PSP) need to account for massive hydraulic transients owing to rapid and frequent switching between pumping mode and turbine mode. The surge chamber design is therefore of crucial importance in order to control and reduce the hydraulic transients. The air cushion surge chamber (ACC) is the most recent surge chamber design in Norway and is also successfully applied in China. The ACC has so far never been applied in alpine hydropower projects, and this paper discusses the potential benefits and challenges of ACCs in the Alps. It is concluded that the ACC may be more beneficial compared with conventional surge chambers for certain hydropower projects. It is however suggested that it should only be applied for projects where the benefits are high, owing to uncertainties regarding geology and storage of pressurized air in the tunnel system.

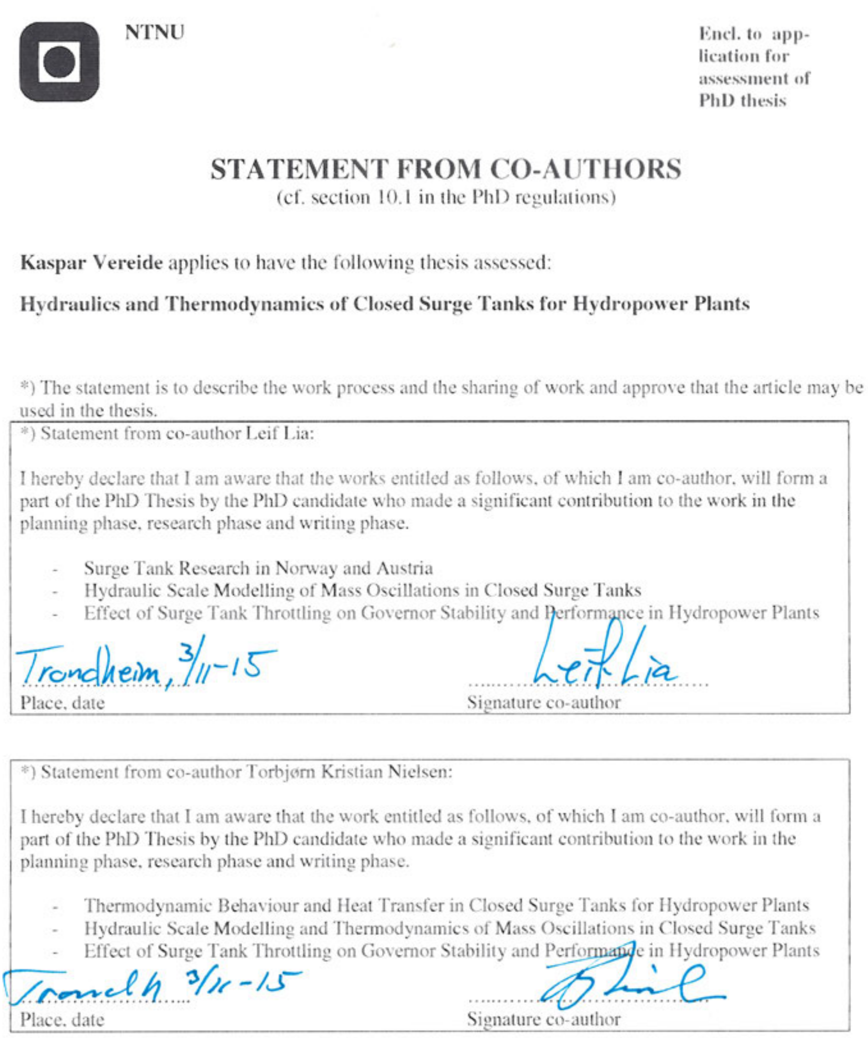
SP4 Wolfgang Richter, Kaspar Vereide, Josef Schneider, Helmut Knoblauch, Leif Lia and Gerald Zenz (2014). "Druckluftwasserschlösser für alpine Hochdruckwasserkraftanlagen." In: Robert Boes, Internationales Symposium Wasser- und Flussbau im Alpenraum, Band 1 (109-120). Internationales Symposium Wasser- und Flussbau im Alpenraum 2014, Zürich, Switzerland, 25-27 June 2014.
Abstract: This article provides a brief historical overview of the progress in high-head hydropower leading to the development of direct connection tunnels in Norway. Since the early 1970s, Air Cushion Chambers (ACCs) are applied successfully in Norwegian high-head hydropower plants, allowing for a direct tunnel connection between the upper reservoir and the power house. Inclined pressure tunnels are mainly constructed unlined owing to favorable rock stress conditions. For Alpine high-head hydropower plants, the hydraulic system has been established with slightly inclined low head sections from the reservoir, leading to an open air surge chamber and then connected through a steel lined pressure shaft to the power house. In this paper a comparison of both Alpine and Norwegian design approaches is described. The potentials and challenges of a possible use of ACCs for the Alpine or similar mountainous locations are presented. Owing to different conditions between the Alps and the hydropower plants in Norway, different requirements for the design and dimensioning of an ACC have to be considered. A use of ACCs can have positive results in terms of ecological and economic demands. An evaluation of these factors is given to highlight advantages and disadvantages of an adapted approach.

SP5 Wolfgang Richter, Kaspar Vereide, and Gerald Zenz (2015). "Hydraulic Design and Modelling of Large Surge Tanks." In: Arris S. Tjisseling, Pressure Surges 2015 (745-759). 12th International Conference on Pressure Surges, Fluid Transients and Water Hammer, Dublin, Ireland, 18-20 November 2015.
Abstract: This paper reflects recent developments and findings from surge tank research at TU Graz (Austria) and NTNU Trondheim (Norway) conducted by the authors. It will give a brief overview about surge tank design and milesteps of surge tank research in the past. An attention will be given on ongoing layout concepts for large surge tank design to cover future demands of optimized operation of flexible hydropower plants.

SP6 Kaspar Vereide, Bjørnar Svingen and Rolv Guddal (2015). "Case Study: Damaging Effects of Increasing the Installed Capacity in an Existing Hydropower Plant." In: Arris S. Tjisseling, Pressure Surges 2015 (745-759). 12th International Conference on Pressure Surges, Fluid Transients and Water Hammer, Dublin, Ireland, 18-20 November 2015.
Abstract: This paper presents a case study of the 960 MW Tonstad hydropower plant, in which the installed capacity was increased from 640 to 960 MW in 1988. In combination with installing new turbine governors, this upgrade resulted in several problems owing to higher water discharge and amplified hydraulic transients. Owing to high headloss, rapid change of produced power, or a combination of these, free surface flow occurred in a sand trap and flushed sand, gravel and rocks down into the turbines. In addition, high pressure on the downstream side of the reservoir intake gates is observed and has caused uncertainty regarding the structural safety of the gate frames and blades. These problems have resulted in restrictions on operation, and economical loss owing to repair and reduced power production revenue. In this work, the layout of the power plant and an analysis of the incidents are presented, and a discussion on how this situation could occur and how it can be avoided in other power plants is conducted. It is concluded that in hydropower plants with complex tunnel systems, very detailed studies are necessary to understand the hydraulic behavior and to foresee potential problems.

Appendix C: Co-Author Statements

This appendix holds the statements from the co-author confirming co-authorship and the contributions made by the PhD candidate.



NTNU

Encl. to application for assessment of PhD thesis

STATEMENT FROM CO-AUTHORS

(cf. section 10.1 in the PhD regulations)

Kaspar Vereide applies to have the following thesis assessed:

Hydraulics and Thermodynamics of Closed Surge Tanks for Hydropower Plants

*) The statement is to describe the work process and the sharing of work and approve that the article may be used in the thesis.

*) Statement from co-author Leif Lia:

I hereby declare that I am aware that the works entitled as follows, of which I am co-author, will form a part of the PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase and writing phase.

- Surge Tank Research in Norway and Austria
- Hydraulic Scale Modelling of Mass Oscillations in Closed Surge Tanks
- Effect of Surge Tank Throttling on Governor Stability and Performance in Hydropower Plants

Trondheim, 3/11-15
Place, date

Leif Lia
Signature co-author

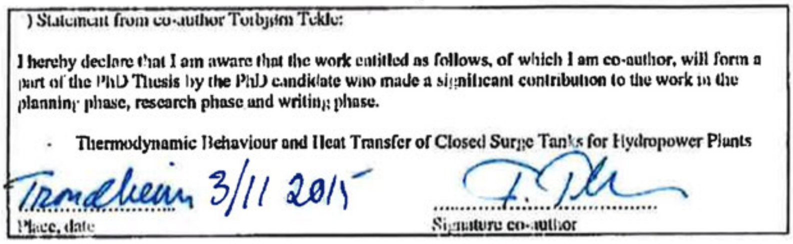
*) Statement from co-author Torbjørn Kristian Nielsen:

I hereby declare that I am aware that the work entitled as follows, of which I am co-author, will form a part of the PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase and writing phase.

- Thermodynamic Behaviour and Heat Transfer in Closed Surge Tanks for Hydropower Plants
- Hydraulic Scale Modelling and Thermodynamics of Mass Oscillations in Closed Surge Tanks
- Effect of Surge Tank Throttling on Governor Stability and Performance in Hydropower Plants

Trondh 3/11-15
Place, date

Signature co-author



) Statement from co-author Torbjørn Tekle:

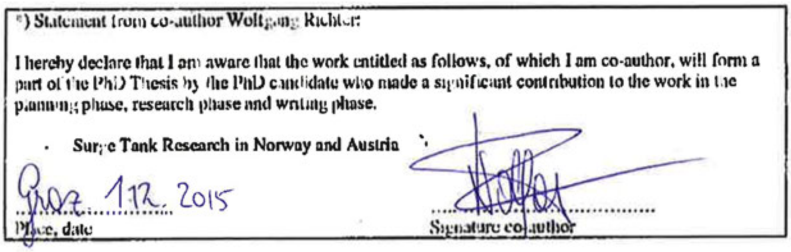
I hereby declare that I am aware that the work entitled as follows, of which I am co-author, will form a part of the PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase and writing phase.

- Thermodynamic Behaviour and Heat Transfer of Closed Surge Tanks for Hydropower Plants

Trondheim 3/11 2015

Place, date

Signature co-author



*) Statement from co-author Wolfgang Richter:

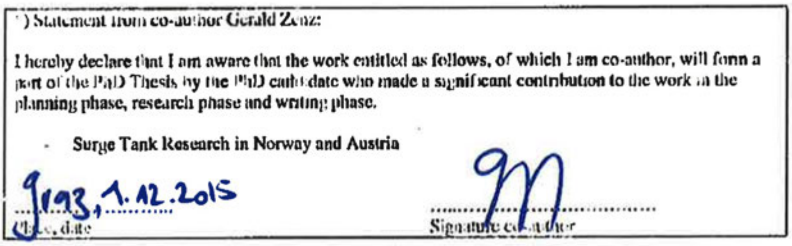
I hereby declare that I am aware that the work entitled as follows, of which I am co-author, will form a part of the PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase and writing phase.

- Surge Tank Research in Norway and Austria

Graz 1.12. 2015

Place, date

Signature co-author



) Statement from co-author Gerald Zenz:

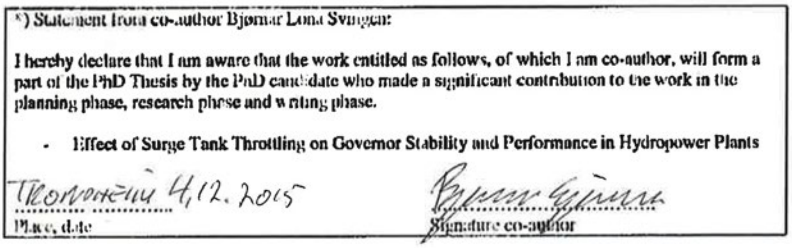
I hereby declare that I am aware that the work entitled as follows, of which I am co-author, will form a part of the PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase and writing phase.

- Surge Tank Research in Norway and Austria

Graz, 1.12.2015

Place, date

Signature co-author



*) Statement from co-author Bjørnar Lona Svingen:

I hereby declare that I am aware that the work entitled as follows, of which I am co-author, will form a part of the PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase and writing phase.

- Effect of Surge Tank Throttling on Governor Stability and Performance in Hydropower Plants

Trondheim 4,12. 2015

Place, date

Signature co-author