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).

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

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

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

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 ($\mathrm{R} = \mathrm{U}L/\upsilon$) 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

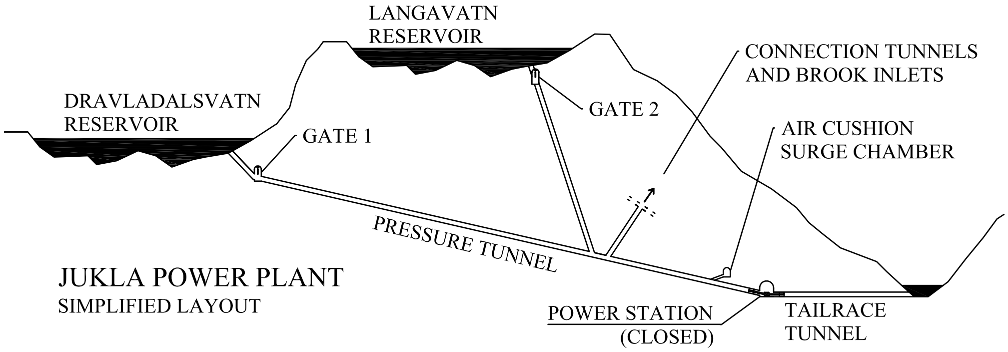

Fig. 1. Jukla power plant layout

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.

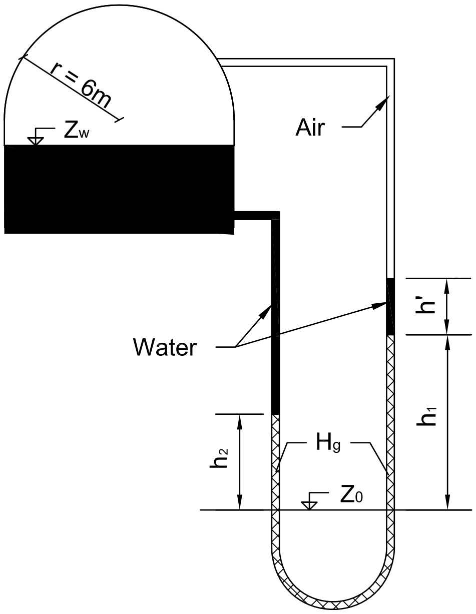

Fig. 2. Measurement principle

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

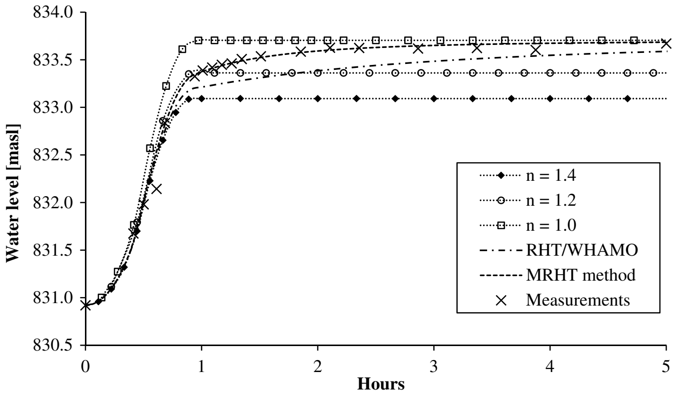

Fig. 3. Comparison of water level simulations and measurements

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.

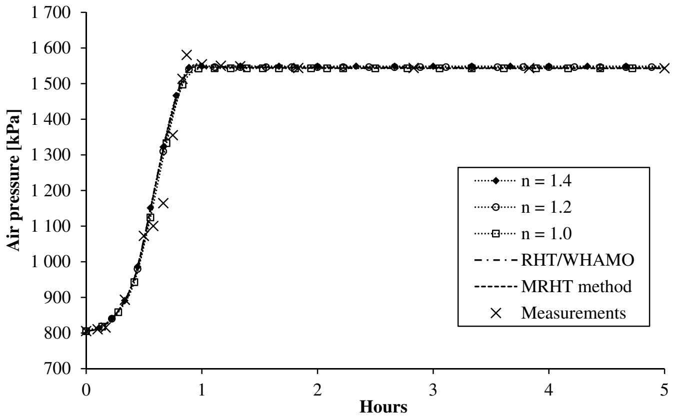

Fig. 4. Comparison of air pressure simulations and measurements

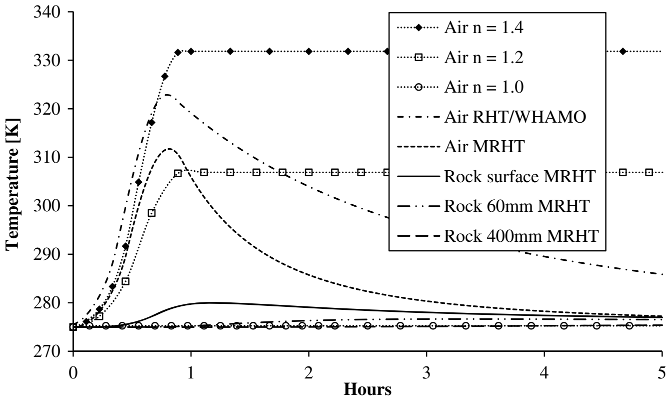

Fig. 5. Simulated temperature in air, rock, and water

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.

References

Bejan, A. (1993). *Heat transfer*, Wiley, New York.

De Martino, G., and Fontana, N. (2012). “Simplified approach for the optimal sizing of throttled air chambers.” *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000633, 1101–1109.

Goodall, D. C., Kjørholt, H., Tekle, T., and Broch, E. (1988). “Air cushion surge chambers for underground power plants.” *Water Power Dam Constr.*, 40(11), 29–34.

Graze, H. R. (1968). “A rational thermodynamic equation for air chamber design.” *3rd Australian Conf. on Hydraulics and Fluid Mechanics*, Institution of Engineers, Sydney, Australia.

Incropera, F. P., and Dewitt, D. P. (2007). *Fundamentals of heat and mass transfer*, Wiley, New York.

Joung, B. S., and Karney, B. W. (2009). “Systematic surge protection for worst-case transient loading in water distribution systems.” *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2009)135:3(218), 218–223.

LVTrans 1.7.11 [Computer software]. Trondheim, Norway, SINTEF.

Moran, M. J., Shapiro, H. N., Boettner, D. D., and Bailey, M. B. (2012). *Principles of engineering thermodynamics*, Wiley, New York.

Steward, E. H., and Borg, J. E. (1989). “Moose river air chamber design and performance.” *Conf. Proc., Waterpower’89*, U.S. Army Corps of Engineers, Buffalo District, NY, 567–576.

Svee, R. (1972). “Surge chamber with enclosed compressed air cushion.” *Proc., 1st Int. Conf. on Pressure Surges*, BHRA Fluid Engineering, Cranfield, England, 15–24.

Thorley, A. R. D. (2004). *Fluid transients in pipeline systems*, Professional Engineering, London.

U.S. Army Corps of Engineers. (1998). “Water hammer and mass oscillation (WHAMO) 3.0 user’s manual.” *USACERL ADP Rep. 98/129*, National Technical Information Service, Springfield, VA.

Wylie, E. B., and Streeter, V. L. (1993). *Fluid transients in systems*, Prentice Hall, New York.

Zhou, L., Liu, D., and Karney, B. (2013a). “Investigation of hydraulic transients of two entrapped air pockets in a water pipeline.” *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000750, 949–959.

Zhou, L., Liu, D., Karney, B., and Wang, P. (2013b). “Phenomenon of white mist in water rapidly filling pipeline with entrapped air pocket.” *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943–7900.0000765, 1041–1051.