Calculation of the Static Pressure Rise in the Hydropower Plant Penstock During Emergency Closing of the Flow

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Abstract: The paper presents an approach to calculate the static pressure rise upstream of a valve in a pressure penstock of a hydropower plant (HPP), i.e. a valve upstream of a turbine, during an emergency closure of the flow. The calculated value of the pressure rise is applied for the design of the appropriate time of the valve emergency closure in the HPP penstock and for the sizing of the various parts of the HPP (structural and mechanical). The basic theoretical background of the problem, calculation relations, the range of validity of the used calculation relations are explained and then the procedure applied to the solution of a specific task from practice is explained.

Keywords: *water hammer; static pressure rise, hydropower plant penstock; water turbine; emergency closing*

1 Introduction

It is a well-known fact that the magnitude of the static pressure rise upstream of the valve in a penstock (during valve closure) depends on the time of valve closure. At the same time, the magnitude of the maximum increase in static pressure decreases with increasing closure time. The total closing time is therefore an important parameter that influences a number of other technical parameters of the hydropower plant (HPP). With very short closure times of the valve in the penstock, the pressure increase upstream of the valve is too large and represents a potential safety risk due to the possible exceeding of the allowable stresses on the penstock and the associated mechanical and structural components of the HPP. In other words, both the structural and the mechanical components of the HPP must be oversized to be able to handle the considered maximum pressure increase in the penstock. Sizing the affected components of the HPP for too large additional load (due to a large increase in the static pressure in the penstock) may be technically infeasible under standard conditions, or it may represent a significant increase in investment costs. On the other hand, for larger closure times the pressure increase is smaller. Here, however, the very purpose of the emergency closing of the valve in the HPP penstock has to be taken into account.

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The need for emergency closing may occur in the event of a sudden machinery failure, or e.g. in the case of so-called energy-free operation of the turbine. This occurs when a grid failure becomes and the generator suddenly disconnects from the electrical grid, causing the turbine to operate without load. This results in an increase in the speed of the whole system up to the value of runaway speed, which in the case of Kaplan turbines can reach about 2.5 times the normal operating speed. Particularly in the case of high specific speed turbines with high operating speeds, the operation of the turbine at runaway speeds can cause significant loads on the entire turbine-generator assembly, particularly the bearings. In more detail, the issue of turbine runaway speed is discussed in the literature, e.g. in [7]. It is necessary to consider the maximum time of possible energy-free operation already at the project and design phase of the HPP and to ensure that all critical structural nodes are designed for the considered duration of energy-free operation at runaway speeds.

In the project, design and to some extent also in the implementation phase of the construction of a power plant, special attention must be paid to the planned safety and reliability of operation. However, the design and construction phase is not the only phase of the HPP life cycle where the safety and reliability of the HPP operation needs to be addressed. Studies investigating the actual operation of the HPP are equally important, as fault and outage-free power generation is highly important for HPP operators and, as experience has shown, problems can occur after years of use, e.g. due to operational wear of the materials.

Computational studies at specific design stages are aimed at safe and reliable operation, so all possible operational situations that may arise should be taken into account. Steady-state operation of the HPP is the safest condition because there are no changes in the hydraulic quantities in the system. However, if any of the hydraulic variables change during operation of the hydropower plant, steady-state operation is violated and the system state changes abruptly – so-called transients, which occur during the change from one steady state to another steady state. They can cause significant static pressure changes in the penstock. Excessively high pressures can lead to considerable physical damage. Damage to turbine parts, valves or the penstock can occur. This damage can in some cases cause environmental damage and also endanger human health and life.

The importance of precise handling of the pressure rise issue during emergency shutdown and subsequent strength analyses of individual structural or building nodes is documented by concrete examples from practice, where the neglect of a precise approach to this issue has led to the devastation of the HPP.

In the past, there have been more or less serious hydropower plant accidents, which have occurred for various reasons. In the accidents mentioned below, the turbine penstock was severely damaged due to the closing of the inlet valve too quickly or the neglect of the effects of ageing of the materials on the reduction of the maximum operating pressure.

In 1950, a catastrophic accident was recorded at HPP Oigawa (Japan). The penstock ruptured 14 years after commissioning due to the sudden closure of the inlet butterfly valve (Fig. 1.). The main cause of the accident described by Bonin [8] was insufficient safe throttle valve adjustment. This accident killed three employees, caused $500 million in damage and the loss of 90 GWh of electricity.

Fig. 1. Failure of the Oigawa (Japan) penstock in 1950 [9].

Another accident occurred in 1997 at the Lapino HPP after 70 years of operation. The steel penstock broke during the loading of only 50 % of the rated capacity during the acceptance tests of the new regulator (Fig. 2.). In this case, the rapid closing of the valve was set to approximately 2 s at 100 % stroke. The cause of this accident was identified by Adamkowski [9] as material fatigue and corrosion of the penstock after 70 years of operation. The fatigue and corrosion led to poor quality welded joints, which affected the MAWP (maximum allowable working pressure) parameter of the penstock. Insufficient reinforcement at points of high stress concentration also contributed to penstock failures.

Fig. 2. Failure of the penstock of the Lapino power plant (Poland) in 1997 [10].

2 Theoretical background

When closing the valve on a HPP penstock quickly, a so-called water hammer may occur. Several approaches can be taken to deal with water hammer. In practice, analytical computational procedures known from "classical" fluid mechanics are commonly used [1, 2]. The problem of water hammer is generally well known and is the subject of a relatively large number of papers, e.g. [3 – 6]. In general, a distinction is made between direct and indirect water hammer.

From the point of view of the occurrence of direct or indirect water hammer, the reflection time of the shock wave (T_r), which is determined according to (1). It depends on the length of the pipe (l) and the velocity of propagation of the pressure wave in the fluid (in the case of a HPP penstock in water v_v). The velocity v_v can be determined from (2) for the case of a flexible 'loose' pipe and water with real compressibility (elasticity). This depends on the volumetric elasticity modulus of the fluid (K), the density (ρ), the diameter of the pipe (d), the elasticity modulus of the pipe wall material (E) and the pipe wall thickness (s).

If the total closure time (T_f) is less than the shock wave reflection time (T_r), a so-called direct water hammer occurs, which causes a relatively high increase in static pressure (5) upstream of the closure and thus poses a rather large safety risk to both the structural and mechanical components of the HPP. In opposite case, if the total closure time (T_f) is longer than the reflection time of the shock wave (T_r), an indirect water hammer will occur, whereby with increasing closure time, the increase in static pressure in front of the valve (6) is smaller. The relationships (1) to (6) are explained in more detail in reference [1].

Table 1. Calculation relations used for pressure rise calculations in the penstock

Shock wave reflection time	[s]	$T_r = \frac{2 \cdot l}{v_v}$	(1)
Velocity of propagation of a pressure wave in a liquid	[m/s]	$v_v = \frac{\sqrt{\frac{K}{\rho}}}{\sqrt{1 + \frac{K \cdot d}{E \cdot s}}}$	(2)
Direct water hammer	[s]	$T_f \leq T_r$	(3)
Indirect water hammer	[s]	$T_f \gg T_r$	(4)
Direct impact pressure rise (in meters of water column)	[mH_2O]	$\Delta H = \frac{v_0 \cdot v_v}{g}$	(5)
Increase in indirect impact pressure (in meters of water column)	[mH_2O]	$\Delta H = \frac{v_0 \cdot v_v}{g} \cdot \frac{2 \cdot l}{v_v \cdot T_f}$	(6)

3 Calculation of pressure rise during emergency valve closing

In this paper, we present the calculation of the pressure rise in a penstock for a specific practical example. The calculation of the static pressure rise has been carried out for the case of closing the valve at the end of the HPP penstock (upstream of the turbine) according to the scheme in Fig. 3.

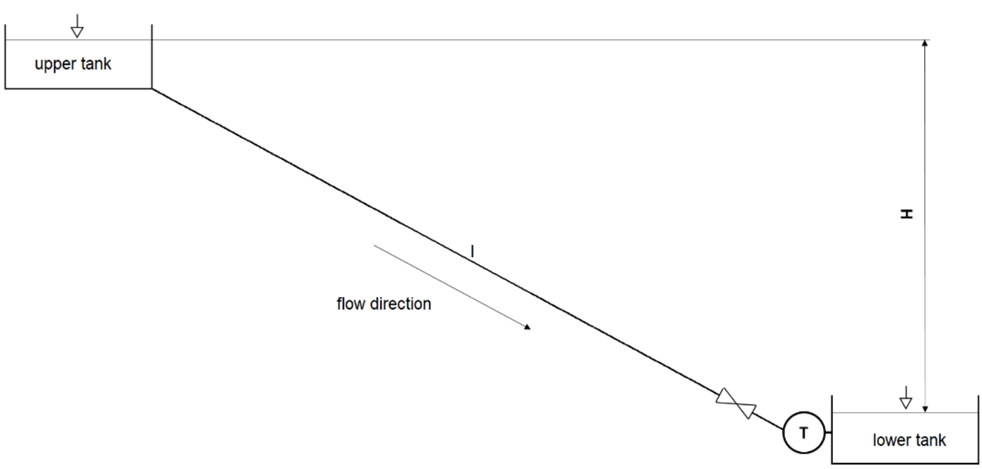

Fig. 3. Schematic of the model penstock of the hydropower plant.

The specific operational, geometrical and material parameters of the system are given in Table 2. Table 2 also lists the values of the pressure wave propagation velocity and the pressure wave reflection time, which determines the occurrence of either direct or indirect water hammer. The calculation of the pressure rise was first carried out for the case of very rapid (virtually instantaneous) closure of the valve ($T_f = 0.05\ s$), which is less than the value of the shock wave reflection time for the system ($T_r = 0.078\ s$) and hence in this case we speak of a direct water hammer. Subsequently, a series of calculations were carried out for several different closure times greater than the shock wave reflection time, corresponding to the indirect water hammer case.

The calculated pressure rise values were then compared (for the direct shock case they are in Table 3 and for the indirect shock case they are in Table 4). At the same time, the results of the indirect water hammer calculations for total closure times of 0.8 s to 30 s are processed graphically in Fig. 4. The obtained results can be used as a basis for an appropriate choice of the total valve closing time so that all the operational, technical and safety conditions mentioned in the introduction of this paper are respected.

Table 2. Parameters of the system on which the pressure rise calculation was performed.

Flow in the penstock	Q	m^3/s	8.02
Net power plant gradient	H	m	7.5
Pipe length	l	m	40
Pipe diameter	DN	m	2
Pipe wall thickness	s	mm	20
Outer diameter of the pipe	d_o	m	2.032
Inner diameter of the pipe	d	m	1.99
Water flow rate upstream of valve	v_0	m/s	2.6
Gravitational acceleration	g	m/s^2	9.81
Water density		kg/m^3	1000
Modulus of volumetric elasticity of water	K	Pa	2030000000
Modulus of elasticity of the pipe wall	E	Pa	220000000000
Pressure wave propagation speed	v_v	m/s	1028.51
Pressure wave reflection time	T_r	s	0.078

Table 3. Calculated values of static pressure rise – direct water hammer.

Closing time – direct water hammer	T_f	s	0.05
Increase in pressure - direct water hammer	Δp	kPa	2646.7
	ΔH	mH_2O	269.80

Table 4. Calculated values of static pressure rise for different valve closing times – indirect water hammer.

Closing time - indirect water hammer	T_f	s	0.8	1	2	3	4	5
Increase in pressure - indirect water hammer	Δp	kPa	257.3	205.9	102.9	68.6	51.5	41.2
	ΔH	mH_2O	26.23	20.99	10.49	7.0	5.25	4.2
Closing time – indirect water hammer	T_f	s	10	15	20	25	30	-
Increase in pressure - indirect water hammer	Δp	kPa	20.6	13.7	10.3	1	6.9	-
	ΔH	mH_2O	2.1	1.4	1.5	0.84	0.7	-

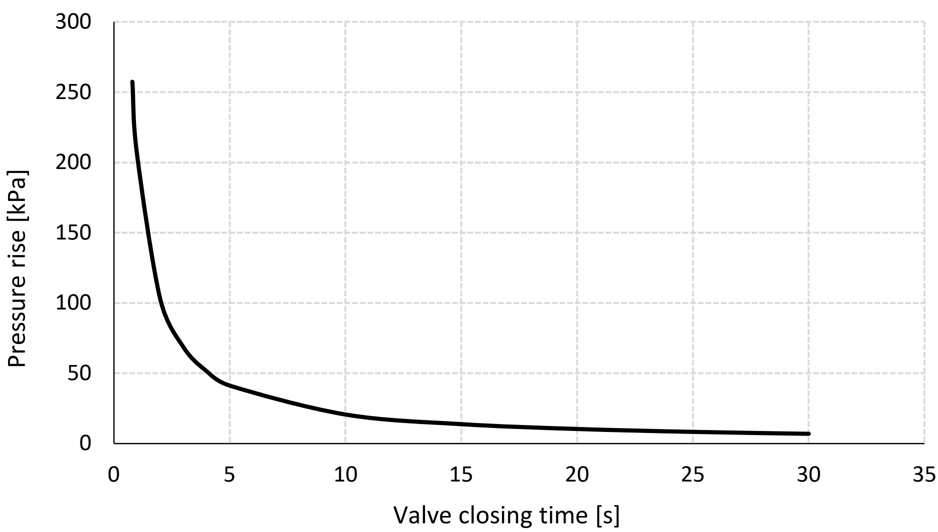

Fig. 4. Calculated dependence of static pressure rise upstream of valve as a function of closing time.

4 Conclusion

In this paper, we have explained the procedure of calculating the static pressure rise that occurs during the emergency closure of the valve at the end of the HPP penstock upstream of the turbine using a specific example. According to the results obtained, it is necessary to select a suitable value of the total time of the valve emergency closure so that the corresponding value of the static pressure increase is satisfactory from the point of view of safety, reliability of the equipment operation and from the point of view of mechanical stress on the machine parts and structural parts of the HPP. At the same time, the total closing time must not be too long so as not to prolong the duration of runaway speed in the case of energy-free operation of the turbine, which also poses a risk in terms of increased stress on the mechanical parts of the HPP (bearings, etc.). The specific value of the calculated pressure rise (for the selected shutdown time) is further used for the purposes of elasticity-strength analyses of individual parts of the structure, or for the purposes of dimensioning specific parts of the penstock and the valve upstream the turbine.

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