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Safe control of air cushion surge chambers in hydropower systems

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Abstract. This paper presents an effective theory for safe control of Air Cushion Surge Chambers (ACSCs) in hydropower systems. On the basis of the emergency pressures and heights of air in chambers, the acceptable limits of the monitoring parameters for three kinds of control mode are derived theoretically to control the air compressor. The prerequisites for each control mode are determined by considering air leakage and the solution. By analyzing these prerequisites, the selection criteria are established to determine the appropriate control mode for a practical hydropower system with ACSC. According to the presented control scheme, the air compressor need not be actuated for any variation in air temperature, and the operating conditions of the hydropower system need not be considered for safe control of ACSCs. Those are favorable for the safety and economy of the hydropower plant. To detail and validate the derived limits and selection criteria for different control modes, the safe control theory is applied to the practical hydropower plant, and a graphic analysis is conducted on the basis of the perfect gas law and the relationship of the initial steady-state pressure and height of the enclosed air in the chambers.

1. Introduction

A surge chamber is usually constructed to reduce the amplitude of pressure fluctuations by reflecting incoming pressure waves and improving the regulating characteristics of a hydraulic turbine. It acts as storage for excess water during load reduction and provides water during load acceptance in hydroelectric power plants [1]. As a typical surge chamber, an Air Cushion Surge Chamber (ACSC), having enclosed air in its top and liquid in its lower part, is a commonly used surge-control device in hydropower systems [1,2]. In general, the controllers, comprising an air compressor and an exhaust valve, are used to supply and reduce the compressed air for an ACSC [1,2].

The initial steady-state volume of the air has direct effects on transient-state pressures in tunnels and water surface oscillations in ACSCs [1,2]. It also influences the stability of ACSCs, which has been investigated by Svee [3], Chaudhry et al. [4], and Yang et al. [5]. Therefore, there must be adequate air in the chambers to satisfy the stability of ACSCs, and to avoid overpressure of the tunnels [1-4]. Furthermore, there must be enough water in the chambers to prevent air from entering the tunnels [1,2]. With these considerations, the emergency levels in the chamber are required to be determined for safety. The objective of safe control of ACSCs is to keep the steady-state water level in chambers within emergency limits by actuating the controllers.

One of the key issues for safe control is the determination of the emergency l evels. It can be attained by a detailed transient analysis using the Method Of Characteristics (MOC) [6,7] and Computational Fluid Dynamics (CFD) [8-11]. During this analysis, an empirical polytropic relationship is commonly utilized for modeling the thermodynamic behavior of

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the enclosed air [12]. It has good performance on predictions of extremes of transient-state pressures and volume of air [13,14]. By using the MOC with the polytropic process, Zhang et al. [15] studied the effects of the initial steady-state volume of the air on water surface oscillations in ACSCs, and presented the critical operating conditions for the emergency levels.

The other key issue is to control the actuation of the air compressor and exhaust valve. There are three kinds of control mode corresponding to different monitoring systems and parameters, namely:

1. PV/T control mode;
2. PV control mode;
3. Water level control mode [16].

The monitoring parameters in the PV/T control mode are the initial steady-state pressure, volume and temperature of the compressed air. These parameters, except the air temperature, are monitored in the PV control mode. In the water level control mode, just the water level in the chamber is monitored [16,17]. The acceptable limits of the monitoring parameters for different control modes are usually determined to actuate the controllers. The lower acceptable limit is used to control the start-up of the air compressor, and the upper acceptable limit is used to open the exhaust valve [16]. For safety of an actual installation, the hydropower plant is shut down automatically prior to the actuation of the controllers [1]. It means the excessive power shutdown is very unsafe and uneconomical for hydropower systems [1,2], so, frequent actuation of the controllers should be avoided.

Gu et al. [16] summarized the operating experiences in Norwegian hydropower engineering with ACSCs, detailed the monitoring systems, and introduced the safe control of many actual ACSCs. In this investigation, the emergency levels and pressures were calculated using the MOC, and used to actuate the controllers. The critical operating conditions for determining the emergency levels were presented as the same as those by Zhang et al. [15]. Nevertheless, the conditions for actuating the controllers were given in the form of data, and could not be applied to other hydropower plants. The effect of air temperature on the monitoring parameters was not considered in that study. Moreover, Gu et al. [16] focused on the introduction of control modes, but rarely on their selection criteria.

In fact, according to the perfect gas law [18], excessive variation of air temperature may result in monitoring parameters exceeding their acceptable limits. In this case, the controllers have to be actuated frequently, and the hydropower plant must be shut down in advance. It is very unsafe and uneconomical for hydropower systems, and should be avoided. With these considerations, the objectives of the present study are to derive, theoretically, the acceptable limits of the monitoring parameters for actuating the controllers by considering the effect of air temperature, and to establish the selection criteria of the control modes.

2. Emergency pressures and heights of the enclosed air

For an ACSC with a constant horizontal cross-sectional area, F, the monitoring of the volume of air is equivalent to that of air height, L_{a0}, in the chamber. Assuming the air enclosed at the top of the ACSC follows the perfect gas law, i.e:

$$\frac{H_{a0}.L_{a0}}{T_{a0}} = \frac{m^* R}{\gamma F} = C, \tag{1}$$

in which H_{a0} and L_{a0} are the initial steady-state absolute pressure head and height of air, respectively. T_{a0} is air temperature, and its maximum and minimum values, $[T_{a0}]_{\max}$ and $[T_{a0}]_{\min}$ are known as basic data. γ is the specific weight of water, m^* is the mass of air, R is the universal gas constant, and C is a constant whose value is determined by air mass and monitored in PV/T control mode. In steady state, it follows from the dynamic equation that:

$$H_{a0} = Z_u + H_b - h_{\omega 0} - (Z_t - L_{a0}), \tag{2}$$

in which Z_u and Z_t are the heights of the water surface in the upstream reservoir and the roof of the ACSC above the datum zero, H_b is the barometric pressure head, and $h_{\omega 0}$ is the head losses in the tunnel.

By using a trial-and-error procedure and the MOC, the emergency levels in the chamber, $Z_{0\,\max}$ and $Z_{0\,\min}$ (i.e., the emergency heights of the air, $[L_{a0}]_{\min}$ and $[L_{a0}]_{\max}$), and the corresponding extremes of air pressure, $[H_{a0}]_{\min}$ and $[H_{a0}]_{\max}$, can be determined by transient analysis, as shown in Figure 1. To facilitate the analysis, the emergency pressure and height of the enclosed air can be integrated as their products, i.e. $[H_{a0}.L_{a0}]_{\min}$ and $[H_{a0}.L_{a0}]_{\max}$. In general, the value

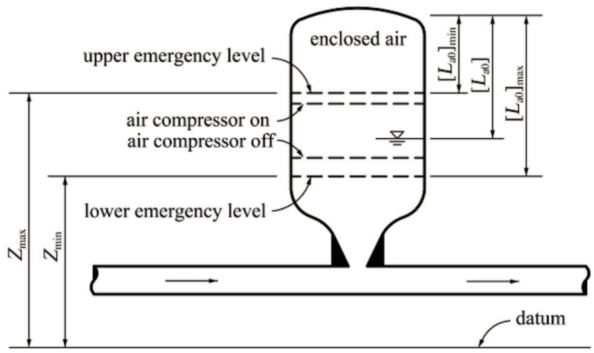

Figure 1. Air cushion surge chamber.

of $[H_{a0}.L_{a0}]_{\min}$ depends on the maximum prescribed pressure of the tunnel and the critical stability area, namely, the Svee area. The value of $[H_{a0}.L_{a0}]_{\max}$ relies on the prescribed safety water depth in the surge chamber. Therefore, the following condition must be satisfied for hydropower systems with ACSCs, i.e:

$$[H_{a0}.L_{a0}]_{\min} \leq [H_{a0}.L_{a0}] \leq [H_{a0}.L_{a0}]_{\max}, \tag{3}$$

in which $[H_{a0}.L_{a0}]_{\min}$ and $[H_{a0}.L_{a0}]_{\max}$ are the lower and upper emergency pressure and height of enclosed air, respectively. According to Eqs. (1) and (2), the effects of the operating conditions and the upstream reservoir level on the steady-state pressure and height of the air need not be considered for satisfying the requirement of Eq. (3).

3. Control scheme of the air compressor and the exhaust valve

Eq. (1) indicates that the product of the pressure and height of the air, $[H_{a0}.L_{a0}]$, changes with air temperature. The variation of air temperature may cause the value of $[H_{a0}.L_{a0}]$ to exceed its emergency limits, and then result in the frequent actuation of the controllers. To avoid that, the acceptable limits of the monitoring parameters should be determined to actuate the controllers by considering the effect of air temperature.

For PV/T control mode, the value of C is monitored. By substituting $[T_{a0}]_{\min}, [T_{a0}]_{\max}$ and the condition:

$$[H_{a0}, L_{a0}]_{\min} \leq [H_{a0}, L_{a0}] \leq [H_{a0}, L_{a0}]_{\max},$$

into Eq. (1), the lower and upper acceptable limits of C are:

$$[C]_{\text{on}} = \frac{[H_{a0}.L_{a0}]_{\min}}{[T_{a0}]_{\min}}, \tag{4}$$

$$[C]_{\text{off}} = \frac{[H_{a0}.L_{a0}]_{\max}}{[T_{a0}]_{\max}}, \tag{5}$$

respectively. When the value of C reaches $[C]_{\text{on}}$ in steady state, the hydropower plant is shut down, and the air compressor then starts up to supply air. When the value of C increases to $[C]_{\text{off}}$ in the air supply, the air compressor stops. After that, the exhaust valve should open to ensure the value of C within acceptable limits.

For PV control mode, T_{a0} and C are unknown. To prevent the controls actuating due to the variation of air temperature, the conditions $[H_{a0}.L_{a0}].[T_{a0}]_{\min}/T_{a0} \geq [H_{a0}, L_{a0}]_{\min}$, and $[H_{a0}.L_{a0}].[T_{a0}]_{\max}/T_{a0} \geq [H_{a0}, L_{a0}]_{\max}$ must be satisfied at any air temperature. Hence:

$$[H_{a0}L_{a0}]_{\text{on}} = \frac{[H_{a0}.L_{a0}]_{\min}}{[T_{a0}]_{\min}}[T_{a0}]_{\max}, \tag{6}$$

$$[H_{a0}L_{a0}]_{\text{off}} = \frac{[H_{a0}.L_{a0}]_{\max}}{[T_{a0}]_{\max}}[T_{a0}]_{\min}. \tag{7}$$

$[H_{a0}.L_{a0}]_{\text{on}}$ and $[H_{a0}.L_{a0}]_{\text{off}}$ are, respectively, lower and upper acceptable limits. In this kind of control mode, the air compressor starts up to supply air at $[H_{a0}.L_{a0}] = [H_{a0}.L_{a0}]_{\text{on}}$ and then stops at $[H_{a0}.L_{a0}] = [H_{a0}.L_{a0}]_{\text{off}}$. After the air compressor stops, the exhaust valve opens to keep the value of $[H_{a0}.L_{a0}]$ within acceptable limits. Because of the misoperation of the controllers, the values of the monitored variables in PV/T and PV control modes may be more than their upper acceptable limits. In these case, the exhaust valve opening is unavoidable and could be conducted at $[H_{a0}.L_{a0}] = [H_{a0}.L_{a0}]_{\max}$ to reduce the air volume.

For the water level control mode, the pressure of the enclosed air is unknown, so the operating conditions and the upstream reservoir level should be known for determining the steady-state pressure of the air to keep the value of $[H_{a0}.L_{a0}]$ within its emergency limits. It is complicated to control the actuation of the air compressor and the exhaust valve. Moreover, the effect of the air temperature must be considered as well. Hence, for the water level control mode, the following control scheme could be adopted by substitution of Eq. (2) into Eqs. (6) and (7), and elimination of H_{a0} from the resulting equation, by considering the extreme levels in the upstream reservoir, so that:

$$[L_{a0}]_{\text{on}} = \frac{1}{2}\sqrt{{z_{b\min}}^2 + 4[T_{a0}]_{\max}[H_{a0}.L_{a0}]_{\min}/[T_{a0}]_{\min}} - \frac{1}{2}z_{b\min}, \tag{8}$$

$$[L_{a0}]_{\text{off}} = \frac{1}{2}\sqrt{{z_{bs\max}}^2 + 4[T_{a0}]_{\min}[H_{a0}.L_{a0}]_{\max}/[T_{a0}]_{\max}} - \frac{1}{2}z_{bs\max}, \tag{9}$$

$$[L_{a0}]_{V\text{off}} = \frac{1}{2}\sqrt{{z_{b\min}}^2 + 4[H_{a0}.L_{a0}]_{\max}} - \frac{1}{2}z_{b\min}, \tag{10}$$

where:

$$z_{b\min} = Z_{u\min} + H_b - h_{\omega 0} - Z_t,$$

$$z_{bs\max} = Z_{u\max} + H_b - Z_t,$$

and $[L_{a0}]_{\text{on}}$ and $[L_{a0}]_{\text{off}}$ are the lower and upper acceptable limits, respectively, for this kind of control mode. The air compressor starts up at $L_{a0} = [L_{a0}]_{\text{on}}$, and then stops at $L_{a0} = [L_{a0}]_{\text{off}}$. The exhaust valve opens to adjust the air volume after the air compressor stops. The hydropower plant is shutdown during air supply, so, $h_{\omega 0} = 0$ for determining the upper acceptable limit, $[L_{a0}]_{\text{off}}$. If the value of L_{a0} is more than $[L_{a0}]_{\text{off}}$ due to the misoperation of the controllers, then the exhaust valve must open at the upper emergency air height $[L_{a0}]_{v\text{off}}$. When the air compressor and exhaust valve are controlled by acceptable limits in different control modes, the variations of air temperature and the upstream reservoir level would not result in a power shutdown of the hydropower plant. However, as the air volume may be reduced due to leakage and solution, the controllers have to be actuated at a scheduled time interval. To lengthen this time interval, the air volume in ACSCs should be as much as possible. Therefore, the critical value of the monitoring parameter corresponding to stopping the air compressor in each control mode is considered to be the upper limit rather than other values within acceptable limits.

4. Selection of control modes

The upper acceptable limit must be more than the lower to ensure validity of formulation and corresponding results. Hence, for adoption of the PV/T control mode, the following condition is derived by Eqs. (4) and (5), i.e:

$$\frac{[H_{a0}.L_{a0}]_{\min}}{[H_{a0}.L_{a0}]_{\max}} < \frac{[T_{a0}]_{\min}}{[T_{a0}]_{\max}}. \tag{11}$$

For the PV control mode, it follows from Eqs. (6) and (7) that:

$$\frac{[H_{a0}.L_{a0}]_{\min}}{[H_{a0}.L_{a0}]_{\max}} < \frac{[T_{a0}]^2_{\min}}{[T_{a0}]^2_{\max}}. \tag{12}$$

For the water level control mode, besides the condition determined by Eq. (12), the following condition from Eqs. (8) and (9) should be satisfied, i.e:

$$Z_{u\max} < Z_{u\min} + \frac{1}{2}\left(\frac{[H_{a0}.L_{a0}]_{\max}[T_{a0}]^2_{\min}}{[H_{a0}.L_{a0}]_{\min}[T_{a0}]^2_{\max}} - 1\right) \cdot\sqrt{z^2_{bs\min} + 4\frac{[T_{a0}]_{\max}}{[T_{a0}]_{\min}}[H_{a0}.L_{a0}]_{\min}} + z_{bs\min}, \tag{13}$$

where $z_{bs\min} = Z_{u\min} + H_b - Z_t$.

In addition, as the air volume may be reduced due to leakage and solution, a scheduled time interval, T_{as}, for air supply is required as a design parameter for an actual ACSC. The approximate rate of air volume reduction, Q_{aw}, for leakage and solution could be estimated by corresponding experiments and formulae [19,20]. It varies for the different pressure and temperature of the air. To meet the requirement of the scheduled time interval, the minimum reduction of the value of C from the stop to the next start-up of the air compressor should be more than the maximum reduction of $C, [\Delta C]_{\max}$, due to leakage and solution. Here, $[\Delta C]_{\max}$ can be obtained by substituting T_{as}, $[T_{a0}]_{\max}$, $[H_{a0}]_{\max}$, and the corresponding value of Q_{aw} into Eq. (1) for safety.

With these considerations, it follows from Eqs. (4) and (5) for the PV/T control mode that:

$$[\Delta C]_{\max} \le \frac{[H_{a0}L_{a0}]_{\max}}{[T_{a0}]_{\max}} - \frac{[H_{a0}L_{a0}]_{\min}}{[T_{a0}]_{\min}}. \tag{14}$$

For the PV control mode, the reduction of the value of C changes with the air temperature. Hence, the following condition from Eqs. (6) and (7) yields:

$$[\Delta C]_{\max} \le \frac{[H_{a0}L_{a0}]_{\max}[T_{a0}]_{\min}}{[T_{a0}]^2_{\max}} - \frac{[H_{a0}L_{a0}]_{\min}[T_{a0}]_{\max}}{[T_{a0}]^2_{\min}}. \tag{15}$$

For the water level control mode, the effects of air temperature and the upstream reservoir level on the reduction in the value of C should be considered. Thus, the following condition determined by Eqs. (8) and (9) should be satisfied that:

$$[\Delta C]_{\max} \le \frac{[H_{a0}L_{a0}]_{\max}[T_{a0}]_{\min}(z_{bs\min} + [L_{a0}]_{\text{off}})}{[T_{a0}]^2_{\max}(z_{bs\max} + [L_{a0}]_{\text{off}})} - \frac{[H_{a0}L_{a0}]_{\min}[T_{a0}]_{\max}(z_{b\max} + [L_{a0}]_{\text{on}}}{[T_{a0}]^2_{\min}(z_{b\min} + [L_{a0}]_{\text{on}})}, \tag{16}$$

where $z_{b\max} = Z_{u\max} + H_b - h_{\omega 0} - Z_t$.

When the PV/T control mode is used in practical engineering, the conditions determined by Eqs. (11) and (14) must be satisfied. The prerequisites for adopting the PV control mode are determined by Eqs. (12) and (15). The prerequisites from Eqs. (12), (13) and (16) must be satisfied for the practical application of the water level control mode. The prerequisites of the PV/T control mode would be achieved easily. However, the monitoring system in this kind of control mode is the most complicated, and expensive. In contrast, the practicability of the water level control mode is restricted by the variations of air temperature and upstream reservoir levels. The prerequisites of this kind of control mode are the most difficult to be satisfied, but the monitoring system is the most simple and reliable. As the selection criteria, these prerequisites and comparisons of the monitoring

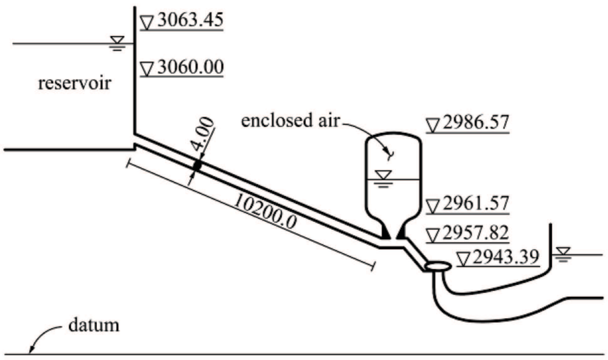

Figure 2. Schematic illustration of the hydropower plant.

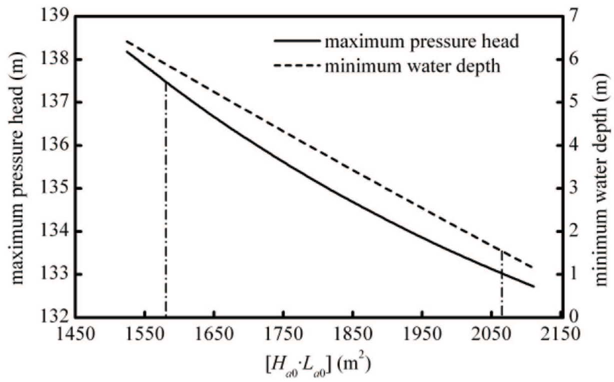

Figure 3. The effects of the initial steady-state pressure and height of the air on the maximum transient-state pressure head, $H_{\max}$, in the tunnel and the minimum transient-state water depth, $h_{\min}$, in the ACSC.

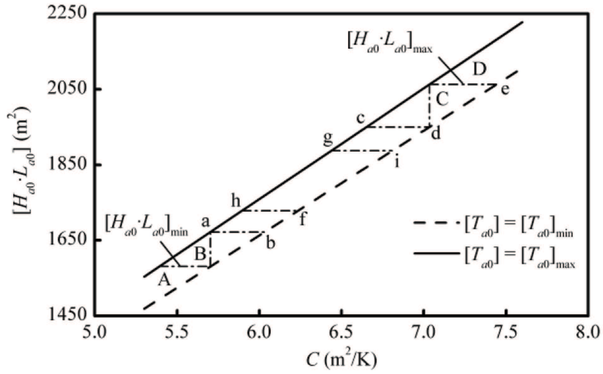

Figure 4. The variation of the initial steady-state pressure and height of the air with the value of C for the maximum and minimum air temperature.

systems for different control modes could be used to determine the appropriate control mode for practical hydropower systems with ACSCs.

5. Application and graphic analysis

As shown in Figure 2, the safe control theory is applied to the practical hydropower plant, which consists of three units with a rated capacity of 10.89 MW per unit, rated head of 105.00 m, rated flow of 12.00 m^3/s, and rated speed of 500.00 rpm. The maximum and minimum water levels in the upstream reservoir are 3063.45 m and 3060.00 m, respectively. The maximum and minimum water levels in the downstream reservoir are 2950.00 m and 2946.15 m, respectively. The horizontal cross-sectional area of the ACSC is 600.00 m^2. The prescribed safety factor, n, for stability is 1.25, and the horizontal cross-sectional area of the ACSC should be n times the Svee area at least. The prescribed maximum transient-state pressure in the tunnel is 137.5 m. The prescribed safety water depth in the ACSC is 1.5 m. The variation range of the air temperature is 277.15-293.15 K. The rate of air volume reduction at the air temperature of 293.15 K and pressure head of 100.0 m is 0.277 m^3/h. The scheduled time interval between air supplies is 150.00 days.

To determine the value of $[H_{a0}.L_{a0}]_{\min}$ and $[H_{a0}.L_{a0}]_{\max}$ transient analyses are carried out using the method of characteristics. The critical operating condition for the maximum pressure head $H_{\max}$, in the tunnel is full-load rejection at $Z_u = Z_{u\max}$, $Z_d = Z_{d\min}$, and $m = 1.4$. The critical operating condition for the minimum water depth, $h_{\min}$, in the ACSC is the permissible maximum load acceptance (i.e., 21.78 MW) at $Z_u = Z_{u\min}$, $Z_d = Z_{d\max}$, and $m = 1.0$. Figure 3 shows the effect of the value of $[H_{a0}L_{a0}]$ on $H_{\max}$ and $h_{\min}$ for these cases. It is observed from this figure that $[H_{a0}.L_{a0}]_{\min} = 1580.59$ m^2, and $[H_{a0}.L_{a0}]_{\max} = 2062.39$ m^2. Moreover, the stability of the ACSC is satisfied and the safety factor is 1.28.

According to Eq. (1), Figure 4 illustrates the relationship between the values of $[C]$ and $[H_{a0}.L_{a0}]$ for the extreme of air temperature. It is clear that in regions A, B, C and D, the value of $[H_{a0}.L_{a0}]$ may exceed the emergency limits due to the variations of air temperature. Therefore, for PV/T and PV control modes, the initial steady-state values of $[C]$ and $[H_{a0}.L_{a0}]$ must be more than those values at point a, and less than those values at point d, respectively. For the PV control mode, $[\Delta C]_{\min}$ is the difference between the values of C at points c and b. It can be seen from this figure that $[\Delta C]_{\min}$ for the PV/T control mode is more than that for the PV control mode. If there is excessive air in the ACSC due to the misoperation of the controls, then the exhaust valve must open at the value of $[H_{a0}L_{a0}]$ at point e.

According to Eq. (2), Figure 5 shows the variation of $[H_{a0}.L_{a0}]$with the air height for steady state and power shutdown. This figure indicates the effect of the upstream reservoir level on the value of $[H_{a0}.L_{a0}]$. Considering the effect of air temperature, $[H_{a0}.L_{a0}]$ should be kept within the limits, which is determined by those values at points a and d in Figure 5. Therefore, for the water level control mode, the value of L_{a0} should

Table 1. Actuations of the controls and selection of control modes

	***PV/T* control mode**	***PV* control mode**	**Water level control mode**
Monitored variable	$[C]$, (m^2/K)	$[H_{a0}L_{a0}]$, (m^2)	$[L_{a0}]$, (m)
Air compressor on	5.70	1671.84	17.14
Air compressor off[a]	7.04	1949.83	20.37
Exhaust valve on[b]	7.04	2062.93	20.46
$[\Delta C]_{\min}$	1.34	0.61	0.19

[a]: Corresponding to power shutdown, and opening the exhaust valve to adjust the air volume.

[b]: Corresponding to misoperation of the controls.

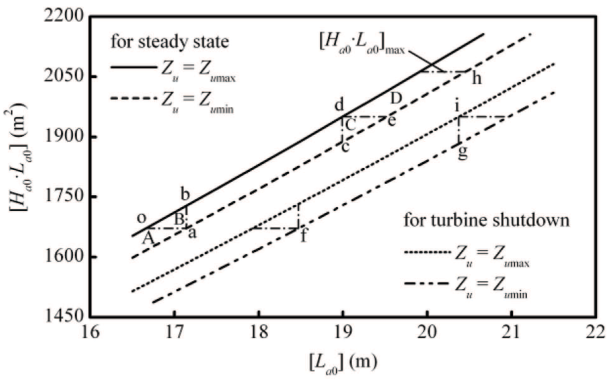

Figure 5. The relationship of the initial steady-state pressure $[H_{a0}]$ and height $[L_{a0}]$ of the air in steady state and power shutdown for the maximum and minimum water levels of upstream reservoir.

be more than that at point a, and less than that at point d. If $[L_{a0}]$ is more than that at point d, due to misoperation of the controls, then the exhaust valve must open at the emergency air height (point g in Figure 5). For power shutdown, the upper and lower limits of L_{a0} are determined by those values at points f and g, respectively. Thus, when the air compressor stops, the minimum value of $[H_{a0}.L_{a0}]$ is its value at point f. The maximum value of $[H_{a0}.L_{a0}]$ for the start-up of the air compressor is its value at point b. The $[\Delta C]_{\min}$ for the water level control mode is the difference between the values of C at points g and f in Figure 4. It is clear that the $[\Delta C]_{\min}$ for the PV control mode is more than that for the water level control mode.

Table 1 lists the graphic results for different control modes. The data in this table are the same as the results from Eqs. (4) through (10), and Eqs. (14) through (16). The maximum permissible reduction in air mass $[\Delta C]_{cr}$ during time interval T_{as} (due to air leakage and solution) is 0.57 m^2/K. It can be observed from this table that the prerequisites for adopting PV/T and PV control modes are satisfied. For the water level control mode, the conditions determined by Eqs. (12) and (13) are satisfied. However, the condition determined by Eq. (16) is not satisfied, because $[\Delta C]_{cr} > [\Delta C]_{\min}$. Consequently, PV/T and PV control modes can be used, and the PV control mode is preferred for this hydropower system.

6. Conclusion

The safe control of ACSCs in hydropower systems has been investigated in this paper. The start-up and stop of the air compressor and exhaust valve are controlled by the acceptable limits of the monitoring parameters. According to that, actuation of the controllers would not be affected by variations of air temperature and the upstream reservoir level. For an actual installation, as the air volume may be reduced due to leakage and solution, the air compressor has to start up at a scheduled time interval. The actuation of the controllers, due to this reduction, is considered by the prerequisites for using every control mode. The prerequisites of the PV/T control mode are achieved easily, but the monitoring system in this kind of control mode is the most complex, and expensive. In contrast, the practicability of the water level control mode is restricted by the variations of air temperature and upstream reservoir levels, but the monitoring system in this kind of control mode is the most simple and reliable. The presented theory for safe control of ACSCs can be used to control the actuation of the air compressor and the exhaust valve, and to choose the appropriate control mode for practical hydropower systems with ACSCs.

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