AIR ENTRAINMENT DUE TO VORTICES – STATE-OF-THE-ART

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Abstract

A major design criterion of intakes has usually been to avoid air entrainment by vortices . This paper gives a review of intake vortices research regarding the quantification of entrained air. Only four publications dealing with air entrainment were found in a literature review. However, no useful information is provided to quantify the air entrainment. A correlation with essential flow parameters is missing. In a large number of publications the term "air entraining vortices" is used, but no information is given regarding air entrainment. The present paper further describes the consequences of air being entrained into a pressure system. It is discussed how the knowledge of the air entrainment rate could be used for a new design concept improving the safety, durability and efficiency of hydropower waterways. Two general measures are emphasized: (1) the common way to avoid air entrainment completely, and (2) a new approach to allow air entrainment. A large-scale model has been built at VAW of ETH Zurich and tests to quantify the air entrainment rate due to intake vortices are currently conducted. Moreover, the physical processes of air transport mechanism in the air core and bubble separation from the air core to a pressure pipe system have been analyzed. The velocity field of an intake vortex is measured by 2D Particle Image Velocimetry (PIV). The results will allow correlating the air entrainment rate to the leading hydraulic parameters, e.g. the circulation of a vortex.

Introduction

Air entrainment into power waterways usually takes place either at hydraulic jumps in tunnels, at drop shafts or by vortices at intake structures. The latter phenomenon occurs at any intake in different forms and is usually the leading entrainment mechanism. Particularly strong vortices have considerable potential for air entrainment. The occurrence of vortices is thus a major problem for the design, retrofitting and operation of water intakes. Almost one hundred years of research has led to a large number of publications regarding intake vortices. Vortices are present in many natural and technological states (Lugt, 1983). Vortices at intakes can be characterized by different vortex-types and vortical flows, respectively. In principle, an intake vortex is an idealized big single free potential surface vortex as shown in Figure 1. The direction of rotation is clockwise as could be expected for the Southern Hemisphere. Appearances are deceptive. Binnie (1964) and Trefethen et al. (1965) have proved the evidence of the influence of the Coriolis effect by extensive experiments on both the Northern and the Southern Hemisphere. The direction of rotation depends merely on the properties of the approach flow. The influence of the Coriolis force on the radial velocity of a vortex is 3×10^7 times smaller than that due to gravity (Shapiro, 1962).

Statements about the length of the air core and about air entrainment into the intake are often not possible from prototype observations, as the accessibility is limited as opposed to model investigations.

Figure 1: The intake vortex turns clockwise during the emptying through the diversion tunnel (diameter = 7.6 m) at Lake Arapuni (New Zealand). The tunnel submergence was about 21 m (Ball, 1933).

If present, the vortex core is a forced vortex which first appears as a dimple at the water surface. If the dimple gets longer and some air bubbles separate from what is called air core, the air entrainment due to a vortex starts. This process is driven by the vortex field, the so-called free vortex. Denny (1956) termed and described the different phases of vortex formation as "stages in development of air entraining vortex". Later on the term "vortex-type" was developed. Hecker (1987a) shows that air entrainment takes place at vortex types 5 and 6 (of in total six stages) after the established Alden Research Laboratory (ARL) vortex type classification (Figure 2). When the air entrainment starts or the air core tip reaches the intake cross section a so-called critical state has been reached. The submergence at this stage is therefore often identified as critical (s_{cr}). In practical design of intakes the minimum water storage elevation is fixed right above this height.

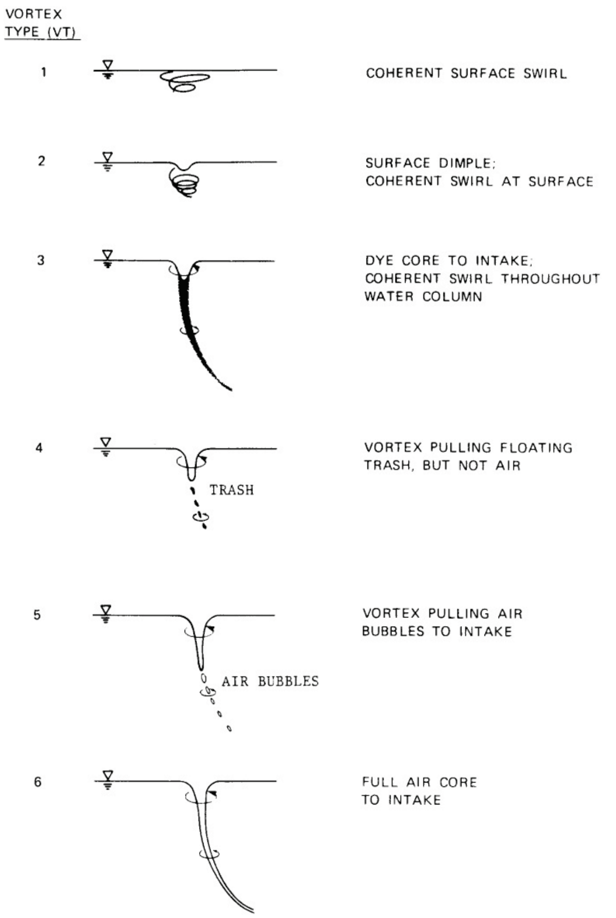

Figure 2: ARL vortex type classification (Hecker, 1987a).

To determine the point of critical submergence several empirical approaches for horizontal intakes have been developed (Gordon, 1970, Anwar et al., 1978, Knauss, 1987, Hecker, 1987b). However, the results of these approaches vary considerably due to the unique character of the investigated intake approach flow. From experience with prototype and model investigations Denny & Young (1957) conclude a general trend between the critical submergence and the intake velocity. At low intake velocities the influence of the submergence is important. However, at high intake velocities the critical submergence asymptotically approaches a constant value. Hydraulic model tests are still a common way to define the required minimum submergence. The formation of a vortex may appear at any kind of intake and is independent of its utilization, but the consequences and their importance differ considerably (Wickenhäuser, 2008).

Consequences of entrained air

At hydroelectric power plants the water for energy production is typically transported in pressure tunnels and pipes. In case air is entrained into the pressure system, the flow properties change from a single phase fluid (pure water) to a two-phase flow (air-water mixture). This may have strong consequences on the operation, safety and efficiency of the whole plant. These effects can be divided into three main groups: (1) reduction in efficiency of turbines and pumps, (2) unsteady flow behavior, i.e. pulsation and pressure surges in the system with corresponding mechanical loads on the involved components, (3) stationary effects, e.g. flow reductions from stationary air bubbles, and local corrosion damage.

As to the first group direct effects of air in hydraulic machinery such as pumps and turbines are quantifiable. Minimum air entrainment rates already cause a reduction in efficiency of around 1 %. An air entrainment rate of 1.5 % leads to an efficiency reduction of up to 16 % (Denny & Young, 1957, Papillon et al., 2000). For air entrainment rates up to 4 % there is a further continuous decrease in efficiency. At air entrainment rates between 7 and 20 %, depending on the type of pump (axial pumps are more sensitive than centrifugal), a sudden drop of efficiency down to a total flow interruption may take place (Chang, 1977). Today the air entrainment rate due to vortices is not sufficiently and universally known. The efficiency reduction cannot be predicted.

As to group (2), the effects due to air bubbles and the resulting compressible air-phase vary depending on bubble size, frequency, absolute pressure and pressure difference. The pressure peaks can reach extreme values and through their periodical return may add a change of load. For example, compressed air bubbles in a pressure pipe of a power plant may expand at the transition from the hydrodynamic service head of up to several hundred meters of water column to atmospheric pressure. This process may be quite explosive. Extreme pressure changes can also cause cavitation. The pulsations may cause hydraulic machinery, parts of the plant or the whole pressure system to oscillate. As a result of fluctuations in discharge, the operating characteristics of hydraulic machines are affected, leading to uneconomic handlings and to an increased wearing of machine bearings and runners.

As to negative stationary effects of consequence group (3) , flow reductions due to decreasing flow cross section after an accumulation of air as well as local corrosion damage of steel lining may occur. These consequences are more static than those of groups (1) and (2), but nevertheless unwanted.

Design practice

Vortices at intakes are a major source of air entrainment, requiring significant reserves to avoid their occurrence. Existing hydropower plants are designed and operated in such a way that no air enters the pressure system at all. This leads to a high submergence and thus to a limitation in terms of storage management and a loss of storage volume, respectively. Nevertheless, the entrainment of air cannot be prevented at every moment – especially for conditions close to operational limits, as even a conservative design constitutes an element of risk with regard to the aforementioned effects.

Two general types of measures are possible, (1) keep air away from the waterways, and (2) handle entrained air appropriately. The first measure is to avoid air entrainment by high submergence and low intake velocities or by anti-vortex devices. The secondary flow above the intake will be disturbed by this measure. The required submergence is typically a function of the pipe Froude number $\mathbf{F}_D = v/(gD)^{0.5}$ and may be expressed by

$$\left(\frac{s}{D}\right)_{\mathrm{cr}} = \mathrm{K}\boldsymbol{F}_D + 0.5 \tag{1}$$

where s = submergence relative to the pipe axis, D = intake diameter, v = intake velocity and g = gravitational acceleration (Figure 7). Note that K = 1.7 for symmetrical and K = 2.3 for asymmetrical approach flow according to Gordon (1970) and K = 2.0 according to Knauss (1987), who further specifies min $(s/D)_{\mathrm{cr}} = 1.5$. Denny & Young, (1957), Knauss (1983) and Rutschmann et al. (1987) give an overview of anti-vortex devices. Figure 3 illustrates anti-vortex devices at embankments.

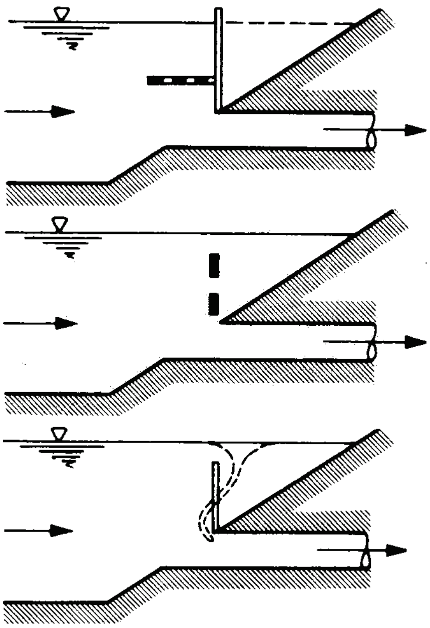

Figure 3: Schematic anti-vortex devices at embankments (Knauss, 1983)

Several publications report about special solutions after hydraulic model investigations of intake structures (Rindels & Gulliver, 1983, Rutschmann et al., 1987, Möller et al., 2010, Amiri et al., 2011).

The second type of measures allows air entrainment and determines the consequences by using a different design approach. The need for power and flexible availability of regulating energy has increased. The rated capacity of both new and existing plants is raised more and more often. By increasing the discharge the air entrainment rate also increases. A controlled air entrainment through intake vortices must be taken into account under certain circumstances. To ensure safe operation and to optimize the efficiency of new and refurbished hydropower plants knowledge of the vortex-induced air entrainment rate is a prerequisite. Once this rate is known, then vortices can be classified as critical ones that must be prevented, or as uncritical ones that may be permitted.

The effects on the plant vary may vary from negligible to uncontrollable. In the simplest case the entrained air passes the pressure conduit and de-aerates at the surge chamber. Air can also concentrate at the tunnel roof and propagate against the flow direction. Its expansion at normal pressure can cause an explosion. The influence of air entering the hydraulic machines is described above.

In many cases a de-aeration device is a simple but effective solution. Wickenhäuser (2008) presents several de-aeration systems by structural means as e.g. a chamber with an attached riser pipe at the top of the conduit to convey the collected air from the tunnel to the atmosphere. The dimensions of the de-aeration device are a function of discharge, conduit diameter and the inflowing amount of air (air entrainment rate β). Wickenhäuser (2008) gives examples how to de-aerate the full air phase from the pressure tunnel or pipe. However, knowledge about the quantity of entrained air is required for an appropriate design.

The existing design criterion to fully avoid air entrainment can therefore be replaced by a flexible assessment strategy.

Knowing the air entrainment rate and quantifying the resulting potential damages finally allows the design of counter-measures such as de-aeration systems, thereby improving the efficiency of a hydroelectric power plant, especially with regard to storage management. 'Classical' measures of type (1) can also be used: For instance, the design of an anti-vortex device could be a good solution to retain the efficiency and flexibility, but this device may need to be large and thus quite expensive. A de-aeration device is an interesting alternative and is worth an economical consideration regarding the design of intakes.

Vortex-air entrainment rate

Vortices at intakes are a major source of air entrainment. Their air entrainment rate, especially any correlation to a flow pattern, is unknown today. The relative air entrainment rate

$$\beta = \frac{Q_\mathrm{a}}{Q_\mathrm{w}} \qquad (2)$$

expresses the relationship between the volumetric air discharge Q_a and the volumetric water discharge Q_w. Sometimes the air concentration $C = Q_\mathrm{a}/(Q_\mathrm{a}+Q_\mathrm{w}) = \beta/(\beta+1)$ is used instead of β. For small amounts of air Q_a the values of β and C are nearly the same. Up to $\beta = C/(1-C) = 1\ \%$ the difference between β and C is less than 1 %. The use of the reference pressure of the compressible air phase is more important and has to be specified.

First approaches on the relative air entrainment rate β at pump sumps are presented by Iversen (1953). Figure 4 shows the air entrainment rate β (denoted "Air to water ratio" here) on the ordinate as a function of relative intake submergence Z/D, and of the relative side wall and bottom distances X/D and Y/D, respectively, where D = intake diameter, X = side wall distance, Y = bottom clearance and Z = submergence. The measurement of air entrainment was performed with a specially developed so-called "air separator". The pipe is interrupted by a closed cylindrical tank in which the air separates from the water and accumulates at the top section.

According to Denny & Young (1957) the air entrainment rate of pump sumps is typically $\beta = 5\ \%$ and may reach $\beta = 10\ \%$ in extreme cases. Investigations of Hattersley (1965) show air entrainment rates between $\beta = 0.06$ and 0.73 %, thus one to two magnitudes smaller than reported by Denny & Young (1957).

For horizontal axis intakes Padmanabhan (1984) gives maximum values of air concentration rates versus the submergence Froude number $\mathbf{F}_s = v/(\mathrm{g}s)^{0.5}$, with v = average velocity at the characteristic intake cross-section, s = intake submergence relative to the center of the pipe axis and g = gravitational acceleration (Figure 7). Figure 5 shows the data measured on a model with two horizontal intake pipes and a basin representing a pump sump. With $C_{\max} = 0.15$, the maximum relative air entrainment rate amounts to $\beta = C/(1-C) = 18\ \%$. The data scatter is considerable, hindering a trend analysis. The air entrainment was not correlated with the flow parameters. The author provides only an envelope line of the maximum air entrainment rate. A systematic evaluation and continuation of attempts to measure the air entrainment rate was not conducted till today (Padmanabhan, 2008).

In Table 1 all air entrainment rates found in the literature review are listed. The rates of the different investigations vary widely over several orders of magnitude.

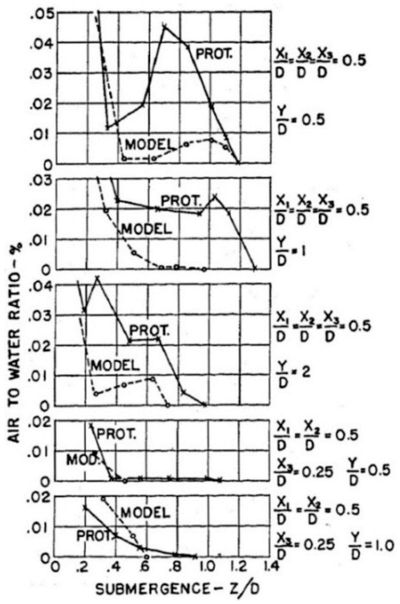

Figure 4: Relative air entrainment rate β ("Air to water ratio") for model and prototype as a function of the relative intake submergence Z/D for various relative wall and bottom distances X/D and Z/D, respectively (Iversen, 1953).

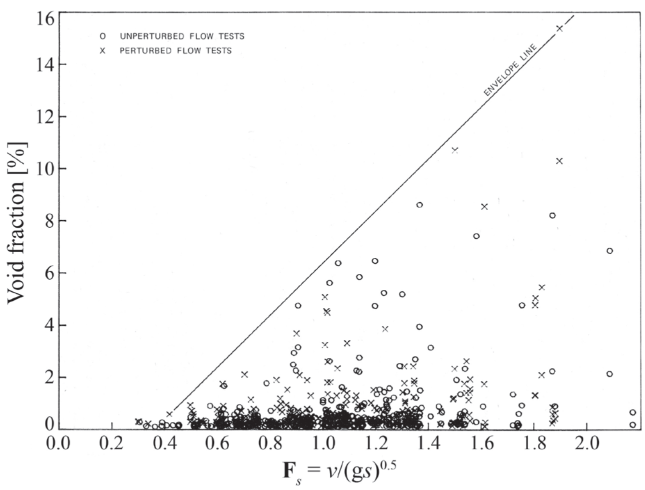

Figure 5: Air concentration $C = \beta/(\beta+1)$ ("Void fraction") vs. submergence Froude number $\mathbf{F}_s = v/(\mathrm{g}s)^{0.5}$, the "envelope line" gives the maximum air entrainment rate as a function of $\mathbf{F}_s$ (Padmanabhan, 1984).

Table 1: Results of investigations of air entrainment rate β.

Publication	Air entrainment rate β	Correlation $\beta = f(\ldots)$
Iversen (1953)	1 - 5 %, extreme > 10 %	n/a
Denny & Young (1957)		n/a
Hattersley (1965)	0.06 - 0.73 %	n/a
Padmanabhan (1984)	max. 18 %	~$\mathbf{F}_s$[1]

[1] The values of submergence Froude number were printed versus the void fraction. A correlation does not exist.

Intake vortex research at VAW

As given above, the significance of the air entrainment rate as an important design criterion is increasing. To close the lack of knowledge regarding air entrainment rates a large-scale physical model consisting of a 50 m^3 laboratory steel tank (Figure 6) has been built at VAW. Two pumps provide a maximum discharge of 500 l/s in a closed loop. The pipe and the submergence Froude numbers $\mathbf{F}_D = v/(gD)^{0.5}$ and $\mathbf{F}_s = v/(gs)^{0.5}$ can be varied from 0 up to 2 and 2.8, respectively, for an usual intake diameter of $D = 0.4$ m. The relative submergence s/D (note that Iversen uses Z/D) varies from 0 to 4. Froude similarity was chosen due to the free surface flow. In this case the influence of viscosity and surface tension cannot be considered adequately.

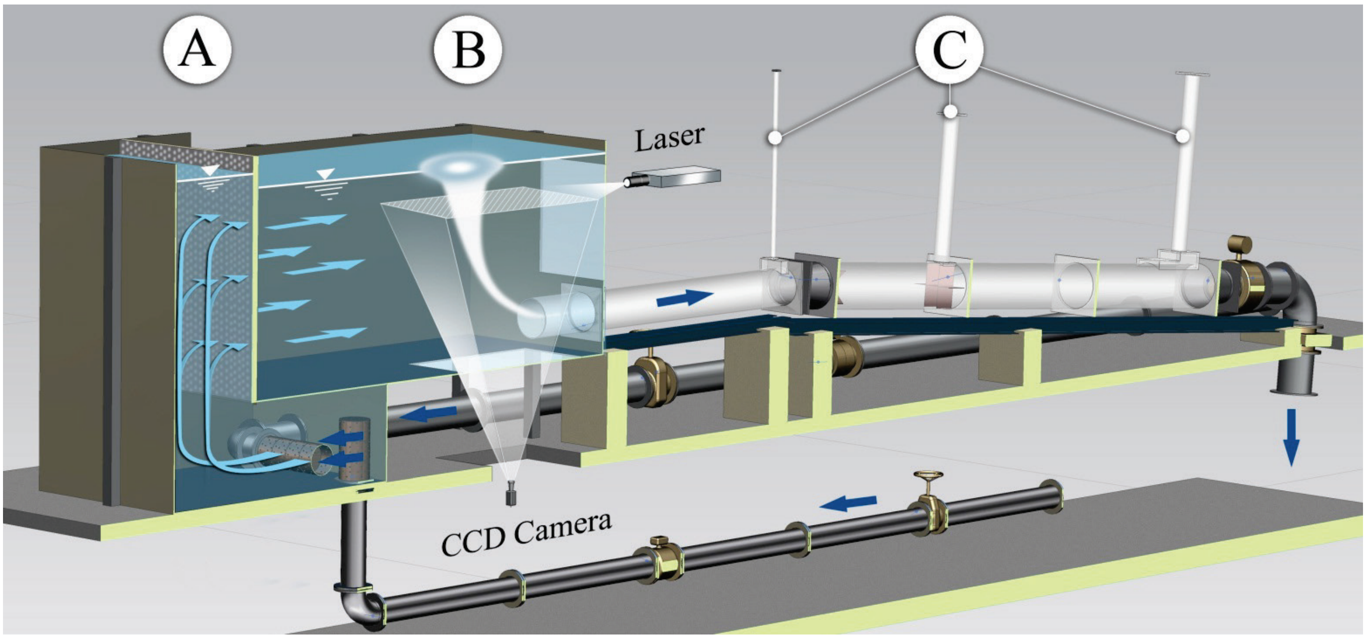

Figure 6: Cross section through the experimental setup at VAW: (A) intake basin and filter fleece to homogenize the flow, (B) tank with 2D Particle Image Velocimetry (PIV), (C) de-aeration devices at the pressure system by means of three rising pipes.

Through the compliance of empirical limits their influence should be negligible to avoid scale effects. The model exceeds several times the generally accepted limits regarding similitude criteria of intake vortex investigations: Viscous effects are small for intake Reynolds numbers $\mathbf{R}_D > 2.4 \times 10^4$ according to Daggett & Keulegan (1974), with $\mathbf{R}_D = vD/\nu$ and ν = kinematic viscosity. Regarding the intake Weber number $\mathbf{W}_D = v(\rho D/\sigma)^{0.5}$, the limit value specified by Raju & Garde (1987) is $\mathbf{W}_D > 11$ in order to avoid decisive effects of surface tension in the model vortex formation. The vortex formation at the intake is not enforced by a certain installation. Thus, the unsteady nature of the hydraulic phenomena is seen to be undisturbed.

The horizontal velocity field around the vortex is measured by means of 2D Particle Image Velocimetry (PIV) on a total area of up to 1 m^2. Figure 7 shows an experimental run. The measured horizontal velocity field around the vortex, whose rotation affects a wide area, confirms the applicability of the analytic solution of the 2D Navier-Stokes equation for the potential vortex. The air entrainment judged from visual observation of the white water is higher than the actually measured maximum concentration of up to 1 %. The device for quantifying the air entrainment is currently being optimized to increase the measurement accuracy at low air entrainment rates. A forthcoming challenge is a complete de-aeration of the entrained air, which is a prerequisite to measure large air entrainment rates. The water level in the rising pipes (Figure 6, C) equals the piezometric head at atmospheric ambient pressure at the beginning of each run. If the pipes are closed on top, the pressure increases above atmospheric pressure with each accumulated bubble rising through the pipe. This results in a water level drop.

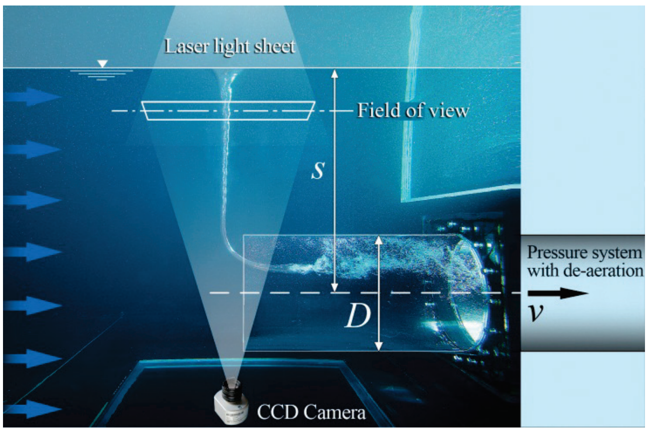

Figure 7: Experimental run in the physical VAW model with air-entraining vortex. A de-aeration device allows to

quantify the vortex-entrained air. A 2D PIV is used to measure the velocity field around the vortex.

Using the ideal gas law the mass of the collected air can be calculated. At a given pressure the volume and thus the air discharge Q_a over the measurement time can be determined. The aim of this project is to enhance the understanding of vortex-induced air entrainment and thus to improve the practical design of intake structures at hydropower plants.

Conclusions

Nowadays, vortex-induced air entrainment at hydroelectric power plant intakes is typically prevented by applying empirical approaches to compute the required submergence. Often, the relatively large submergence results in a loss of flexibility, of storage volume and of efficiency of the plant. However, with many storage plants being newly built or upgraded in the course of increasing regulating energy demand, the knowledge of air entrainment rate becomes more and more important. No useful information on this parameter has been found in the present literature review. For this reason the air entrainment is experimentally investigated at VAW using a large-scale hydraulic model. The results can be analysed towards practical approaches to design and operate intakes of hydroelectric power plants with respect to an acceptable, damage-free air entrainment rate.

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