JET IMPACT ANGLE ON CHUTE DOWNSTREAM OF AERATOR

M. Pfister

Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL),
Switzerland, michael.pfister@epfl.ch

Abstract: Chute aerators protect spillways from cavitation damage. Several parameters affect their efficiency, which were intensively discussed in literature. One implicit parameter is the cavity jet impact angle at the re-attachment point of the flow on the chute bottom, which may however not be defined *a priori* by the designer. The herein conducted experimental research derived this angle and a related general prediction of it, and shows its effect on the aerator performance. The experiments indicate that no distinctive effect occurs if considering the air entrainment coefficient, but that the relative air detrainment rate downstream of the re-attachment point significantly augments with increasing impact angle.

Keywords: aerator, de-aeration, deflector, impact angle, jet.

INTRODUCTION

Chutes operating under high-velocity flows were observed to experience severe cavitation damages in the past. Subsequently, measures were intensively studied and proposed to prevent such incidents, of which flow aeration was the most effective in terms of cavitation prevention, constructional ease and cost. Today, spillways are thus often equipped with chute aerators. They consist of a discontinuity of the chute bottom, typically including a deflector and a bottom offset. The air entrained into the flow is usually provided by lateral ducts connected with the atmosphere. Several investigations were conducted during the past decades to provide design guidelines for chute aerators, including numerical and physical modeling, as well as prototype observations. Chanson (1988), Kramer (2004) and Pfister (2008) focused on the streamwise air transport downstream of these devices. Former studies indicated that one key aspect related to chute aerator performance is the impact of the cavity jet on the chute bottom downstream of aerators. There, a notable air detrainment was observed (Wood 1988, Chanson 1988, Chanson 1994, Attari and Zarrati 1997, Qi et al. 2007). The test campaign conducted by Pfister (2008) allows to determine the jet impact angle on the chute bottom and to define its impact on the de-aeration process.

PHYSICAL MODEL

The herein presented results were derived from a hydraulic model investigation conducted in a 0.3 m wide and 6.0 m long sectional chute model at the *Laboratory of Hydraulics, Hydrology and Glaciology* (VAW) of ETH Zurich (Pfister 2008), systematically analyzing the performance of various chute aerators. Beside the variation of other relevant parameters (Fig. 1), flows of variable approach (subscript o) flow depths h_o and Froude numbers $\mathsf{F}_o=V_o/(gh_o)^{0.5}$ were generated with a jet-box, with V_o= approach flow velocity and g= acceleration due to gravity. The discharge was measured with an electromagnetic flowmeter, the water levels upstream of the aerator with a point gauge, and the pressure heads h_s in the air cavity with a U-shaped manometer.

The air entrained by the tested aerators was supplied through a lateral duct to the cavity below the jet and measured using a thermoelectric anemometer. The spatial air concentration C distribution was measured with a fiber-optical probe with two sapphire tips (RBI Instrumentation). This measurement principle is based on the different refraction indices between the sapphire tip and the surrounding air or water phase. Light supplied to the tip is reflected and detected if the tip is positioned in the air phase, while it is 'lost' in the water phase otherwise. This probe measured the totally conveyed air flow without a distinction between entrapped and entrained air. The local air concentration $C(x,z)$ of the two-phase air-water-flow resulted from an acquisition period of typically 20 s with a streamwise spacing of Δx=0.2 m and a grid point spacing of 2 mm<Δz<5 mm perpendicular to the chute bottom.

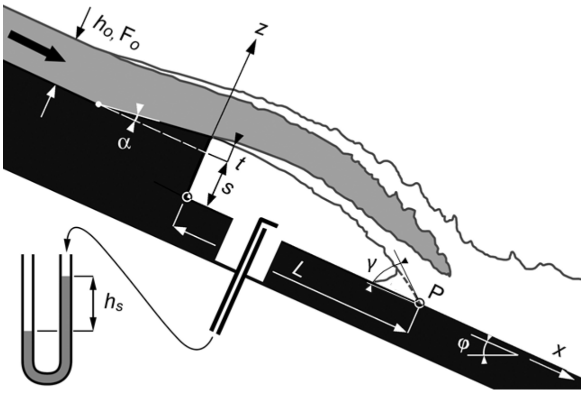

Fig. 1 – Aerator geometry and parameter definition

The following parameters influence the air entrainment and transport process at chute aerators (Pfister and Hager 2010a, b), so that they were systematically varied: Deflector height t (0.000 m$\leq t \leq$0.027 m), deflector angle α (0.0°$\leq \alpha \leq$26.6°), offset height s (0.000 m$\leq s \leq$0.100 m), chute bottom angle φ (12°$\leq \varphi \leq$50°), approach flow Froude number F_o (5.8$\leq \mathsf{F}_o \leq$10.4) and depth h_o (0.038 m$\leq h_o \leq$0.094 m) measured just upstream of the deflector (Fig. 1). If normalizing the parameters related to a length, a range including $0.1\leq((t+s)/h_o)\leq 2.1$ was investigated. The cavity sub-pressure $P=h_s/h_o$ was kept atmospheric herein ($P\approx 0$, Pfister 2011), as the air supply system was designed using sufficient cross-sectional area to avoid significant energy losses. The flow surface and the jet trajectories were defined along their iso-concentration lines of C=0.90. In total 108 tests were conducted, considering three types of chute aerators: (1) Deflector without offset, (2) Offset without deflector, and (3) Combinations of deflector and offset. Scale effects related to chute aerators were discussed by Pfister and Hager (2010a) and denoted as irrelevant.

JET IMPACT ANGLE ON CHUTE

At the downstream end of an aerator generated cavity, i.e. downstream of the small bottom roller near point P in Fig. 1, the lower jet trajectory impinges on the chute bottom at angle γ. As the lower jet trajectories have been measured in the frame of the resent study, γ can explicitly be derived from the data. The jet impact angle is defined relative to the chute bottom as $\tan\gamma=\Delta z/\Delta x$ using the larger value Δz of two options: (1) the last two trajectory points immediately upstream of the jet impact with both $z>0$ m, or (2) one point with $z>0$ m and the second with $z=0$. The value $\Delta x=0.2$ m was constant due to the continuous measurement grid. Then, the data analysis indicates that

$$\tan\gamma = 0.15\sqrt{\frac{s+t}{h_o}}\left(1+\tan\alpha\right)^2\left(1+\sin\varphi\right)^{-1} \tag{1}$$

The coefficient of determination between Eq. (1) and the measured values is $R^2=0.92$. Note that no significant effect of F_o was found, whereas classical trajectory computations include in particular the related V_o. In Eq. (1), the dominant parameter is α. Figure 2a shows the data normalized with $\Gamma=((s+t)/h_o)^{0.5}(1+\tan\alpha)^2(1+\sin\varphi)^{-1}$, beside Eq. (1). The latter is valid for deflector- and offset aerators, as well as for combinations.

COMPARISON WITH THEORETICAL TRAJECTORY

Tan (1984) systematically investigated chute aerators in a physical model. Among others, he measured the jet length L and proposed an estimation of the latter on the basis of the gravity driven theoretical parabola. However, the measured values and the predictions differed significantly: The computed lengths exceed the measured ones by some 85% on average. He explained the difference with the inaccuracy of the visual jet length determination, the side wall effect and the inability of the upper streamlines to follow the abrupt bottom slope change at the deflector. Chanson (1995) reconsidered the work of Tan (1984) and derived an explicit function for the jet impact angle at point P, also based on the theoretical jet trajectory, as

$$\gamma = \arctan\left(\frac{\frac{gT}{V_o}\cos\varphi-\sin\delta}{\frac{gT}{V_o}\sin\varphi+\cos\delta}\right) \tag{2}$$

Herein, the sub-pressures were set as $P=0$ and then canceled, and the flight time T was computed with the equations provided by Chanson (1995). The take-off angle δ of the cavity trajectory has to be known in Eq. (2). In parallel, e.g. Steiner et al. (2008) showed that the latter differs from the deflector angle α, with typically $\delta\leq\alpha$. The value δ is defined between the cavity jet trajectory immediately downstream of the deflector lip and a reference parallel to the chute bottom. To compare the measured angles γ with the theoretical values according to Eq. (2), five assumptions of δ are analyzed (Table 1).

Table 1 – Assumptions for δ as a base to compute γ using Eq. (2)

No	Value	Description
1	$\delta=\alpha$	Take-off and deflector angle are identical (Tan 1984, Chanson 1995)
2	δ from Eq. (3)	Proposal of Steiner et al. (2008)
3	δ from Eq. (4)	Proposal of Rutschmann and Hager (1990)
4	δ from Eq. (5)	Proposal of Wu and Ruan (2007)
5	δ present study	Effective take-off angle as measured herein

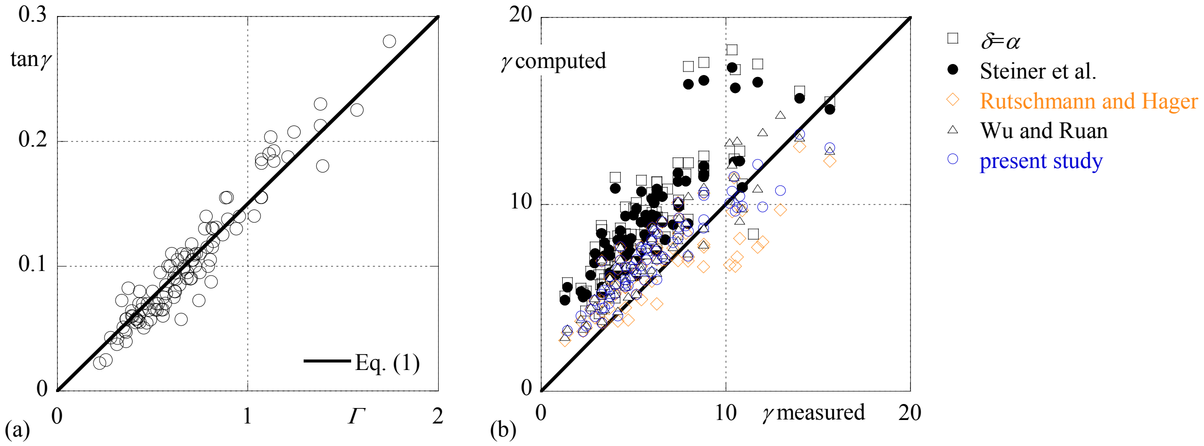

Fig. 2 – (a) Measured jet impact angles γ versus Γ, and (b) comparison of measured γ with theoretically computed value based on different assumptions for δ (Table 1), (–) perfect agreement

Figure 2b shows computed values γ resulting from the approaches of Table 1. They are compared with the herein effectively measured values of γ given on the abscissa. It is seen that

1. the assumption $\delta=\alpha$ clearly overestimates γ.
2. the δ following Steiner et al. (2008) reduces the values as compared to $\delta=\alpha$, but still overestimates γ. It has to be noted that Steiner et al. (2008) do not describe the effective take-off angle, but a virtual value. They fitted the measured jet trajectories to gravity driven theoretical parabolas, thereby deriving the virtual value for δ. Furthermore, they used a physical model with $\varphi=0°$ and measured the trajectories with a point gauge, both differing from the herein presented study. For deflector generated jets they propose

$$\frac{\delta}{\alpha}=0.89\left[1.05-\frac{t}{h_o}(\tan\alpha)\mathsf{F}_o^{-1}\right] \tag{3}$$

3. the δ considering Rutschmann and Hager (1990), who analyzed own model measurements and those of Pan et al. (1980), give more reliable results, with R^2=0.64 between their prediction and the herein measured values. The computed values have a considerable scatter, but their average is near the perfect agreement. Based on a “trajectory approach” they give

$$\frac{\delta}{\alpha}=\sqrt{\tanh\left(\frac{t/h_o}{\alpha}\right)} \tag{4}$$

4. the results of Wu and Ruan (2007) correlate better (R^2=0.85), but generally overestimate the effective impact angles. They also use the approach of Pan et al. (1980) and add a term considering the normal turbulence intensity T_o of the approach flow. Herein, the latter is estimated as constant with T_o=0.06 (Pfister et al. 2011), but no effective measured values are available. Wu and Ruan (2007) propose

$$\delta=0.48\sqrt{\tanh\left(\frac{t/h_o}{\alpha}\right)}\alpha+0.52\left(\alpha-\arctan T_o\right) \tag{5}$$

5. the herein effectively measured take-off angles, as described below, indicate a good correlation (R^2=0.85) but still a general overestimation of γ. Note that Fig. 2b does not compare the measured γ with the values derived from Eq. (1), but with the measured δ inserted in Eq. (2), thus also basing on the theoretical trajectory approach.

It may be summarized that the prediction of γ via δ according to Table 1, Eq. (2) and Fig. 2b is hardly satisfactorily. Even the herein derived effective take-off angles at the deflector lip give slightly overestimated γ values, although a reasonable coefficient of determination occurs. This leads to the conclusion that Eq. (2) and the approach of gravity driven parabolas are partially inaccurate if applied to describe the aerator generated nappe shape and the impact angle on the chute bottom. It seems that the flow near the take-off is subjected to phenomena affecting the lower trajectory, as mentioned by Tan (1984), i.e. the inability of the streamlines to follow the abrupt bottom slope change at the deflector. The explicit Eqs. (1) and (6) may thus be more reliable if analyzing the nappe shape downstream of a chute aerator, beside the prediction of L by Pfister and Hager (2010a). For long jets, however, the assumptions of Steiner et al. (2008) are more precise. Note that Pfister and Hager (2009) describe the deflector generated jet trajectories also with a parabola, but normalized with the maxima thus avoiding the link to gravity.

EFFECTIVE JET TAKE-OFF ANGLE

Instead of using the Eqs. (3) to (5) to compute δ, the latter may be derived directly from measurements. Note that the effective measured take-off angles were derived using the two trajectory points just downstream of the jet take-off. For the data of Steiner et al. (2008), this includes a streamwise distance Δx between 0.047 m and 0.146 m, and the herein derived values include Δx=0.2 m. The angle δ is defined as $\tan\delta=\Delta z/\Delta x$. If considering the data of the present study and the raw data of Steiner et al. (2008), the effective take-off angle follows as

$$\tan\delta = 0.17\left[\sqrt{1+\frac{t}{h_o}}\left(1+\tan\alpha\right)^{1.5}\left(1+\sin\varphi\right)^{-0.5}\mathsf{F}_o^{\;0.2}\right]-0.26 \tag{6}$$

The coefficient of determination is R^2=0.92. Equation (6) is valid for deflector- and offset aerators, as well as for combinations. In Fig. 3a, $\Delta=(1+t/h_o)^{0.5}(1+\tan\alpha)^{1.5}(1+\sin\varphi)^{-0.5}\mathsf{F}_o^{0.2}$ on the abscissa, open symbols give own measurements and full symbols values derived from the raw data of Steiner et al. (2008). The application range of Eq. (6) exceeds that of Eq. (1), because also the data of Steiner et al. (2008) were included. The adapted limitations are thus: Deflector height 0.000 m$\leq t \leq$0.075 m, deflector angle 0.0°$\leq\alpha\leq$33.2°, chute bottom angle 0°$\leq\varphi\leq$50°, approach flow Froude number 3.0$\leq\mathsf{F}_o\leq$10.4 and depth 0.030 m$\leq h_o \leq$0.094 m. In dimensionless terms, the range is $0.0\leq t/h_o\leq 1.7$.

Figure 3b compares the effective take-off angles δ as measured herein with those derived from Eqs. (3) to (6). It is visible that the prediction of

- Steiner et al (2008, Eq. 3) generally overestimate δ, and correlates with the measured data with R^2=0.62.
- Rutschmann and Hager (1990, Eq. 4) drastically underestimates δ, in particular for large values. Their equation $\tanh(f[\alpha^{-1}])$ stagnates for large realistic values of α, whereas small δ are correctly predicted.
- Wu and Ruan (2007, Eq. 5) adjust the stagnant trend of the proposal of Rutschmann and Hager (1990) by adding the summand (α–arctanT_o), so that R^2=0.73.
- The herein presented approach according to Eq. 6 considers effectively measured values, so

that a better coefficient of determination is achieved with R^2=0.92.

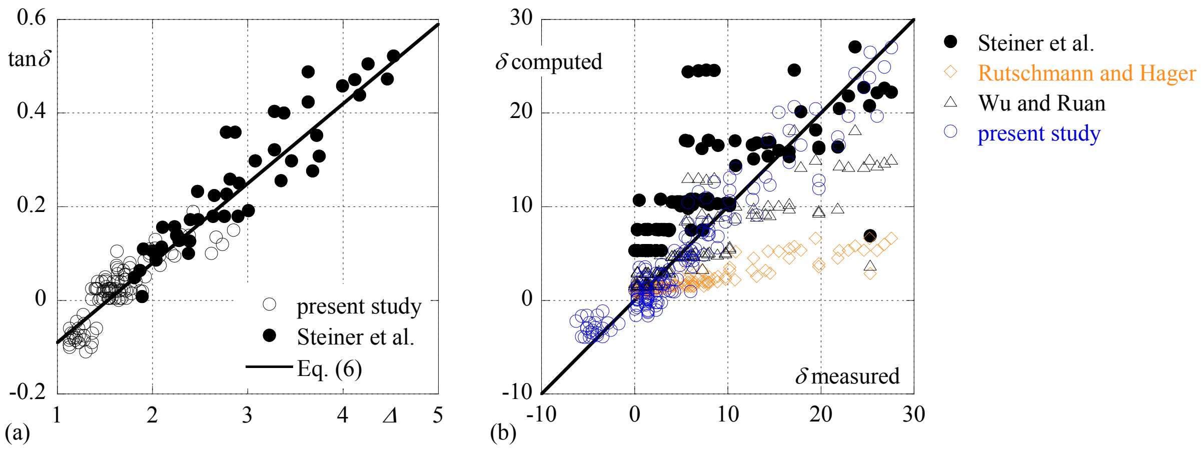

Fig. 3 – (a) Tangent of effective take-off angles as measured in the model for the present study as well as derived from raw test data of Steiner et al. (2008) versus *Δ*, and (b) comparison of measured *δ* with computed values according to literature, (–) perfect agreement

EFFECT ON AERATOR PERFORMANCE

The efficiency of a chute aerator is typically described with its air entrainment coefficient $\beta=Q_A/Q$, with Q= discharge and Q_A= air discharge entrained through the duct (Chanson 1988, Rutschmann and Hager 1990, Pfister and Hager 2010b). The effect of γ on β was investigated for instance by Attari and Zarrati (1997), who added bottom insets at the point P to vary γ independently of other parameters. They conclude that steep γ reduce β and that P approaches atmospheric pressure, i.e. $P\rightarrow 0$. It may be estimated, however, that L and the cavity volume, influencing P, are probably also affected by these insets, both being relevant for aerator performance. The present tests do not indicate a significant correlation between γ and β (Fig. 4a). As stated in the base data analysis (Pfister and Hager 2010b), mainly F_o determines β, whereas F_o has no distinctive effect on γ as shown in Eq. (1). However, β is not considered as key parameter of the aerator performance, as it gives no indication on the air transport at point P and further downstream.

To know the effect of γ on the de-aeration process at point P, the average air concentration C_a of a jet or flow section was considered, integrated between the surfaces at C=0.90 for jets or considering the bottom for chute flow (Pfister and Hager 2009, 2010b). Two values of C_a are consequently compared: (1) C_{aM} just upstream of point P, say at 0.95L, representing the maximum air transport at the end of the jet, and (2) C_{am} at 1.25L giving the value after jet impact.

The streamwise air discharge Q_{AF} transported within the flow may be defined as

$$\frac{Q_{AF}}{Q}=\frac{C_a}{1-C_a} \tag{7}$$

Equation (7) was applied at the two above defined locations 0.95L and 1.25L with the related concentrations $C_a=C_{aM}$ and $C_a=C_{am}$, resulting in Q_{AFM} and Q_{AFm}. Chanson (1994) quantifies the de-aeration at point P in terms of the relative air detrainment rate $D=(Q_{AFM}-Q_{AFm})/Q_{AFM}$ as

$$D=0.0762\gamma \tag{8}$$

He considered impact angles around $3°\leq\gamma\leq 9°$ including his own measurements and few values from other sources. The γ values of the present investigation are between 1.3°≤γ≤15.6° thus exceeding the limitations of Eq. (8). The herein derived data suggest (R^2=0.58)

$$D = 0.8 \cdot \tanh[8 \cdot \tan\gamma] \tag{9}$$

As shown in Fig. 4b, Eq. (8) as proposed by Chanson (1994) lays within the herein measured points. It tends to D=1 at γ=13°, pointing at black water flow downstream of point P. The experiments showed, however, that D=0.7 to 0.8 for γ between 13° and 16°, so that Eq. (9) was set-up to asymptotically tend to this value. Note furthermore that Fig. 4b indicates de-aeration rates up to 70% to 80% for γ exceeding some 10°.

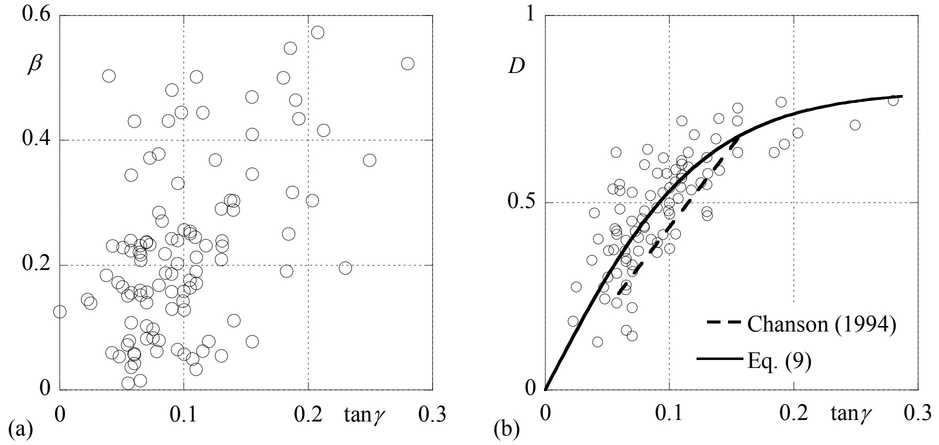

Fig. 4 – (a) $\beta(\tan\gamma)$ indicating a weak correlation, and (b) $D(\tan\gamma)$, with Chanson (1994) equal to Eq. (8)

CONCLUSIONS

Various parameters affect the performance of chute aerators. An implicit parameter related to the de-aeration process at the end of the nappe, i.e. at the jet re-attachment on the chute, is the jet impact angle γ. Former studies observed that a significant de-aeration occurs if γ is high. Comprehensive hydraulic model tests related to chute aerators allowed derivation of the latter angle and comparison with the aerator performance.

A herein presented equation allows explicitly predicting γ, without basing on a trajectory computation. The trajectory approach, which is physically based and a standard in literature, results in partially inaccurate values of γ, even if carefully choosing the required jet take-off angle δ. A discussion of the latter, including several proposals from literature as well as herein effectively measured values, indicates that an overestimation of γ results, even if applying the effectively measured values. It seems therefore that the nappe surface does not precisely follow the gravity driven parabola in the vicinity of aerators.

The effect of γ on the aerator performance indicates that the air entrainment coefficient β is not significantly depending on the latter, as β is mainly affected by different parameters than γ. Nevertheless, a considerable de-aeration depending on γ is observed in terms of the relative air detrainment rate. An air discharge decrease rate up to 70% was observed if passing the jet re-attachment point P with high values of γ.

REFERENCES

Attari, J., Zarrati, A.R. (1997). The effect of nappe impact angle on aerator performance. *Proc. 27 IAHR World Congress*, San Francisco, USA, D, pp. 601-606.

Chanson, H. (1988). *Study of Air Entrainment and Aeration Devices on Spillway Model*. Ph.D. Thesis, University of Canterbury, Christchurch.

Chanson, H. (1994). Aeration and de-aeration at bottom aeration devices on spillways. *Can. J. of Civil Eng.,* Vol. 21, No. 3, pp. 404-409.

Chanson, H. (1995). Predicting the filling of ventilated cavities behind spillway aerators. *J. Hydr. Res.*, IAHR, Vol. 33, No. 3, pp. 361-372.

Kramer, K. (2004). *Development of Aerated Chute Flow*. Mitteilung 183, Laboratory of Hydraulics, Hydrology and Glaciology (VAW), H.-E. Minor, ed. ETH, Zurich.

Pan, S., Shao, Y., Shi, Q., Dong, X. (1980). The self-aeration capacity of the water jet over the aeration ramp. *J. Hydr. Eng. (Shuili Xuebao)*, Beijing, China, 5, Oct., 13-22 (in Chinese, English abstract).

Pfister, M. (2008). *Schussrinnenbelüfter: Lufttransport ausgelöst durch interne Abflussstruktur* ('Chute aerators: Air transport due to internal flow features'). Mitteilung 203, Laboratory of Hydraulics, Hydrology and Glaciology (VAW), H.-E. Minor, ed. ETH: Zurich (in German).

Pfister, M., Hager, W.H. (2009). Deflector-generated jets. *J. Hydr. Res.*, IAHR, Vol. 47, No. 4, pp. 466-475.

Pfister, M., Hager, W.H. (2010a). Chute aerators. I: Air transport characteristics. *J. Hydr. Eng.,* ASCE, Vol. 136, No. 6, pp. 352-359.

Pfister, M., Hager, W.H. (2010b). Chute aerators. II: Hydraulic design. *J. Hydr. Eng.*, ASCE, Vol. 136, No. 6, pp. 360-367.

Pfister, M. (2011). Chute aerators: Steep deflectors and cavity sub-pressure. *J. Hydr. Eng.*, ASCE, Vol. 137, No. 10, pp. 1208-1215.

Pfister, M., Lucas, J., Hager, W.H. (2011). Chute aerators: Pre-aerated approach flow. *J. Hydr. Eng.*, ASCE, Vol. 137, No. 11, pp. 1452-1461.

Qi, L., Liao, H., Li., L. (2007). Numerical simulation of bottom aeration devices in a mildly sloping spillway tunnel with large unit discharge and low Froude number. *Proc. 32 IAHR World Congress*, Venice, Italy, CD, 295, pp. 1-10.

Rutschmann, P., Hager., W.H. (1990). Air entrainment by spillway aerators. *J. Hydr. Eng.*, ASCE, Vol. 116, No. 6, pp. 765-782.

Steiner, R., Heller, V., Hager, W.H., Minor, H.-E. (2008). Deflector ski jump hydraulics. *J. Hydr. Eng.*, ASCE, Vol. 134, No. 5, pp. 562-571.

Tan, T.P. (1984). *Model Study of Aerators on Spillways*. Research Report 84-6, University of Canterbury, Christchurch, New Zealand.

Wood, I.R. (1988). Aerators – The interaction of nappe and duct air entrainment. *Proc. The International Symposium on Hydraulics for High Dams*, Beijing, China. 611-618.

Wu, J., Ruan, S. (2007). Estimation of cavity length behind aerators. *Proc. 32 IAHR World Congress*, Venice, Italy, CD, 1033, pp. 1-8.