Effect of pre-aerated approach flow on deflector-generated jets

M. Pfister[1], J. Lucas[2] and W.H. Hager[2]
[1]Laboratory of Hydraulic Constructions (LCH)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
CH-1015 Lausanne, Switzerland
E-mail: michael.pfister@epfl.ch
[2]Laboratory of Hydraulics, Hydrology and Glaciology (VAW)
ETH Zürich
CH-8092 Zurich, Switzerland

Abstract: *Flip buckets are terminal spillway elements, generating free jets for energy dissipation. Deflectors are an alternative to flip buckets with constructional ease yet of similar hydraulic features. A first experimental study published at the 33rd IAHR Congress, Vancouver, investigated deflector-generated jets in terms of their air concentration characteristics. For jet impact onto a movable bed, the scour potential reduces as the jet air content increases. It was demonstrated that the jet air concentration development is a function of its relative black-water core length, depending on the approach flow parameters and the deflector geometry.*
Jet-generating structures are located at the end of spillways, where high-speed flow with considerable air transport prevails, affecting the jet parameters, such that additional experiments were conducted involving pre-aerated approach flow. The effect of pre-aeration on the air concentration development of deflector-generated jets is discussed and compared with un-aerated approach flow.

Keywords: *Air concentration, Deflector, Jet, Pre-aeration, Spillway.*

1. INTRODUCTION

Free jets are often generated downstream of spillways or bottom outlets to direct the discharge to a plunge pool, where the residual energy is dissipated (Rajaratnam, 1976). Such jets typically disintegrate in the streamwise direction and expand transversally, resulting in air entrainment into the flow decreasing the jet density. Both, the resulting larger 'jet-footprint' on the plunge pool surface and the decreased jet density reduce the scour potential of impinging jets on loose river beds (Pagliara et al., 2006). Jets are typically generated using various chute end structures, as flip buckets (Khatsuria, 2005, Novak et al., 2007) or deflectors (Steiner et al., 2008). The air transport characteristics of jets was described by Toombes and Chanson (2007) for jets issued at overfalls downstream of bottom outlets, and by Schmocker et al. (2008) for flip bucket-generated jets.

A preliminary study of the Authors analyzed the streamwise air concentration characteristics of these deflector-generated jets (Pfister and Hager, 2009).There, jets generated at drops and at deflectors were compared. The air concentration development depended on the jet black-water core length, which was a function of the approach flow velocity, expressed with the related Froude number, and of the additional turbulence generated by a deflector, expressed with its take-off angle. Based on this length, equations for the streamwise increase of the average and the minimum jet air concentrations were derived.

2. HYDRAULIC MODEL

Additional experiments were conducted in the sectional chute model at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, which was previously used for a related basic study (Pfister and Hager, 2009). In addition to the previous study, pre-aerated approach flow was generated upstream of the deflectors, so that the related jet characteristics could be compared with these of the un-aerated black-water approach flow of the basic study. The average approach flow air concentration C_{ao} was systematically varied between $0.04 \leq C_{ao} \leq 0.25$, measured immediately upstream of the deflector. The minimum relates to un-aerated approach flow with a slightly-roughened surface generating a small average air concentration, as in the basic study, while the maximum is close to the uniform (subscript u) flow average air concentration C_{au} for the present model set-up.

Furthermore, flows of variable approach (subscript o) flow depths h_o and Froude numbers $F_o=V_o/(gh_o)^{0.5}$ were generated, where V_o= approach flow velocity and g= gravitational acceleration. Both parameters h_o and F_o relate to un-aerated black-water approach flow. The mixture flow depth h_{90} associated with the two-phase flow depth is defined up to the free surface at an air concentration of C=0.90. Beside F_o, h_o, and C_{ao} two additional parameters affecting the air entrainment of aerators were varied, namely the deflector height t and the deflector angle α (Fig. 1, Table 1). The pressures below and above the jet were atmospheric, i.e. not affecting the jet features, and the chute bottom angle was constant with φ=12° relative to the horizontal. Note that the latter parameter was systemically varied in the basic study. Series consisting of three tests were conducted, in which exclusively C_{ao} was varied, while the other parameters were kept constant. Then, the isolated effect of C_{ao} on the black-water core length L, the minimum and the average air concentrations resulted. Six of these test series were conducted according to Table 1, including various hydraulic conditions and deflector set-ups.

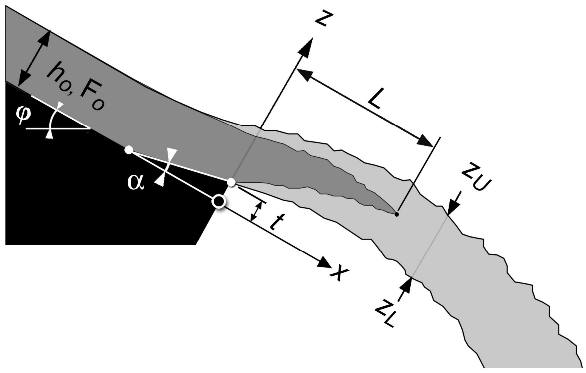

Figure 1 Definition sketch with notation

Table 1 Test program

Series	Test	C_{ao} [-]	F_o [-]	h_o [m]	α [°]	t [m]
	164	0.04	7.5	0.065	5.7	0.013
S1	165	0.21	7.5	0.066	5.7	0.013
	166	0.17	7.4	0.066	5.7	0.013
	167	0.04	7.6	0.065	11.3	0.013
S2	168	0.21	7.6	0.064	11.3	0.013
	169	0.15	7.7	0.064	11.3	0.013
	170	0.06	8.9	0.066	5.7	0.013
S3	171	0.25	9.3	0.064	5.7	0.013
	172	0.14	9.1	0.066	5.7	0.013
	173	0.06	8.0	0.080	5.7	0.013
S4	174	0.21	8.1	0.080	5.7	0.013
	175	0.13	8.2	0.080	5.7	0.013
	176	0.06	8.9	0.066	5.7	0.027
S5	177	0.24	9.1	0.065	5.7	0.027
	178	0.15	9.1	0.065	5.7	0.027
	179	0.04	6.2	0.064	5.7	0.013
S6	180	0.21	6.3	0.064	5.7	0.013
	181	0.17	6.3	0.063	5.7	0.013

The specific discharge was varied between 0.58 and 0.31 m^3/sm and measured with an electromagnetic flowmeter (Krohne®, Germany). The black-water approach flow depth $h_o=h_{90}(1–C_{ao})$ was derived from air concentration measurements providing C_{ao} and h_{90}. The two-dimensional (2D) jet air concentration distribution was measured using a dual fiber-optical probe (RBI® Instrumentation, France). Additionally, a second fiber-optical probe was inserted into the approach flow to derive C_{ao}. The air concentration measurement grid space was 0.20 m in the streamwise direction x, and 2 to 3 mm perpendicular to z. The pre-aerated approach flow was generated by supplying pressurized air into the jet-box providing the variable approach flow conditions. The jet-box produced a fully-developed turbulent boundary layer at the deflectors.

Scale effects relating to the model tests were discussed in the basic study and found small. A dynamic similarity of free-surface aeration of water jets is impossible for geometrically similar models because the internal jet turbulence, represented by the Reynolds number $R_o=V_oh_o/v$, is underestimated, while surface tension, represented by the Weber number $W_o=V_o/[\sigma/(\rho h_o)]^{0.5}$, is overestimated (Ervine and Falvey, 1987). Here, v= kinematic viscosity, and σ= surface tension of water. The additional tests relating to pre-aeration ranged within $144 \leq W_o \leq 240$ and $7.8 \cdot 10^5 \leq R_o \leq 1.4 \cdot 10^6$, which is considered sufficient to avoid significant scale effects The tests involve a large scale model, as proposed by Toombes and Chanson (2007). Scale effects relative to jet trajectories were discussed by Juon and Hager (2000) and Heller et al. (2005), recommending $h_o \geq 0.05$ m and $h_o \geq 0.04$ m, respectively. It may be concluded that the present results involve no significant scale effects, therefore.

3. APPROACH FLOW CONDITIONS

Straub und Anderson (1958) define the average (subscript a) cross-sectional air concentration C_a as integration of the local air concentration distribution $C(z)$ over the flow section. For jets, these boundaries involve the lower jet trajectory z_L and the upper jet trajectory z_U (Fig. 1), both defined where C=0.90, so that

$$C_a = \frac{1}{z_U - z_L} \int_{z_L}^{z_U} C(z) \mathrm{d}z \tag{1}$$

For chute flow, the boundaries are represented by the chute bottom at z=0 and the flow surface h_{90}. Considering a fully-developed air concentration profile in uniform air-water mixture flow, Hager (1991) proposed $C_{au}=0.75(\sin\varphi)^{0.75}$, equivalent to C_{au}=0.23 for the present set-up.

The model air concentration profile $C(z)$ at the approach flow section immediately upstream of the deflector has to be in agreement with characteristic two-phase flow profiles. As a reference, the data of Straub und Anderson (1958) further analysed by Hager (1991) were used, who provided a general relation for uniform flow conditions. All herein measured approach flow air concentration profiles are shown in Fig. 2 as $C(z/h_{90})$. For un-aerated approach flow with $C_{ao}\approx 0.04$ to 0.06 the profiles indicate only a small air concentration near the flow surface, whereas black-water was measured below (Fig. 2a). This surface-air resulted from the slight surface roughness entrapping small quantities of air. For medium $C_{ao}\approx 0.13$ to 0.17, the air distribution differs from the uniform profile, so that these values shown in Fig. 2b are smaller than for $C_{ao}\approx 0.23$, yet the typical profile shape is maintained. The measured profiles for the tests with $C_{ao}\approx 0.21$ to 0.25 are shown in Fig. 2c and compared with the uniform flow profile, resulting in excellent agreement. It may be concluded therefore that the approach flow concentration profiles in the model are similar to these of prototypes.

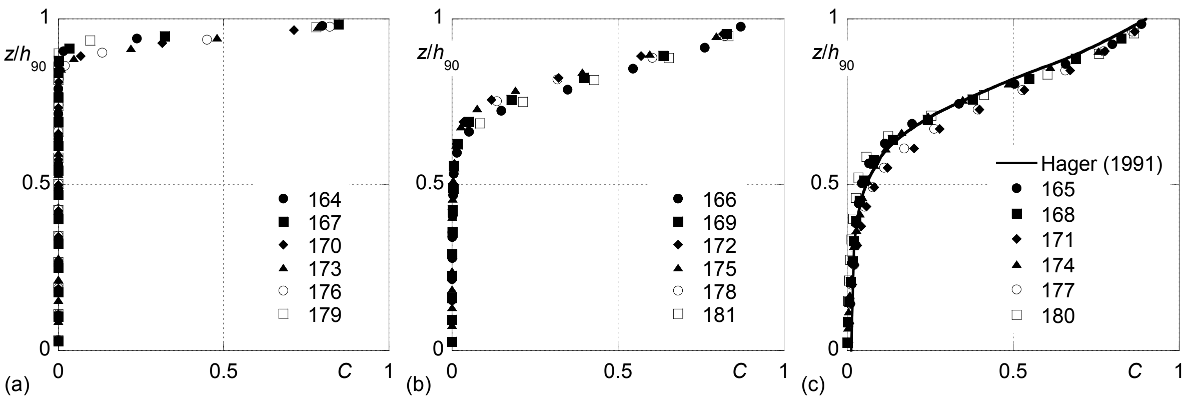

Figure 2 Approach flow air concentration profiles $C(z/h_{90})$ for C_{ao}= (a) 0.04 to 0.06, (b) 0.13 to 0.17, and (c) 0.21 to 0.25. Legend gives test numbers according to Table 1

4. CONCENTRATION DISTRIBUTION

4.1. General

The effect of pre-aerated approach flow on a specific model jet is shown in Fig. 3, in which the chute bottom was rotated to the horizontal. The three photos visualize jets of similar hydraulic conditions, except for pre-aeration. Mainly the jet surface is affected as pre-aeration increases. At the take-off section (*x*=0), the turbulent flow surface becomes more pronounced and thicker if the flow is pre-aerated, whereas flow zones below the jet surface are only slightly turning to white indicating lower air concentrations. Further, the black-water core within the jet starting at take-off is distinctively shorter for pre-aerated than for black-water approach flows.

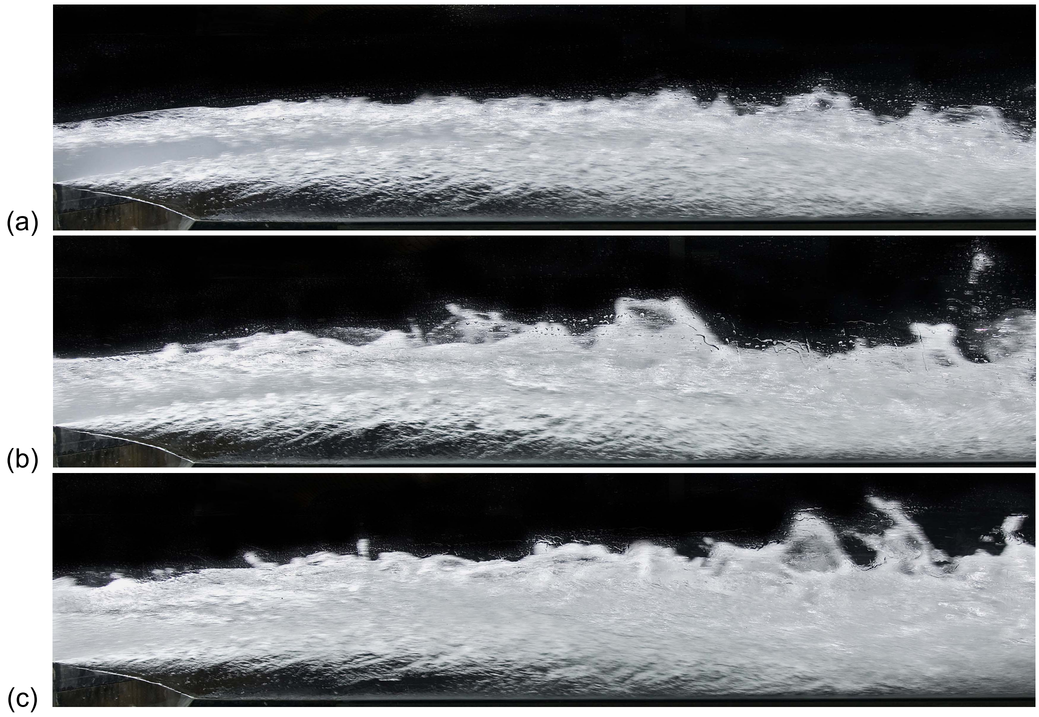

Figure 3 Model jets for F_o=9, h_o=0.065 m, α=5.7°, t=0.027 m, and C_{ao}= (a) 0.06, (b) 0.15, and (c) 0.24 (Series 5)

The coordinate *z* was normalized with the jet thickness (z_U–z_L) at each section *x* as (Fig. 1)

$$Z = \frac{z - z_L}{z_U - z_L} \tag{2}$$

resulting in cross-sectional air concentration profiles between the upper *Z*=1 and the lower *Z*=0 jet surfaces. Figure 4 shows typical profiles for a deflector-generated jet with and without pre-aeration, under otherwise similar conditions. The jet with un-aerated approach flow (Fig. 4a) has a black-water core of minimum (subscript *m*) sectional air concentration of C_m<0.01 up to *x*≅0.73 m, whereas this length is only *x*≅0.25 m for the pre-aerated jet (Fig. 4b). Downstream of the black-water core the minima C_m are located roughly at 0.7*Z* for black-water approach flow, and at roughly 0.4*Z* for pre-aeration. This again points at the dominant effect of pre-aeration on flow zones close to the upper jet surface (Fig. 2a), whereas the lower jet zones are hardly affected. It is furthermore visible that the total air transport in terms of C_a (Eq. 1) is larger for pre-aerated than for black-water approach flows.

Figure 5 shows the effect of pre-aeration C_{ao} on the value C_a(*x*=0) at jet take-off, both normalized with C_{au}. Note that all values of C_a(*x*=0) are above these of C_{ao} as indicated by the grey area in the figure, corresponding to an average air concentration at jet take-off that is larger than at approach flow due to pre-aeration. This results from the deflector generating additional surface air entrainment due to the increased turbulence as a consequence of flow deflection (Ervine et al., 1995). An increasing trend is further observed: as C_{ao} increases, also $C_a(x=0)$ becomes larger. Yet there is a limit for $C_a(x=0)$ at C_{au}, i.e. only few points are located above $C_a(x=0)/C_{au}=1$. This relates to the maximum transport capacity for uniform flow conditions. For a high degree of pre-aeration, for instance $C_{ao}/C_{au}=1$, the effect of the deflector air entrainment is close to zero, whereas it reaches to almost $0.7C_{au}$ for $C_{ao}/C_{au}=0.2$. "Saturated" flows, as those with $C_{ao}=C_{au}$, can therefore not entrain additional air, even with a deflector and its air entraining potential due to the saturation limit.

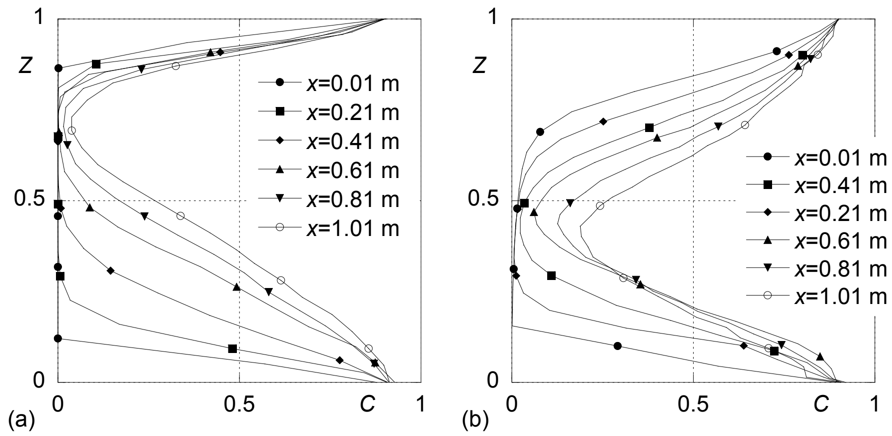

Figure 4 Air concentration profiles $C[Z]$ of Tests (a) 176 with $C_{ao}=0.06$ and (b) 177 with $C_{ao}=0.24$, for otherwise identical conditions

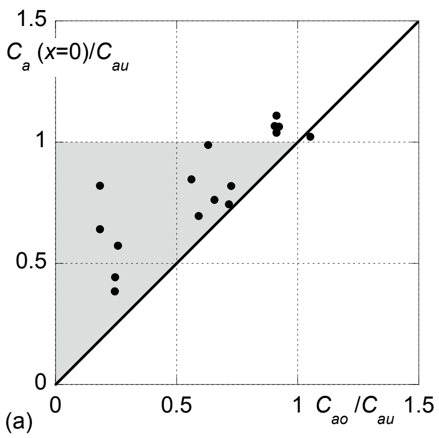

Figure 5 $C_a(x=0)$ compared with pre-aerated value C_{ao}, both normalized with C_{au}

4.2. Black-water core length

The black-water core length L describes the distance between jet take-off at $x=0$ and the cross-section, where $C_m=0.01$ within a jet profile. Accordingly, a black-water core with $C_m<0.01$ results along L, while the residual jet consists of mixture flow with $C_m>0.01$. As shown in Fig. 6a, a small pre-aeration of up to $C_{ao}\cong 0.15$ hardly reduces L/h_o, as compared with the reference value $C_{ao}=0$, whereas an intense pre-aeration in the range of $C_{ao}=C_{au}=0.23$ drastically reduces L. The derivation of L as a function of the relevant parameters is given in the basic study (Pfister and Hager, 2009). Here, the effect of C_{ao} is additionally considered, resulting in the addition of the term $-6C_{ao}^3$ to the original equation. Accordingly, L reduces with increasing C_{ao} (Fig. 3), yet with a small effect for marginal C_{ao}, but for instance with $-7h_o$ for $C_{ao}=0.25$. This modification results in

$$\frac{L}{h_o} \cong 74\left[\mathsf{F}_o^{-1}(1+\tan\alpha)^{-0.5}(1+\sin\varphi)-6C_{ao}^{3}\right] \quad \text{for } 4<L/h_o<20 \tag{3}$$

Equation (3) and the measured values are compared in Fig. 6b, with the abscissa normalization as $\Phi_L = \mathsf{F}_o^{-1}(1+\tan\alpha)^{-0.5}(1+\sin\varphi)-6C_{ao}^3$ from Eq. (3), indicating a good agreement. The data of the basic study are also included in the figure, because it may be estimated that $C_{ao}<0.10$ there, so that its small effect of C_{ao} on L is around $-0.4h_o$. Note that the herein used definition of L up to $C_m=0.01$ implies that smaller values of C_m exist upstream of L. This may not be the case for very steep chutes, where $C_m>0.01$ even in the approach flow, asking for a revision of the present definition of L.

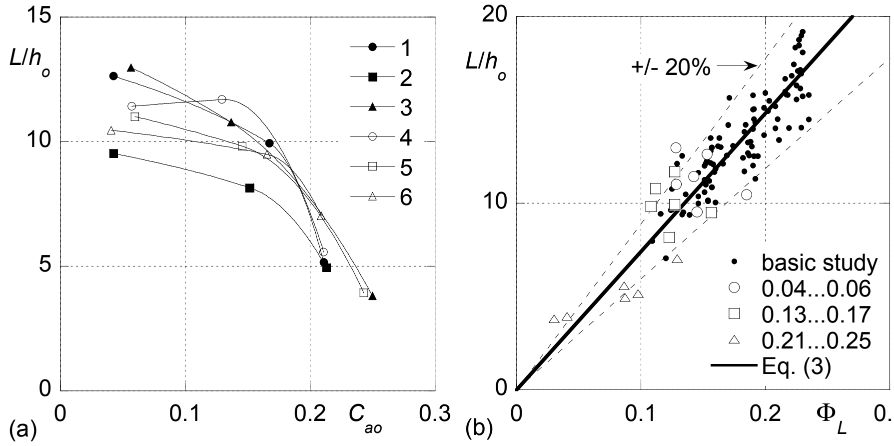

Figure 6 Relative black-water core length L/h_o versus (a) C_{ao} with test series numbers (Table 1) and (b) Φ_L for various C_{ao} ranges

The jet air concentration development was found to depend on L in the basic study, such that the streamwise coordinate x is normalized as

$$\chi = \frac{x}{L} \tag{4}$$

4.3. Minimum air concentration

The vertical location of the minimum jet air concentration C_m depends on the degree of approach flow pre-aeration. For the basic study and the additional tests with $C_{ao}<0.10$, all C_m were located at approximately 0.6 to 0.8Z, as shown in Fig. 7a. The elevation z_m of C_m was inserted in Eq. (2) to derive Z. For these jets, the disintegration takes place mainly along the lower jet trajectory initiated by the deflector-generated turbulence, whereas the flow surface remains relatively smooth. For intermediate C_{ao} values between 0.13 and 0.17 the minima occur in the jet centre around $Z=0.5$, and for maximum C_{ao} they were measured at roughly 0.4 to 0.5Z. With increasing pre-aeration, the minimum air concentrations are consequently shifted toward the jet centre or even slightly below it, resulting from increasing air transport close to the flow surface in the approach flow, as shown above.

The minimum cross-sectional jet air concentration at $\chi=1$ is by definition $C_m=0.01$ and significantly increases further downstream. The test data were found to depend on both, χ and the degree of pre-aeration. If applying the equation derived in the basic study as $C_m=0.1(\chi-1)^{1.5}+0.01$, the highly-pre-aerated tests are over-predicted. The term added in Eq. (3) therefore overestimates the effect of C_{ao}, so that a slightly modified equation for C_m as compared to the basic study was derived, yet by including the basic test data, assuming that there $C_{ao}=0.05$ equal to $C_{ao}/C_{au}=0.2$, as for the tests 164, 167, 170, 173, 176 and 179 “without” pre-aeration (Table 1). Then, the minimum cross sectional air concentration C_m follows as ($R^2=0.95$)

$$C_m = 0.17(\chi - 1)^{1.5}\left(1 + \frac{C_{ao}}{C_{au}}\right)^{-2.25} + 0.01 \qquad \text{for } 1 \le \chi \le 4 \qquad (5)$$

The exponent relating to pre-aeration is negative, so that C_m values decrease with increasing C_{ao}. The effect of C_{ao} on C_m is accordingly smaller than that on L. Figure 7b shows the data of the basic and the present study, and compares them with Eq. (5). The data with pre-aerated flow essentially collapse with the other values. The abscissa of Fig. 7b was normalized as $\lambda=(\chi-1)(1+C_{ao}/C_{au})^{-1.5}$ from Eq. (5), with a best data fit for $0.17\lambda^{1.5}$ validating Eq. (5).

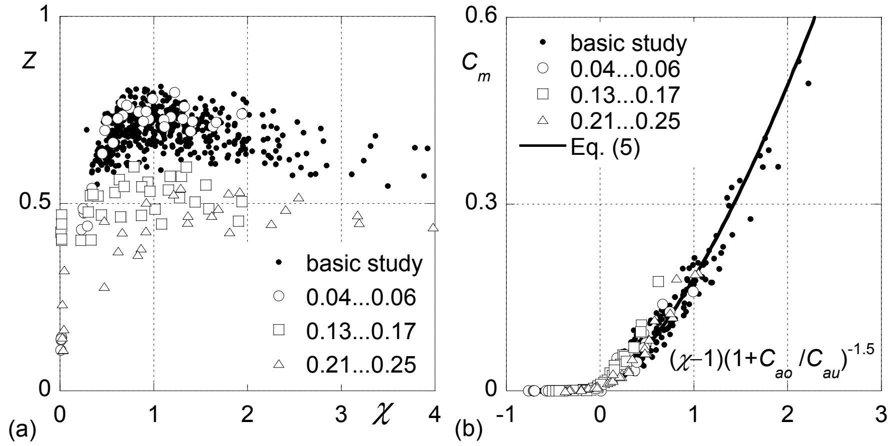

Figure 7 (a) Location of C_m expressed with $Z(\chi)$ within jet, and (b) C_m versus λ for various ranges of C_{ao} according to legend

4.4. Average air concentration

The most relevant parameter describing the jet features is, besides C_m, the streamwise development of the average air concentration C_a, analogous to Eq. (1). The data trend indicates that the identical equation as proposed in the basic study may be applied, taking into account the effect of pre-aeration via Eqs. (4) and (3). The present data and these of the basic study are described as (R^2=0.93)

$$C_a = \tanh\left(0.4\chi^{0.6}\right) \qquad \text{for } 0 \le \chi \le 4 \qquad (6)$$

Figure 8 compares the test data with Eq. (6) showing good agreement. For intense jet aeration, say $C_a \rightarrow 0.9$, a development length of $\chi \rightarrow 9$ is necessary, which is however beyond the limitation of Eq. (6).

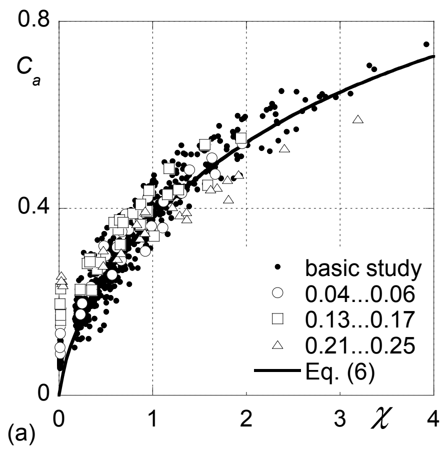

Figure 8 Test data and Eq. (6) for $C_a[\chi]$

In Fig. 8, some measured C_a values at χ=0 are above the prediction of Eq. (6). These include the pre-aeration as well as the additional deflector-generated air entrainment, as explained in the context of Fig. 5. Accordingly, mostly points for large C_{ao} are above other values. The effect on the further development of $C_a[\chi]$ is, however, included in Eqs. (3) and (4), as is demonstrated by Fig. 8.

5. CONLUSIONS

Chute deflectors are jet-generating structures with constructional advantages as compared to flip buckets. The related streamwise jet air concentration distributions were systematically investigated in a basic study, analysing the effect of the relevant flow parameters including the approach flow depth h_o, the approach flow Froude number F_o, and the geometrical parameters deflector height t, deflector angle α and chute bottom slope φ. The effect of pre-aerated approach flow was ignored so far. Additional model tests were therefore conducted herein to systematically vary the average approach flow air concentration. A pre-aerated approach flow is more realistic in prototypes than un-aerated black-water, as jets occur at the chute end, where the flow is typically aerated to a certain extent.

Pre-aeration mainly affects flow zones close to the water surface and along the upper jet trajectory, because the additional air is *a priori* transported close to the surface as known from the standard uniform flow air profile in chutes. It was further found that the air concentration development may be correlated with the jet black-water core length. A term including the effect of pre-aeration was added to the equation derived in the basic study, indicating that pre-aeration reduces the black-water core length. Based on this length, equations for the streamwise growth of the average and minimum jet air concentrations were derived generalizing the original proposals to pre-aerated approach flow conditions. The minimum cross-sectional air concentration is reduced under pre-aeration if expressed as a function of the (also reduced) relative black-water core length. The average air concentration development, in contrast, is exclusively represented by the relative black-water core length.

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