THE ONSET OF AIR ENTRAINMENT

AT BOTTOM SLOTS

by

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Der Beginn des Lufteintrages bei Sohlennischen

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THE ONSET OF AIR ENTRAINMENT AT BOTTOM SLOTS

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SUMMARY

With certain kinds of structures on the bottom of a channel, air can be entrained in a highly turbulent flow. Above some minimum air content, small air bubbles just above the bottom afford protection against "cavitation erosion." In this connection, the onset of air entrainment at slots is studied, and a relation is found between the flow velocity and the water depth at which the inmixing of air begins. The results are in agreement with observations of water-air mixing processes due to turbulence at the interface.

1. Introduction

The interaction of water and air, in the aspect of importance to hydraulic engineering, has been studied many times. On the basis of these results, which are set forth in numerous publications--a few essential monographs can be cited [1-6]--this article states some physically well-established laws that bear on the onset of water-air mixing in special aeration structures (slots).

The way in which a water-air mixture is generated depends on the type of entrainment process. For example, air can be entrained in a natural way or artificially, such as by injection. Air entrainment at slots--this is one of many aeration arrangements (Fig. 1)--is due to

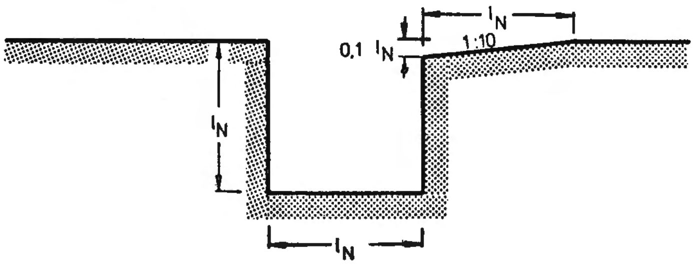

Fig. 1. Dimensions of the bottom slot studied.

the injector action of the water flow as it passes the slot. The process is therefore called "self-aeration." When the slot is fully functional, the process results from turbulence at the interface between water and air and/or high turbulence that is localized, that is, over a well-defined part of the flow perimeter. Fig. 2 shows the flow for optimal air entrainment in the immediate vicinity of the slot illustrated in Fig. 1. In the mixing process it is assumed that the

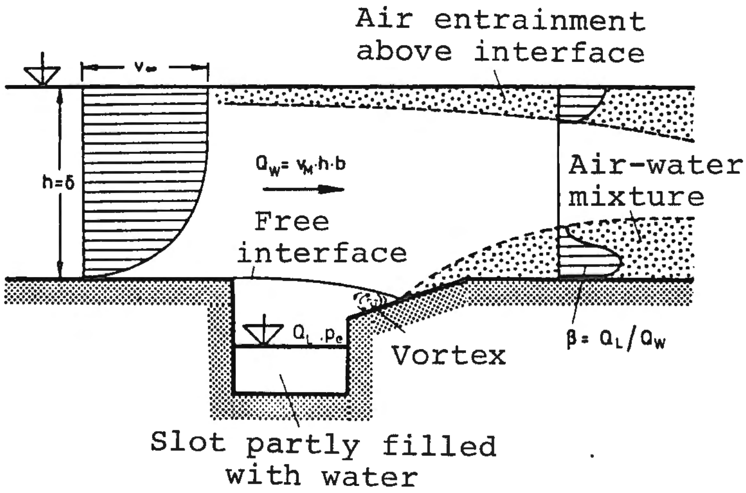

Fig. 2. Air entrainment at a slot.

water is oxygen-saturated, so that no air in the form of atmospheric oxygen goes into solution in the water.

At the onset of air entrainment, the water-air interface is not yet present over the slot (Fig. 3). Instead, there is a well-defined

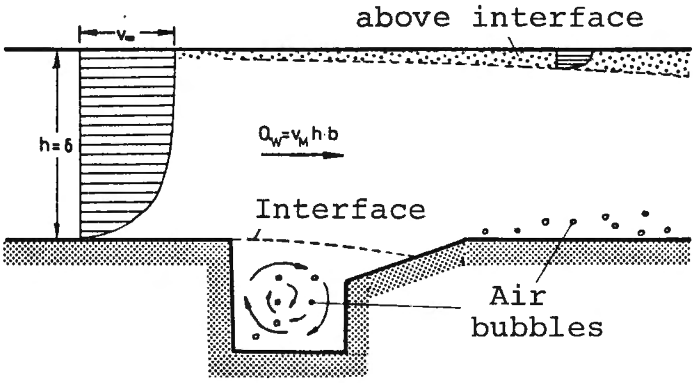

Fig. 3. Flow over the slot at the onset of air entrainment.

(but sometimes guided) turbulent shear flow that gives rise to water circulation in the slot by transmitting shear stresses across the interface. The water not only fills the slot but also stands in the lateral slots provided as air shafts. Despite this air exclusion, air bubbles above the slot are mixed into the flow starting at a critical velocity. The air bubbles are generated at the free water surface in the air shafts, which moves vigorously and resembles a vortex field fed by the circulation in the slot. By the conservation of angular momentum, the angular momentum excited in the slot ought to be of the same order of magnitude as the critical angular momentum at the free surface, at which air is entrained. Because of the shape of the air shaft, especially the 90° deflection, the vortex field is not only distorted but also attenuated in its intensity.

The onset of air entrainment is defined as the condition in which a few air bubbles revolve in the slot and are carried out with the flow from time to time. The air flow rate Q_L cannot yet be measured.

2. Formula for Computing the Onset of Air Entrainment

In flow over a slot, air is transported into the slot from the space over the free surface starting at a critical velocity v_{crit} (Fig. 4). This critical velocity depends on the process that governs the material parameters:[1] the density of the air ρ_L, the dynamic viscosity of the air η_L, the density of the water ρ_W, the dynamic viscosity of the water η_W, and the capillarity at the interface $\kappa_{L,W}$.

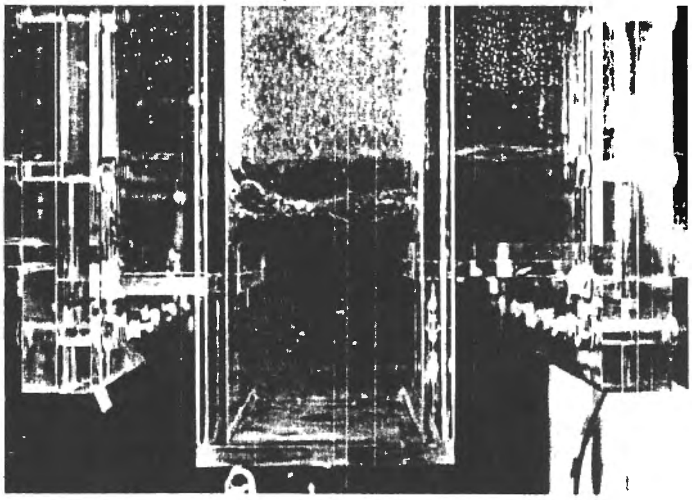

Fig. 4. Air bubbles are entrained through the free surface in the lateral slot (air shaft). The air shaft (foreground) always has the same dimensions as the bottom slot. The flow cross section and air shaft are separated by a partition.

The critical velocity is also affected, however, by geometric parameters such as water depth h and slot dimension $\mathcal{l}_N$. The relation becomes simpler if we assume that the flow inside the entrained air bubbles has only a negligibly small influence in comparison with the liquid flow. If, further, the gravity-controlled flow process is regarded as two-dimensional and the degree of turbulence is constant, the functional relation is then

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[1]Translator's Note: The original has "...ist von dem den Stoffwerten...bestimmenden Vorgang abhängig," with the meaning stated above. Possibly "depends on the parameters...governing the process" or "depends on the process governed by the parameters..." was meant.

$$f(h, \ell_N, v_{crit}, g, \rho_W, \eta_W, \kappa_{L,W}) = 0 \qquad (1)$$

A dimensional analysis yields the parametric equation

$$\Phi\left(\frac{h}{\ell_N}, \frac{v_{crit}}{(gh)^{1/2}}, \frac{v_{crit}h}{\eta/\rho}, \frac{v_{crit}^2 h}{\kappa/\rho}\right) = 0 \qquad (2)$$

where $v_{crit}/(gh)^{1/2}$ is the Froude number of the flow,

$v_{crit}h/v$ is the Reynolds number, and

$v_{crit}^2/(\kappa/\rho)$ is the Weber number.

If we further assume that the ratio h/ℓ_N is constant, Eq. (2) simplifies to

$$v_{crit} = \sqrt{gh}\ \ \phi_1\,(Re, We) \qquad (3)$$

Thus the critical velocity depends only on the depth of the flow and the function Φ_1(Re,We); that is, in the experiment we seek the relation Fr = f(Re,We).

3. Experimental Determination of the Function Φ_1(Re,We)

The experiments were conducted at the Institut für Wasserbau und Wasserwirtschaft [Institute for Hydraulic Engineering and Water Resources Management], Berlin Technical University, with support from the Deutsche Forschungsgemeinschaft [German Research Foundation]. Fig. 5 is a view of the experimental setup. Dipl.-Ing. D.-W. Lante's participation in the tests was crucial.

Tests were performed on five square slots (Fig. 1) of different sizes (ℓ_N = 2, 4, 6, 8 and 10 cm). In the series of trials with one slot size, the ratio h/ℓ_N was varied over the range of $0.1 \leqq h/\ell_N \leqq 5$, including the value $h/\ell_N = 1.0$, so that the condition of constant h/ℓ_N could be satisfied.

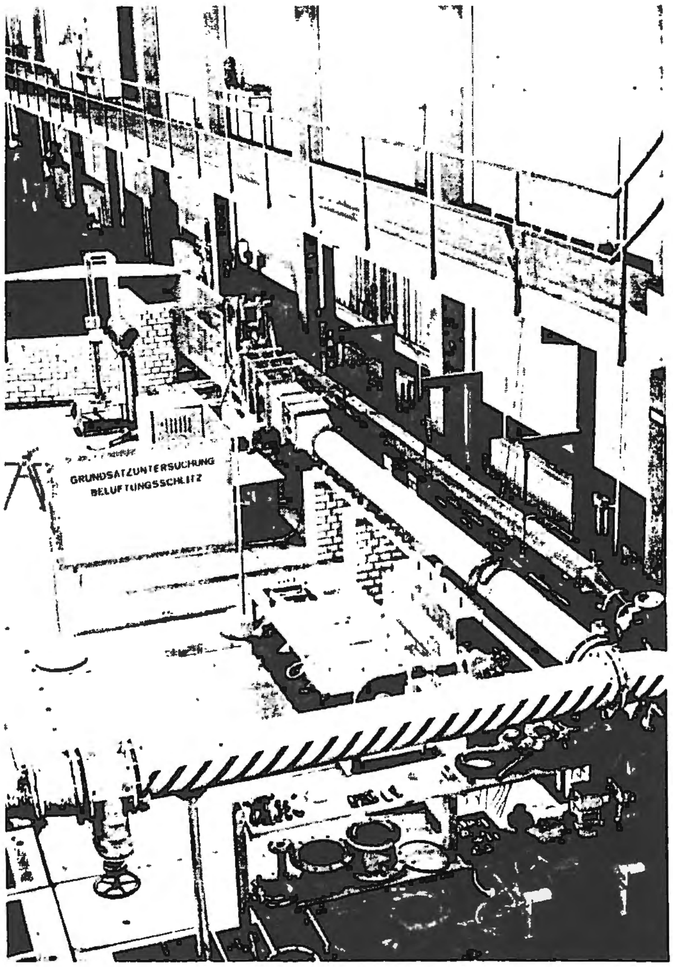

Fig. 5. View of the experimental setup with overhead tank.
[Translator's Note: The sign, center left, reads "Fundamental Study: Aeration Slot."]

The experimental method was as follows. First, a predetermined water depth was established with a weir. Then the cylindrical-piston valve in the supply line was opened until air bubbles appeared in the water-filled bottom slot (Fig. 4). The critical velocity was determined at this time.

The results are plotted in the form Re = f(We) in Fig. 6. They can be described as

$$\log Re = \log a + b \log We,$$

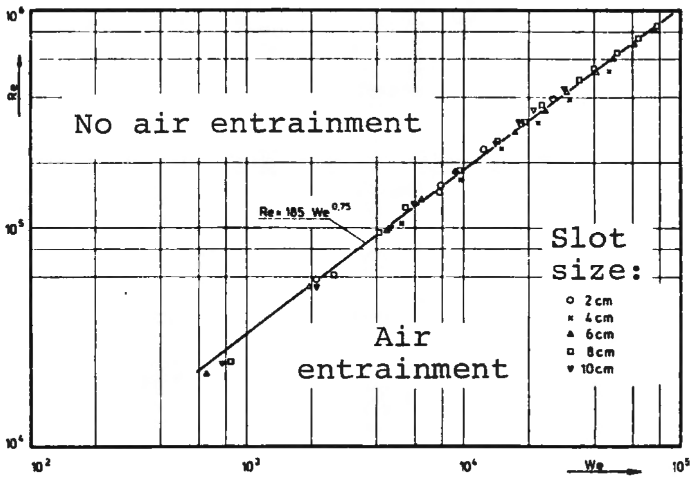

Fig. 6. Re = f(We) for the onset of air entrainment.

which yields

$$Re = 185\ We^{0.75} \tag{4}$$

after linear regression analysis.

This equation for the onset of air entrainment, in the form

$$\frac{Re}{We^{3/4}} = 185,$$

can be transformed to

$$v_{crit}/(gh)^{1/2} = \frac{(\kappa/\rho)^{3/2}}{\nu^2\sqrt{g}}\,\frac{1}{185^2} \tag{5}$$

Thus the Froude number at the onset of aeration can be calculated as

$$Fr = \text{const}\ Z^{1/2}. \tag{6}$$

The material parameter Z was used earlier by Engels [7]; other than the acceleration of free fall, it depends only on the properties of liquids.

If a water temperature of T = 20°C is assumed, then with the values

capillarity κ = 0.0726 N/m,
water density ρ = 998.2 kg/m^3,
kinematic viscosity v = 10^{-6} m^2/s,
acceleration of free fall g = 9.81 m/s^2, and thus[2]

$$Z = \frac{(\kappa/\rho)^3}{\upsilon^4\, g} = \frac{(0{,}0726/998{,}2)^3}{(10^{-6})^4 \cdot 9{,}81} = 3{,}92 \cdot 10^{10}$$

it follows from Eq. (6) that the Froude number is

$$Fr = (1/185^2)(3.92 \cdot 10^{10})^{1/2} = 5.8,$$

so that the critical velocity from Eq. (3) is proportional to the square root of the water depth:

$$v_{crit} = 18.17h^{1/2}. \quad (7)$$

4. Onset of Natural Air Entrainment in Other Cases

The statement that air entrainment begins at certain Froude numbers is not novel. Dorer [1] says that the occurrence of "white water" in flow through chutes marks the beginning of air entrainment. Using further model results [8], he derives the relation

$$Re = 119\ We^{3/4}, \quad (8)$$

which implies that the Froude number varies with the temperature, from Fr = 8.1 (T = 10°C) to Fr = 13.4 (T = 20°C). It must be noted, however, that the parameters here relate to flow in rectangular channels, so that the hydraulic radius was used instead of the depth.

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[2]Translator's Note: In reproduced numbers, commas denote decimal points.

Besides the data on air entrainment through turbulence at the water-air interface, there is other information about the onset in water jets entering cushioning pools. Here too, air is entrained because of the turbulence at the interface between the jet and the still water. Experiments performed by Lin [9] with laminar jets led to the relation

$$\mathrm{Re} = 0.045\ \mathrm{We}^{1.35}. \tag{9}$$

As a representative length he uses the jet diameter d before submersion. The critical velocity at the onset of air entrainment is given approximately by

$$v_{crit} = \mathrm{const}\ d^{-1/5}. \tag{10}$$

This means, first, that only when the jet diameter is very small does it affect the onset of air entrainment, but otherwise air entrainment begins at a constant velocity of $v \simeq 10.8$ to 12.5 m/s. Second, from Eq. (10) it follows that there is a dependence on the Froude number.

A similar result is found for air entrainment when a liquid jet ascends vertically into a liquid and is deflected at the free surface. Higginbottoms' [10] equation for the onset of air entrainment is

$$\mathrm{Re} = 575\ \mathrm{We}^{0.62}. \tag{11}$$

The Reynolds and Weber numbers here were formed with the fictitious velocity v and the fictitious jet diameter d at the level of the undisturbed free surface (see the sketch), which in turn can be calculated from v_0, d_0 and h.

5. Discussion

An important finding is that the onset of air entrainment does not depend on the size of the slot $\mathcal{l}_N$. From this we can conclude that the length of the interface has no effect and that the process is controlled only by the difference between the pressure below the interface and atmospheric pressure and by the degree of disturbance of the free surface in the aeration shaft. It can be asked whether this behavior is typical of all types of aeration equipment or applies only to slots. No results are available on this point. The author intends to find an answer to this question, at least for a bottom slot with a ramp.

It is interesting to observe that, after the onset of air entrainment, there is not much change in the state of flow if the velocity is further increased. The air flow rate Q_L is now measurable, but the interface is still present. Starting at a certain velocity, the free bottom surface appears suddenly, and it can be seen that from this point on there is a completely different state of flow subject to different laws. Incompletely interpreted trials with slots appear to bear this statement out.

The relationship between flow velocity and depth in the channel, as stated in Eq. (7), shows that the velocity at the onset of air entrainment may be fairly low (e.g., a water depth of h = 0.05 m gives v_{crit} = 4.06 m/s), while it is substantially greater than the values cited in the literature (e.g., a water depth of h = 1 m gives v_{crit} = 18.17 m/s). A similar relation is known from boundary-layer theory, where the rate of shearing v_0* is proportional to $h^{1/2}$.

An important conclusion is that the results can be applied in roughly the same form to all flows over slots. The generality of Eq. (7), which gives the onset of air entrainment, is restricted if the Reynolds or Weber number is below some limit. According to the experiments, this value is $Re \leqq 5 \cdot 10^4$ or $We \leqq 2 \cdot 10^3$.

A further result is that the onset of air entrainment through slots is not subject to any scale effect if Froude's law of similarity holds and the stated limits on the Re and We numbers are not violated. It must be established that these conditions were not always met in the model tests carried out elsewhere.

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