DISCUSSION / DISCUSSION

Discussion of "Effect of jet aeration on hydrodynamic forces on plunge pool floors"¹

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The Discussers congratulate the Authors for their interesting work in the field of hydrodynamic forces on plunge pool floors. The Authors present the effect of jet aeration on mean dynamic pressures at pool floors, based on both analytical computations and small-scale laboratory measurements. Based on air sucked into low-velocity water jets (V = 3.53 m/s), they obtained air concentrations close to the stagnation point of the developed jet at the pool floor of max. 30%. The exact pool depth is not provided by the Authors, but has been estimated by the Discussers at roughly 0.70 m, for a jet thickness at impact of roughly $0.70/11.5 \sim 0.06$ m (*h/b* = 11.5, being the diffusion length). The corresponding mean dynamic pressure head at jet issuance is thus about 0.65 m. Superposition with the static water head of 0.70 m provides a total relative head of about 1.35 m at the pool floor.

The Discussers measured mean air concentrations in plunge pools at the Laboratory of Hydraulic Constructions of the École Polytechnique Fédérale de Lausanne, Switzerland for high velocity plunging jets (Manso 2006; Manso et al. 2006). The experiments document void fractions at singular points in plunge pools with a flat bottom. Air was entrained naturally in the pool at the jet plunging section. Rough turbulent water jets with very high velocities (up to 30 m/s) were used to replicate prototype pool aeration conditions typically found at large dam spillways. This allows creating air entrainment conditions exempt of significant scale effects in terms of Weber, Reynolds, and Froude numbers.

Air concentrations (void fractions) were measured by means of a double fibre-optical probe. Three measurement points (MP) were selected inside the pool (Fig. 1): (i) in the impingement zone of the jet (MP1), (ii) in the transition to the wall jet region (MP2), and (iii) just above the impinging jet region (MP3), 10 cm above the pool floor for different pool depths and run times.

The results are presented as a function of jet issuance ve-

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locity in Fig. 2 for Y/D (~h/b following the Authors' nomenclature) between 2.8 and 9.3, in which Y stands for the plunge pool depth and D for the jet diameter at impact. At the jet's stagnation point, measured void fractions were only between 2% and 8%, regardless of the jet issuance velocity and the total acquisition time. Radially away from the stagnation point, but still along the pool floor, void fractions are highly dependent on the jets' issuance velocity and reached up to 40%.

In other terms, at low jet velocities (V < 10 m/s), void fractions at the jet's stagnation point are quite similar to the ones measured radially outwards, while at high jet velocities (V > 20 m/s), void fractions at the jet's stagnation point are up to about 5–6 times less than the ones measured radially outwards. A similar trend has been observed at measurement point 3 (MP3, Fig. 2), although less expressed than at MP2.

Second, for h/b = 9.3, i.e., close to the Authors' value of 11.5 and also generating fully developed and aerated jets, the measured void fractions have been compared for the three measurement locations (Fig. 3). At low jet velocities (V < 10 m/s), all locations generate about the same void fractions, while at high jet velocities (V > 20 m/s), the region radially outwards from the jet's stagnation point has the highest void fractions, followed by the region 10 cm above the pool floor but still along the jet's centreline. The radially outwards wall jet region has the lowest void fractions.

Hence, the void fraction seems to be related to the pressure built-up when approaching the jet's stagnation point and to the sudden pressure decrease following radial jet deflection after pool floor impact. By applying the ideal gas law, $pV^{nn} = mRT =$ cte, in which p stands for pressure, T for temperature, R for a thermodynamic constant, m for the mass of the moles of the gas in a given volume V and n a constant that depends on the type of thermodynamic process (n = 1 for adiabatic processes), the volume reduction ΔV of a given quantity (mass) of air is inversely proportional to the rise in absolute pressure Δp . The amount of air does not change, only the size of the bubbles changes due to a variation of absolute water pressure.

Following this law and assuming near atmospheric pressures upon jet impact in the water cushion, Table 1 lists the so-computed air volume reduction ratios as a function of jet velocity. Based on high-velocity measurements, the mean dynamic pressures at the pool floor can be roughly estimated at $0.5V^2/2g$ (average value within the range Y/D = 2.8-9.3), to which the static pressure of 0.67 m (water cushion) has been added. Figure 3 compares the so determined void fracFig. 1. Positioning of optical probe and measurement points of void fraction (Manso 2006).



Fig. 2. Void fractions measured for different pool depths (2.8 < Y/D < 9.3) and different acquisition times (Manso et al. 2006): (*a*) at point 1 (MP1) located at the jet stagnation point (centreline); (*b*) at point 2 (MP2), in the wall jet region away from the stagnation point.



Fig. 3. Measured void fractions as a function of jet issuance velocity, measured for Y = 0.67 m (Y/D = 9.3) at the three measurement points.



tions close to the jet's stagnation point with the measured values at both points MP1 and MP3. A striking similarity can be observed for all jet velocities.

As pointed out in Bollaert (2002) and Manso et al. (2006), other phenomena may influence the void fraction near the stagnation point of the jet, such as air bubble migration to



Table 1. Estimate of the void fraction reduction ratio as a function of jet velocity, based on the ideal gas law.

Jet velocity, V (m/s)	Water cushion impact, <i>P</i> _{impact} (m abs)	Pool floor impact, <i>P</i> _{floor} (m abs)	Air reduction ratio = $1/(P_{impact}/P_{floor})$
5	10	11.3	1.13
10	10	13.2	1.32
20	10	20.9	2.09
25	10	26.6	2.66
30	10	33.6	3.36

lower pressure regions or air solution and gasification. Bollaert (2002) and Bollaert and Schleiss (2003) estimated from pressure measurements void fractions inside joints of the pool floor between 1% and 10%, i.e., of the same order of magnitude of the aforementioned measurements of Manso (2006) at the pool floor itself.

As such, the Discussers would like to point out the importance of using prototype values of jet velocities and stagnation pressures at impact when determining the influence of air on the mean dynamic pressures at the pool floor. It is obvious that when artificially aerating a low-velocity jet, void fractions of 30%–40% may easily be reached, not only at the point of impact of the jet in the water cushion, but also close to the stagnation point on the pool floor itself. Based on the Discussers' high-velocity jet impact tests, however, this seems only possible on a small-scale laboratory model, for which absolute stagnation pressures remain quite low due to the scale of the model.

The Discussers' prototype velocity measurements of void fractions show that, at jet impact in the water cushion, very high void fractions can be reached, but that, at the jet's stagnation point on the pool floor, typical void fraction values are only between 2% and 8%. At such low fractions, the buoyancy effect as determined based on eq. [10] of the Authors becomes rather marginal.

Furthermore, the Discussers believe that jet stability and prototype turbulence intensity have significant influence on both the mean and fluctuating dynamic pressures at the stagnation point of the jet on the pool floor. Pressure recordings at high jet velocities have shown this influence (Bollaert and Schleiss 2003).

As a conclusion, the Discussers would like to state that scale effects of aeration are also important close to the pool floor, and not only at the surface of the water cushion as pointed out by the Authors. Also, the assumption of a constant air volume $V_{\rm air}$ (eq. [7]) throughout the water depth becomes questionable when accounting for the Discussers' results on significant pressure built-up near the stagnation point of a prototype jet on the pool floor. In principal, this effect should be considered when testing the importance of the depth of a real plunge pool onto hydrodynamic forces on concrete slabs.

Finally, the air content at the pool floor has a direct influ-

ence on the air content inside the joints underneath the concrete slabs, and the so generated dynamic pressure fluctuations underneath the slabs may, beside the mean pressure value, also be of importance to compute slab uplift (Bollaert 2003).

References

- Bollaert, E.F.R. 2002. Transient water pressures in joints and formation of rock scour due to high-velocity jet impact. Ph.D. thesis, No. 2548, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, Communication No. 13 of the Laboratory of Hydraulic Constructions. *Edited by* A. Schleiss.
- Bollaert, E.F.R. 2003. The influence of joint aeration on dynamic uplift of concrete slabs of plunge pool linings. *In* Proceedings of the XXXth IAHR Congress, Thessaloniki, Greece, Theme D. pp. 503–510.
- Bollaert, E.F.R., and Schleiss, A.J. 2003. Scour of rock due to high velocity plunging jets: Part II: Experimental results of dynamic pressures at pool bottoms and in one-and two-dimensional closed-end rock joints. Journal of Hydraulic Research, 41(5): 465–489.
- Manso, P.A. 2006. The influence of pool geometry and induced flow currents in rock scour by high-velocity plunging jets. Ph.D. thesis No. 3430, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, Communication No. 25 of the Laboratory of Hydraulic Constructions. *Edited by* A. Schleiss.
- Manso, P.A., Bollaert, E.F.R., Schleiss, A.J., and Matos, J. 2006. Experimental investigation on plunging jets: The behaviour of entrained air bubbles in the vicinity of a flat pool bottom. *In* Proceedings of the International Symposium on Hydraulic Structures, Ciudad Guayana, Venezuela. pp. 370–379.