Understanding Air-Water Mass Transfer in Rectangular Dropshafts

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Abstract: A dropshaft is a vertical structure connecting two channels with different invert elevations. Four configurations of rectangular dropshafts were investigated systematically to study the effects of outflow direction and pool depth on particle residence times and flow aeration. The best hydraulic design was that with 180° outflow direction and deep pool shaft. For that design, a full-scale study was conducted, the scaling ratio between prototype and model being 3.1:1. Although similar trends were seen in both model and prototype, scale effects were observed in terms of particle residence times and bubble swarm depths. In the prototype, detailed air-water flow measurements were performed in the shaft pool and the mass transfer equation was integrated using measured interfacial areas and particle residence times. The results demonstrate that the air-water mass transfer is the largest at low flow rates (regime R1) because of large residence times and significant interfacial area. Overall the present study provides new understanding of the basic mechanisms of air-water mass transfer in rectangular dropshafts.

Key words: dropshaft, mass transfer, aeration, hydraulics

Résumé

Mots-clés:
**Introduction**

A dropshaft is a vertical structure connecting two channels with different invert elevations (Fig. 1 & 2). Figure 1 presents a full-scale dropshaft (prototype AA, see below) operating under controlled flow conditions in laboratory. Figure 1A shows a small discharge while Figure 1B illustrates a large flow rate. Dropshafts are commonly used in sewers and storm water systems: e.g., in München, Paris, Tokyo (Rajaratnam et al. 1997, Toda and Inoue 1999, Merlein et al. 2002). Small dropshafts are also used upstream and downstream of culverts (Apelt 1984), while large spillway shafts were built (Vischer and Hager 1998). The dropshaft is an ancient design. For example, some Roman aqueducts included series of dropshafts (Chanson 2002a). There is however a controversy if these dropshafts were used solely for energy dissipation or in combination with flow re-aeration, but it will be shown that their design was efficient for both applications. Despite such long usage, the hydraulics of dropshafts has not been systematically documented, but for few studies: Apelt (1984); Rajaratnam et al. (1997); Merlein et al. (2002).

In modern water treatment plants, the combination of flow aeration and high flow turbulence enhances greatly the mass transfer of volatile organic compounds such as chlorine (Corsi et al. 1992). Detailed studies of mass transfer at dropshafts are limited however (Rahme et al. 1997). The literature often relies upon air-water mass transfer experimental results at free-overfall and drop structures: e.g., Avery and Novak (1978); Nakasone (1987).

**Basic equations of air-water gas transfer**

Fick's law states that the mass transfer rate of a chemical across an interface normal to the x-direction and in a quiescent fluid varies directly as the coefficient of molecular diffusion $D_{gas}$ and the negative gradient of gas concentration:

$$\frac{\partial}{\partial t} M_{gas} \propto - D_{gas} \left( \frac{\partial}{\partial x} C_{gas} \right)$$

where $C_{gas}$ is the concentration of the dissolved chemical in liquid and $t$ is the time. The analysis of the fluid layers surrounding a gas bubble is very complicated because of the bubble shape, the presence of laminar or turbulent flow, a mobile interface in the case of large
air bubbles and the interactions between concentration boundary layers from adjacent bubbles. When the particular chemical is volatile (e.g. oxygen, chlorine), the transfer is controlled by the liquid phase and the coefficient of transfer is almost equal to the liquid film coefficient which is a function of the salinity, temperature, surfactants and to a lesser extent the pressure. For volatile gas in a liquid, the mass transfer equation [1] becomes:

\[ \frac{\partial}{\partial t} C_{\text{gas}} = K_L \cdot a \cdot (C_s - C_{\text{gas}}) \]

where \( a \) is the specific surface area defined as the air-water interface area per unit volume of air and water, \( C_s \) is the concentration of dissolved gas in water at equilibrium and \( K_L \) is the liquid film coefficient (Gulliver 1990, Jirka 1991). Although some studies implied that the term \( (K_L \cdot a) \) was constant, this assumption is incorrect. Detailed studies showed that the mass transfer coefficient \( K_L \) in turbulent gas-liquid flows is almost constant regardless of bubble sizes and flow situations (Kawase and Moo-Young 1992), but the interface area varies greatly along a hydraulic structure as a function of the air-water flow properties.

[2] demonstrates that the rate of mass transfer is proportional to the residence time and air-water interfacial area. In a dropshaft, both contributions are significant (see below) and the mass transfer of chemicals is significant. The large amount of entrained air bubbles increases the air-water interface area due to the cumulative bubble surface area. For oxygen transfer at drop structures, Corsi et al. (1992) observed a linear increase of the coefficient of transfer \( (K_L \cdot A) \) with increasing drop heights or discharges when the other parameter was held constant, where \( A \) is the total air-water interface area. Their experiments showed also that the VOC emission of a 2-m high drop structure was significant.

It is the purpose of this paper to detail the hydraulics and aeration properties of rectangular dropshaft designs. Detailed experiments were conducted systematically in four configurations (Table 1) with a focus on residence time and flow aeration. For the most efficient design, new air-water flow measurements were performed in a full-scale structure. The results provide an unique understanding of air-water mass transfer characteristics in rectangular dropshafts.
2. Experimental setup

Four dropshaft geometries were studied basically in two flumes (Table 1, Fig. 1). Four models were built in marine plywood and perspex with a vertical rectangular shaft. The upstream channels were open while the downstream conduits were covered and ended with a free overfall. Both upstream and downstream channels were horizontal. All the shaft dimensions were identical, but for the outflow direction (i.e. 90º and 180º) and the presence (or absence) of deep shaft pool (Fig. 2). A full-scale shaft was built (Prototype AA) corresponding to Model A configuration (Fig. 1, Table 1). The prototype was designed to be geometrically similar based upon a Froude similitude with undistorted scale (e.g. Henderson 1966, Chanson 1999, 2004). The geometric scaling ratio was \( L_R = 3.1 \). Similar experiments were conducted for identical dimensionless inflow critical depth \( d_c/h \) where \( d_c \) is the critical depth at the brink and \( h \) is the invert drop in elevation.

Instrumentation

In laboratory models, the discharges were deduced from the brink depth measurements which were first calibrated in-situ with volume-per-time discharge data. In the full-scale shaft, the flows rates were estimated from bend meters which were calibrated in-situ with a 90-degree V-notch weir.

Free-surface elevations were recorded with pointer gauges in the upstream and downstream channels, while the free-surface height in the shaft was measured with rulers. The total head was measured with a total head tube (\( \varnothing = 1 \) mm). Measurements were conducted at five transverse profiles and averaged over the cross-section. The averaging method was particularly important in the 90º bend dropshaft configurations and in the prototype shaft.

Particle residence times were recorded using neutrally-buoyant particles (relative density between 0.95 and 1.05) made of wax and aluminium. Several particle sizes were used: 3.3, 3.9, 5, 9 & 15 mm. The four smallest sizes were used in the models while the three largest sizes were used in the prototype. The particles were introduced, one at a time, in the inflow channel about 1 m upstream of the brink and each particle was collected at the downstream end of the outflow channel, before the next particle was injected. The total travel times were
recorded with digital chronometers. The residence time in the shaft was deduced by subtracting the calculated travel times in the inflow and outflow channels to the measured time.

Air-water flow properties were measured with a single-tip conductivity probe (needle probe design). The probe consisted of a sharpened rod (platinum wire \( \varnothing = 0.35 \text{ mm} \)) which was insulated except for its tip and set into a metal supporting tube (stainless steel surgical needle \( \varnothing = 1.42 \text{ mm} \)) acting as the second electrode. The probe was excited by an electronics (Ref. AS25240) designed with a response time less than 10 \( \mu \text{s} \) and calibrated with a square wave generator. During the present study, the probe output signal was scanned at 5 kHz for three minutes.

Additional information were obtained with high-speed photography and video-camera. Further details and all the data set were reported in Chanson (2002b).

**Data processing**

The measurement principle of conductivity probes is based upon the difference in electrical resistivity between air and water. The air concentration, or void fraction \( C \), is the proportion of time that the probe tip is in the air. Past experience showed that the probe orientation with the flow direction has little effect on the void fraction accuracy provided that the probe support does not affect the flow past the tip (e.g. Sene 1984). In the present study, the probe tip was aligned with the flow direction. The bubble count rate \( F \) is the number of bubbles impacting the probe tip. The measurement is sensitive to the probe tip size, bubble sizes, velocity and discrimination technique, particularly when the sensor size is larger than the smallest bubble sizes.

For any bubble size distribution and chord length distribution, the specific air-water interface area derives from the mass conservation for air:

\[
[a] = \frac{4 \times F}{V}
\]

where \( V \) is the local velocity. The derivation of [3] is simple for spherical particles. It may be extended to ellipsoidal particles following the method of Clark and Turton (1988) (also
Moursalie et al. 1995). In the present study, the velocity was not measured and the specific interface area was approximated as:

\[ a \approx \frac{4 \* F}{V_i} \]

where \( V_i \) is the free-falling nappe impact velocity deduced from basic trajectory equations (Fig. 2). For plunging jet flow data of Cummings and Chanson (1997), a comparison between [3] and [4] shows that [4] underestimates the measured specific interface area [3] by 20% in average (Fig. 3).

3. Hydraulic properties

3.1 Basic flow patterns

The upstream and downstream channels operated as free-surface flow for all investigated flow conditions. The inflow conditions were subcritical, while the outflow channel operated with supercritical flows. Chanson (2002a) and Rajaratnam et al. (1997) reported a similar finding.

Three flow regimes were observed as functions of the flow rate for 180º shaft configurations (Table 2). At low flow rates, the free-falling nappe impacted into the shaft pool (regime R1, Fig. 1A & 2A). Substantial air bubble entrainment took place in the shaft pool. In the downstream channel, the flow was supercritical and shock waves developed. For intermediate discharges, the free-falling nappe impacted into the outflow channel (regime R2). The pool free-surface level increased significantly, almost no air bubble entrainment was seen in the pool and very-intense invert pressures were observed in the outflow channel. At large flow rates, the free-jet impacted onto the opposite wall above the downstream conduit obvert (regime R3) (Fig. 1B). Significant water deflections took place in the shaft associated with substantial air entrainment in the shaft pool. For the largest flow rates, the outflow channel inlet became submerged (regime R3b). These observations were consistent with the earlier study of Chanson (2002a), although the downstream conduit was higher and the sub-regime R3b was not observed then.
For a 90-degree shaft configuration, the above observations were generally valid, but the regime R2 did not exist (Table 2). Only regimes R1, R3a (free-surface outflow channel inlet) and R3b (submerged outflow channel inlet) were observed. In the models with no pool (i.e. \( P = 0 \)), the same findings were basically valid, but air entrainment in the shaft was limited by the shallow invert while greater splashing was seen in the shaft.

3.2 Energy dissipation

Residual energy data are presented in Figure 4. The data are presented as \( \frac{H_{res}}{H_1} \) as a function of the dimensionless flow rate \( \frac{d_c}{h} \) where \( H_{res} \) is the specific energy in the downstream channel, \( H_1 \) is the upstream total head measured above the downstream channel invert, \( d_c \) is the critical depth in the upstream channel and \( h \) is the drop in invert elevation. The results showed small residual heads, associated with high energy dissipation, at low flow rates (regime R1) (Fig. 4). Poor dissipation performances are observed in regime R2. In regime R3, the dimensionless residual head ranges from 20 to 35% depending upon the model geometry. Note the relatively good agreement between model and prototype data. Comparative results showed that the absence of pool had little effect on the residual energy (Fig. 4). But greater rate of energy dissipation was observed with the 90º outflow direction, all other parameters being identical. The finding is illustrated in Figure 4 where the dimensionless residual head in Models B and D (90º outflow direction) are consistently smaller than those in Models A and C, especially in regimes R2 and R3. The result agrees with the study of Chanson (2002a) on the Valdepuentes dropshaft models.

3.3 Bubble swarm length

The dimensionless bubble penetration depth is plotted in Figure 5 as a function of the dimensionless flow rate \( \frac{d_c}{h} \) for dropshaft configurations with deep pools, where \( D_{ab} \) is the visually-observed bubble plume length, \( y_P \) is the pool height above the outflow channel invert and \( P \) is the pool depth (Fig. 2A). (In absence of shaft pool, bubble penetration was limited by the shaft invert.) In flow regimes R1 (\( \frac{d_c}{h} < 0.04 \)) and R3 (\( \frac{d_c}{h} > 0.05 \)), substantial flow aeration took place, the bubbles plunged deep down to the shaft pool and the bubble cloud
occupied a sizeable shaft pool volume. In flow regime R2 (0.04 ≤ d_c/h ≤ 0.05), the nappe interacted with the downstream conduit inlet and lesser flow aeration was observed. In turn the bubble swarm was smaller. Interestingly, visual observations of bubble penetration depth showed consistently smaller bubble swarm depths in the prototype (Fig. 5). The prototype observations were consistent with air concentration measurements conducted in the shaft pool (paragraph 5.1). It is likely that the result is related to some form of scale effects as air entrainment cannot be scaled by a Froude similitude (Wood 1991, Chanson 1997).

4. Particle residence times
The residence times of neutrally-buoyant particles were measured in the shaft, where the residence time T was defined from take-off at the brink of the inflow channel to the entry into the outflow channel. Such particles were used to simulate the water flow behaviour and to characterise large-scale vortical structures. The results indicated that the residence time T was basically independent of the particle sizes (3.3 to 9 mm in model, 5 to 15 mm in prototype) for all flow regimes and configurations. For one dropshaft configuration and one flow regime, the probability distribution functions of dimensionless residence time T*V_c/d_c were nearly independent of the flow rate, where d_c is the critical depth at the inflow channel brink and V_c is the corresponding critical velocity. Hence, the data were regrouped for one geometry and one flow regime and a statistical summary is presented in Table 3. Typical probability distribution functions of dimensionless residence times are presented in Figure 6 for a dropshaft configuration with deep pool and 180° outflow direction. In regime R1, the dimensionless particle residence time was comparatively the greatest, corresponding to the entrainment of particles in the shaft pool and, sometimes, their trapping in large-size vortical structures for a significant duration. In the regime R2, the free-falling nappe flowed directly into the outflow channel. Most particles were directly entrained into the outflow conduit, corresponding to a very-small residence time. The residence time was about the free-jet trajectory time. In the regime R3, particles were sometimes entrained down the shaft pool.
but most exited the shaft rapidly. The same trends were observed in both model and prototype, as emphasised by mean particle residence time results (Table 3, column 4).

In regime R1, the residence time probability distributions exhibited a bi-modal shape. For the data shown in Figure 6, Mode 1 is centered around $T*V_c/d_c = 66$ and 33 for Model A and Prototype AA respectively, while Mode 2 is centered roughly around $T*V_c/d_c = 1770$ and 1230 for Model A and Prototype AA (Table 3, columns 10 and 11). These values may be compared with the average filling time of the shaft pool of about $Vol/Q*V_c/d_c = 770$ where $Vol$ is the shaft pool volume (Table 3, column 12). Physically, about 40-50% of the particles flowed downwards at nappe impact and were entrained rapidly into the outflow channel (Mode 1). The rest of particles (i.e. 50-60%) were trapped in large scale vortices (Mode 2). They were seen to recirculate in large-scale flow structures, sometimes passing from one structure to another, until they were finally entrained in the downstream conduit. In average, these Mode 2 particles stayed in the shaft pool for about 2.5 times the average filling time of shaft pool.

In regime R3, dimensionless particle residence time data suggested also a kind of bimodal distribution, although not as marked as in regime R1. The results are summarised in Table 3 (columns 10 and 11).

In a dropshaft with 90-degree outflow direction and deep pool, particles had to be subjected to change in flow direction before exiting. Visually most particles tended to be entrained deep down the pool shaft, to twist around near the shaft bottom and to flow outwards rapidly. The same pattern was observed in both regimes R1 and R3. In turn the mean residence times were smaller than those with the 180º shaft configuration (Table 3, column 4).

In dropshafts with 180-degree outflow direction, some particles were trapped for several minutes in large scale vortical structures. Sometimes, particles were trapped in corner recirculation zones, below the outflow channel invert, before being entrained into the outflow conduit. These observations were noted on both model and prototype.

For dropshaft configurations without pool (models C and D), most particles exited rapidly. The mean residence time was typically 4 to 8 times shorter than those in deep pool shafts.
Discussion

A similar trend was noted between Model A and Prototype AA. However prototype results suggested consistently smaller dimensionless residence times for all flow regimes (Fig. 6). Model data tended to overestimate residence times, and hence overestimated mass transfer rates, based upon a Froude similitude. Such observations imply some scale effect between model and prototype. It is believed that particle residence times is strongly related to vortical motion in the shaft pool which cannot be scaled by a Froude similitude. (Vortical motion are dominated by viscous effects implying the need for Reynolds similitude.)

For all configurations, significant data scatter was noted, as evidenced by large standard deviations of dimensionless particle residence time (Table 3, column 5) and by large maximum observed residence times (Table 3, column 9). The finding was surprising especially for the Models C and D (no pool).

5. Application to air-water mass transfer

5.1 Air-water flow properties

The experimental results demonstrated that both bubble swarm lengths and particle residence times were the greatest in the dropshaft configuration with deep pool and 180° outflow direction (Model A). In turn this design (i.e. "Roman dropshaft") has the greatest potential for air-water transfer according to [2].

Detailed air-water flow measurements were conducted with a sturdy single-tip conductivity probe in the Prototype AA (Fig. 1, Table 4). Preliminary measurements conducted at various transverse locations y indicated that the void fraction distributions were basically two-dimensional, but next to the outside edges of the free-falling nappe impact. Measurements were conducted next to the jet centreline to characterise the two-dimensional flow region while additional profiles were performed next to the jet outer edges (Table 4, column 6). Typical distributions of void fraction C and dimensionless specific interface area a*d_c are presented in Figure 7, where x is the horizontal distance measured from the downstream shaft wall, z is the vertical direction positive downwards with z = 0 at the pool free-surface and y is the horizontal transverse distance from the shaft centreline (Fig. 2). Experimental results in
the prototype AA demonstrated high void fractions next to the free-surface for all three discharges: that is, for $z \leq 50$ mm (Fig. 7). Large measured void fractions could not be attributed to measurement error: the plunge point region was visually aerated and it had an appearance somehow similar to a hydraulic jump roller. Further the pool free-surface elevation fluctuated at low frequency with time. (The natural sloshing period of shaft pool was about 0.5 s.) It is conceivable that the probe tip was in air for brief periods, although this was not visually observed. Void fraction distributions showed that the measurements were performed in the fully-developed flow region: i.e., $10 \leq z/d_{i} \leq 70$ typically where $d_{i}$ is the jet thickness at impact. For comparison, the experiments of Cummings and Chanson (1997) were conducted in the developing flow region corresponding to $z/d_{i} < 10$.

Distributions of specific interface areas exhibited a marked peak (Fig. 7) corresponding to a maximum of up to 140 m$^{-1}$. Such values are lower than observations in plunging jet flows with comparable impingement velocities (Cummings and Chanson 1997, Brattberg and Chanson 1998) (e.g. Fig. 3), but the present study was conducted with a coarser probe sensor than these studies (0.35 mm versus 0.025 mm). In the bubbly flow region, the cross-sectional averaged specific interface area $a_{\text{mean}}$ ranged from 2 to 11.5 m$^{-1}$ (Table 4, column, 8) where:

$$a_{\text{mean}} = \frac{1}{B L} \int_{y=-B/2}^{+B/2} \int_{x=0}^{+L} a \, dx \, dy$$

in which $B$ is the shaft width, $L$ is the shaft length, and $x$ and $y$ are the horizontal coordinates (Fig. 2). In the shaft pool, the cumulative air-water interface area $A$ ranged from 1.1 to 2.8 m$^2$ (Table 4, column 9) where:

$$A = \int_{z=0}^{y_{P}} \int_{y=-B/2}^{+B/2} \int_{x=0}^{+L} a \, dx \, dy \, dz$$

Note that $A$ is the cumulative interfacial area in the bubble swarm. It does not account for the shaft pool free-surface area $B \times L$.

5.2 Air-water mass transfer

If the bubble residence time and specific interface area are known, the mass transfer equation may be integrated along the dropshaft. The results are often expressed in terms of the aeration efficiency $E$ defined as:

$$E = \frac{M_{a}}{M_{a} + M_{w}}$$
where the subscript u/s and d/s refer to the upstream and downstream flow conditions.

Assuming that the bubble residence time is about the particle residence time, the integration of [2] yields in first approximation:

\[
E \approx 1 - \exp\left(-KL \cdot \frac{A}{Vol} \cdot T\right)
\]

where Vol is the shaft pool volume, and T is the particle residence time. For the investigations in the Prototype AA, results are plotted in Figure 8 in terms of oxygen transfer at 20 Celsius. They are compared with the empirical correlations of Avery and Novak (1978) and Nakasone (1987) developed for free-overfall and drop structures, and the correlation of Rahme et al. (1997) for circular dropshafts without pool and 180° outflow direction.

Present results suggested a decrease in aeration rate with increasing flow rate. The trend is consistent with the findings of Avery and Novak (1978) and Rahme et al. (1997), although these studies used different configurations. Aeration rate was maximum at low flows (regime R1) because of larger residence time and significant aeration. Indeed similar interfacial properties were observed in both flow regimes R1 and R3 (Table 4), but the dimensionless residence times were in average four times larger in regime R1 (Table 3).

5.3 Discussion

The aeration efficiency results were one order of magnitude lower than dissolved oxygen measurements and correlations. It is hypothesised that the underestimate derives from the instrumentation which could not detect bubble sizes smaller than 0.5 mm. With a 0.025 mm sensor, Cummings and Chanson (1997) measured interface area up to 1,000 m\(^{-1}\) (Fig. 3) : that is, about one order of magnitude greater than present results. (For specific interface areas 10 times greater, the integration of [2] would yield \(E = 0.46\) to 0.21 for \(Q = 0.0076\) to 0.067 m\(^3\)/s.) Further, for a given probe sensor, [4] underestimates the air-water interface area by 20% in average.
Summary and Conclusions

Four configurations of rectangular dropshafts were investigated systematically to study the effects of outflow direction and pool depth on particle residence times and flow aeration. Shaft configurations without pool were characterised by residence times 4 to 8 times shorter than those with deep pool shafts. The best design was that with 180° outflow direction and deep pool shaft (Model A), for which optimum operation was achieved at low flow rates (regime R1).

For the best design (Model A, "Roman dropshaft"), a full-scale study was conducted, the scaling ratio between prototype and model being 3.1:1. Although similar trends were seen in both model and prototype, scale effects were observed in terms of particle residence times and bubble swarm depths. That is, model results overestimated dimensionless residence time $T^*V_c/d_c$ and bubble penetration depth $D_{ab}/(y_p+P)$.

In the prototype, detailed air-water flow measurements were performed in the shaft pool. Distributions of void fractions and specific interface area exhibited maxima next to the impingement point. The mass transfer equation was integrated using measured interfacial areas and particle residence times. The results demonstrate that the air-water mass transfer is the largest at low flow rates (regime R1) because of large residence times and significant interfacial area. Quantitative estimates of aeration efficiency in terms of dissolved oxygen appear lower than laboratory and prototype measurements at drop structures. It is suggested that the sturdy probe used in the present study could not detect fine bubbles and underestimated the interfacial area by one order of magnitude.

Overall the present study provides new understanding of the basic mechanisms of air-water mass transfer in rectangular dropshafts. Dropshaft performances are directly related to the residence times and flow aeration. The former is enhanced by deep shaft pools, especially at low flows, while the latter is significant for all flow rates (but regime R2).

Interestingly the full-scale dropshaft was a 1:1 scale model of a dropshaft built by the Romans along the Yzeron aqueduct to supply water to the city of Lyon (France). That aqueduct was equipped with at least 2 series of at least 2 to 6 dropshafts each (possibly more). The design permitted to achieve DO saturation and to improve water quality. Definitely the Roman
engineers produced an excellent design in terms of energy dissipation and flow aeration, particularly at low flow rates (regime R1).

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References


List of symbols

A  
gas-liquid interface area (m$^2$) in the shaft pool;
a  
specific interface area (m$^{-1}$) defined as the air-water surface area per unit volume of air and water;
a$_{\text{mean}}$  
mean interface area (m$^{-1}$) in a horizontal cross-section;
B  
dropshaft width (m);
b  
open channel width (m);
C  
air concentration defined as the volume of air per unit volume of air and water; it is also called void fraction;
C$_{\text{gas}}$  
concentration of dissolved gas in water (kg/m$^3$);
D  
1- conduit diameter (m);
2- conduit height (m);
D$_{ab}$  
bubble penetration depth (m) measured vertically from the free-surface;
D$_{\text{gas}}$  
molecular diffusivity of gas in water (m$^2$/s);
d  
flow depth (m) measured perpendicular to the channel bed;
d$_c$  
critical flow depth (m); in a rectangular channel: d$_c$ = $3\sqrt{q^2/g}$;
d$_i$  
nappe thickness (m) at impact: i.e., thickness of the free-falling jet at impact;
E  
aeration efficiency;
F  
air bubble count rate (Hz) defined as the number of detected air bubbles divided by the scanning time;
g  
gravity constant (m/s$^2$); g = 9.80 m/s$^2$ in Brisbane;
H  
total head (m);
H$_{\text{res}}$  
residual head (m): H$_{\text{res}}$ = H$_1$ - $\Delta$H;
H$_1$  
upstream total head (m);
h  
drop (m) in invert elevation;
K$_L$  
liquid film coefficient (m/s);
L  
dropshaft length (m);
L$_R$  
geometric scaling ratio: i.e., ratio of prototype to model dimensions;
l  
brink overhanging (m) over the shaft;
M\textsubscript{gas} mass of dissolved gas (kg);
P (shaft) pool height (m), measured from the shaft bottom to the downstream conduit invert;
Q total volume discharge (m\textsuperscript{3}/s) of water;
q discharge per meter width (m\textsuperscript{2}/s); for a rectangular channel : q = Q/b;
T particle residence time (s) in the shaft;
t time (s);
V velocity (m/s);
V\textsubscript{c} critical flow velocity (m/s); for a rectangular channel : V\textsubscript{c} = \sqrt{g\cdot d\textsubscript{c}};
V\textsubscript{i} velocity (m/s) at nappe impact;
Vol shaft pool volume (m\textsuperscript{3}) : Vol = (P+\textit{y}\textsubscript{p})\cdot B\cdot L;
x horizontal Cartesian co-ordinate (m) measured from the downstream shaft wall;
y transverse distance (m) measured from the shaft centreline;
\textit{y}\textsubscript{p} free-surface height (m) in a shaft pool above the downstream conduit invert;
z vertical distance (m) the pool free-surface, positive downwards;

\textbf{Greek symbols}

\Delta H head loss (m) : i.e., change in total head;
\varnothing diameter (m);

\textbf{Subscript}

c critical flow conditions;
i nappe impact flow conditions;
1 upstream or inflow conditions;
2 downstream or outflow conditions;

\textbf{Abbreviations}

D/S (or d/s) downstream;
R1 flow regime R1;

R2  flow regime R2;
R3  flow regime R3;
U/S (or u/s)  upstream;
VOC  volatile organic compound.
Table 1. Experimental investigations of rectangular dropshafts.

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<th>Ref.</th>
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<th>P (m)</th>
<th>L (m)</th>
<th>B (m)</th>
<th>l (m)</th>
<th>b₁ (m)</th>
<th>D₁ (1)</th>
<th>b₂ (m)</th>
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<td>Model C</td>
<td>0.548</td>
<td>0</td>
<td>0.243</td>
<td>0.246</td>
<td>0.039</td>
<td>0.161</td>
<td>0.25</td>
<td>0.209</td>
<td>0.097</td>
<td>180</td>
</tr>
<tr>
<td>Model D</td>
<td>0.548</td>
<td>0</td>
<td>0.243</td>
<td>0.246</td>
<td>0.039</td>
<td>0.161</td>
<td>0.25</td>
<td>0.209</td>
<td>0.097</td>
<td>90</td>
</tr>
<tr>
<td><strong>Chanson (2002a)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Recret model</td>
<td>0.505</td>
<td>0.365</td>
<td>0.30</td>
<td>0.30</td>
<td>0</td>
<td>0.144</td>
<td>0.25</td>
<td>0.15</td>
<td>0.25</td>
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</tr>
<tr>
<td>Valdepuentes model 1</td>
<td>0.668</td>
<td>0.201</td>
<td>0.20</td>
<td>0.30</td>
<td>0</td>
<td>0.110</td>
<td>0.25</td>
<td>0.11</td>
<td>0.21</td>
<td>90</td>
</tr>
<tr>
<td>Valdepuentes model 2</td>
<td>0.668</td>
<td>0.201</td>
<td>0.20</td>
<td>0.30</td>
<td>0</td>
<td>0.110</td>
<td>0.25</td>
<td>0.11</td>
<td>0.21</td>
<td>180</td>
</tr>
<tr>
<td>Apelt (1984)</td>
<td>0.325</td>
<td>0</td>
<td>0.152</td>
<td>0.152</td>
<td>0</td>
<td>Pipe : Ø = 0.152 m</td>
<td>Pipe : Ø = 0.152 m</td>
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</tbody>
</table>

Notes: (1) : sidewall height; Notation: see Figure 2.

Table 2. Flow conditions d_c/h for the change in flow regimes.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>180° outflow direction</th>
<th>90° outflow direction</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1-R2</td>
<td>R2-R3a</td>
<td>R3a-R3b</td>
</tr>
<tr>
<td>Prototype AA</td>
<td>0.037</td>
<td>0.046</td>
<td>--</td>
</tr>
<tr>
<td>Model A</td>
<td>0.039</td>
<td>0.051</td>
<td>0.10</td>
</tr>
<tr>
<td>Model B</td>
<td>0.038</td>
<td>0.046</td>
<td>0.099</td>
</tr>
<tr>
<td>Model D</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Recret model</td>
<td>0.09</td>
<td>0.175</td>
<td>--</td>
</tr>
<tr>
<td>Valdepuentes model 2</td>
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<td>0.042</td>
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<tr>
<td>Valdepuentes model 1</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Note: (--) : information not available;
Table 3. Distributions of dimensionless particle residence times $T^*V_c/d_c$ - Statistical summary.

<table>
<thead>
<tr>
<th>Config.</th>
<th>Regim</th>
<th>Nb of particles</th>
<th>$T^*V_c/d_c$</th>
<th>$T^*V_c/d_c$</th>
<th>$T^*V_c/d_c$</th>
<th>Vol*V_c</th>
<th>Q*d_c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>Std</td>
<td>Skew</td>
<td>Kurt</td>
<td>Min.</td>
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<td>Prototype</td>
<td>R1</td>
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<td>830</td>
<td>1150</td>
<td>1.87</td>
<td>3.22</td>
<td>13</td>
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<tr>
<td></td>
<td>R2</td>
<td>86</td>
<td>188</td>
<td>503</td>
<td>3.56</td>
<td>13.28</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>227</td>
<td>209</td>
<td>459</td>
<td>2.72</td>
<td>7.17</td>
<td>6</td>
</tr>
<tr>
<td>AA (180°)</td>
<td>R1</td>
<td>253</td>
<td>1050</td>
<td>1635</td>
<td>2.66</td>
<td>8.08</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>99</td>
<td>80</td>
<td>170</td>
<td>3.66</td>
<td>14.86</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>180</td>
<td>246</td>
<td>519</td>
<td>4.76</td>
<td>32.34</td>
<td>6</td>
</tr>
<tr>
<td>Model A</td>
<td>R1</td>
<td>189</td>
<td>653</td>
<td>1119</td>
<td>3.06</td>
<td>12.02</td>
<td>27</td>
</tr>
<tr>
<td>(180°)</td>
<td>R2</td>
<td>99</td>
<td>80</td>
<td>170</td>
<td>3.66</td>
<td>14.86</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>180</td>
<td>246</td>
<td>519</td>
<td>4.76</td>
<td>32.34</td>
<td>6</td>
</tr>
<tr>
<td>Model B</td>
<td>R1</td>
<td>189</td>
<td>653</td>
<td>1119</td>
<td>3.06</td>
<td>12.02</td>
<td>27</td>
</tr>
<tr>
<td>(90°)</td>
<td>R2</td>
<td>99</td>
<td>80</td>
<td>170</td>
<td>3.66</td>
<td>14.86</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>180</td>
<td>246</td>
<td>519</td>
<td>4.76</td>
<td>32.34</td>
<td>6</td>
</tr>
<tr>
<td>Model C</td>
<td>R1</td>
<td>59</td>
<td>51</td>
<td>55</td>
<td>2.25</td>
<td>6.26</td>
<td>2</td>
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<tr>
<td>(180°)</td>
<td>R2</td>
<td>60</td>
<td>53</td>
<td>60</td>
<td>2.01</td>
<td>3.53</td>
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<tr>
<td>Model D</td>
<td>R1</td>
<td>60</td>
<td>203</td>
<td>360</td>
<td>4.37</td>
<td>22.54</td>
<td>1</td>
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<tr>
<td>(90°)</td>
<td>R2</td>
<td>65</td>
<td>31</td>
<td>14</td>
<td>1.34</td>
<td>2.16</td>
<td>12</td>
</tr>
</tbody>
</table>

Notes: Kurt: Fisher kurtosis; Skew: Fisher skewness; Vol: shaft pool volume; Q: flow rate.

Table 4. Summary of air-water interfacial area measurements in dropshaft prototype AA.

<table>
<thead>
<tr>
<th>Q (m³/s)</th>
<th>Flow regime</th>
<th>Vᵢ (m/s)</th>
<th>dᵢ (mm)</th>
<th>yᵢ (m)</th>
<th>y (m)</th>
<th>z</th>
<th>aᵢ mean</th>
<th>A (m²)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0076</td>
<td>R1</td>
<td>5.81</td>
<td>0.0026</td>
<td>0.015</td>
<td>0, 0.20, 0.22</td>
<td>1.12</td>
<td>dₑ = 0.02867 m.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.016</td>
<td>R1</td>
<td>5.74</td>
<td>0.0056</td>
<td>0.080</td>
<td>0, 0.20, 0.25</td>
<td>1.50</td>
<td>dₑ = 0.0471 m.</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.067</td>
<td>R3</td>
<td>5.58</td>
<td>N/A</td>
<td>0.266</td>
<td>0, 0.20, 0.30</td>
<td>2.84</td>
<td>dₑ = 0.12237 m.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: Vᵢ, dᵢ: jet impact velocity and thickness deduced from trajectory equations (¹); (²): measured; (³): bubbly flow interface area only.

List of captions

Fig. 1 - Rectangular dropshaft in operation (shaft dimensions: 0.76 m × 0.75 m)
(A) Regime R1 - Flow from the top right to the bottom left - Note the bubbly flow region of the free-jet impact into the shaft pool
(B) Regime R3 - Flow from the top right to the bottom left - Note the jet impact onto the opposite wall, the 'white waters' in the shaft pool, and the highly-aerated outflow channel waters

Fig. 2 - Definition sketch - Flow from top left to bottom right
(A) Shaft with 180º outflow direction and regime R1
(B) Shaft with 90º outflow direction and regime R3

Fig. 3 - Comparison between measured specific interface area [3] and [4] for the plunging jet data of Cummings and Chanson (1997) : vertical supported jet, \( d_i = 0.012 \) m, \( V_i = 6.0 \) m/s

Fig. 4 - Dimensionless residual head \( \frac{H_{res}}{H_1} \) as a function of the dimensionless flow rate \( \frac{d_c}{h} \)

Fig. 5 - Dimensionless bubble penetration depth \( \frac{D_{ab}}{(y_p+h)} \) as a function of the dimensionless flow rate \( \frac{d_c}{h} \) (dropshafts with deep pool)

Fig. 6 - Probability distribution functions of dimensionless residence time \( T^*V_c/d_c \)
(A) Model A (180º outflow)
(B) Prototype P2 (180º outflow)

Fig. 7 - Dimensionless distributions of void fractions C and specific interface area \( a*dc \)
(A) Regime R1, \( Q = 0.0076 \) m³/s, \( z = 0.050, 0.110, 0.150 \) m
(B) Regime R3, \( Q = 0.067 \) m³/s, \( z = 0.050, 0.150, 0.250 \) m
Fig. 8 - Aeration efficiency in terms of dissolved oxygen at 20 Celsius - Comparison between the integration of the mass transfer equation (i.e. Eq. [8]) and empirical correlations

(a)

Dropshaft with 180-degree outflow direction and operating in regime R1

Section A-A

(b) Dropshaft with 90-degree outflow direction and operating in regime R3.
Data: Cummings, $V_i = 6.0 \text{ m/s}, z = 0.005 \text{ to } 0.25 \text{ m}$

(a)

(b)

(a) Q=7.6 L/s, Centreline data, z = 50 mm

(b) Q=7.6 L/s, Centreline data, z = 110 mm

(b)

- **Q = 67 L/s, Centreline data, z = 50 mm**
- **Q = 67 L/s, Centreline data, z = 150 mm**
- **Q = 67 L/s, Centreline data, z = 250 mm**