CLUSTERING PROCESS AND INTERFACIAL AREA ANALYSIS IN A LARGE-SIZE DROPSHAFT

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Abstract

Dropshafts are commonly used in sewers and stormwater channels as energy dissipator systems. Since recent effort has been devoted to characterize dropshaft hydraulics and air-water flow properties, and the present paper develops an analysis of the bubble clustering process using new experimental data collected in a large-size facility. The results highlight some significant patterns in clusters production. Finally, interfacial areas for mass-transfer were measured.

1 Foreword

A dropshaft is an energy dissipator connecting two channels with different invert elevations. This type of structure is commonly used in sewers [1] and storm water systems. Small dropshafts are also used upstream and downstream of culverts [2], while large spillway shafts were built [3]. The dropshaft is an ancient design since Roman aqueducts [4] but there is however some controversy if it was used solely for energy dissipation or in combination with flow reaeration. Despite such long usage, the hydraulics of dropshafts has not been systematically documented [1] [2] [5]. Recent works [4] [6] [7] studied the hydraulics and the air-water flow properties. The present paper deals with the results of new experimental work conducted in a large-size rectangular dropshaft located at the University of Queensland (Australia). Particularly, the paper develops an analysis of bubble clustering process and some estimate of

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interfacial area. The average number of clusters and the percentage of clustered bubbles were estimated over the depth of the shaft pool. Also, the ratio between the number of clusters and the number of detected bubbles was evaluated. Finally, the interfacial area leading to enhanced gas-transfer process was estimated in the dropshaft depth.

2 Experimental setup

The experiments herein described were performed in a large-size rectangular dropshaft built in marine plywood and perspex at the Hydraulics Laboratory at the University of Queensland (Australia). The dropshaft was 3.1 m high, 0.76 m wide and 0.75 long. The drop in invert was 1.7 m and the shaft pool was 1.0 m deep. The inflow and outflow channels were both horizontal, 0.5 m wide and 0.30 m deep. The upstream channel was open while the downstream conduit was covered and ended with a free overfall (Figs. 1 & 2).

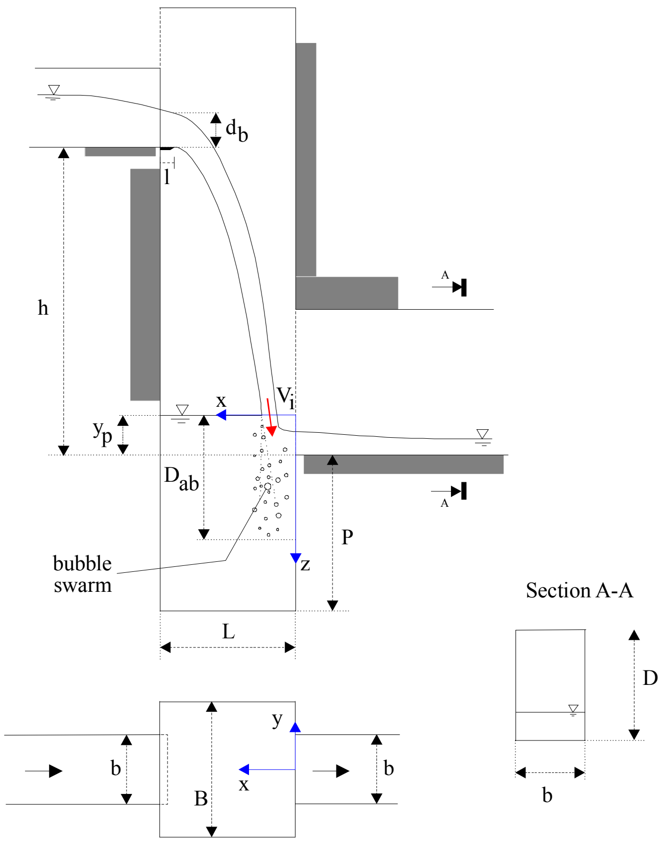

Figure 1. Definition sketch of rectangular dropshafts

A flow rate of 12 L/s was used, for which the free-falling jet impacted into the shaft pool (Figs. 1 & 2), also called R1 regime [4]. Detailed air-water flow properties were measured with a single-tip conductivity probe (needle probe design). The probe consisted of a sharpened rod (platinum wire Ø=0.35 mm) which was insulated except for its tip and set into a metal supporting tube (stainless steel surgical needle Ø=1.42 mm) acting as the second electrode. The probe was excited by an electronics designed with a response time less than 10 μs and calibrated with a square wave generator. During the present study, the probe output signal was scanned at 25 kHz for 100 seconds. Measurements were conducted at several cross-sections along the shaft centreline beneath the nappe impingement, with depths ranging from 0.03 m to 0.25 m (Table 1). The positions of the measurement points are listed in Table 1.

Table 1 – Position of measurement points

Depth z - mm	x – mm
30	60-205
50	85-505
80	80-205
110	75-200
150	70-205
200	75-205
250	60-170

The measurement principle of conductivity probes is based upon the difference in electrical resistivity between air and water. When the probe tip is in contact with an air bubble, the current between the tip and the supporting metal becomes zero. Although the signal is theoretically rectangular, the probe response is not square because of the finite size of the tip, the wetting/drying time of the interface covering the tip and the response time of the probe and electronics. The data processing yielded the air concentration or void fraction C, the bubble count rate F and the bubble chord time t_{ch}, The 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 [8]. In the present study, the probe tip was aligned with the flow direction. Maximum value of C for each depth ranged from 0.13 to 0.60. 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. The bubble chord time t_{ch} is defined as the time spent by the bubble on the probe tip. The chord times were transformed in terms of pseudo-bubble chord length ch_{ab} as:

$$ch_{ab} = V_i t_{ch} \quad (1)$$

where V_i is the jet impingement velocity $[L \cdot T^{-1}]$ and t_{ch} is the measured bubble

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chord time [T]. Chanson et al. [9] compared Equation (1) with chord length measurements by Chanson & Brattberg [10] concluding that Equation (1) predicts the exact shape of bubble size probability distribution functions although it overestimates the bubble chord lengths by about 10 to 30%.

Figure 2. Dropshat in operation with Q=12 L/s

3 Cluster analysis. Results. Discussion

Instantaneous air and water chord times were recorded in the bubbly flow region of the shaft pool. The records were subsequently post-processed to study the air-water flow structure and the existence (or not) of bubble clusters. A cluster of bubbles is defined as a group of two or more bubbles, with a distinct separation from other bubbles before and after the cluster. In a cluster, the bubbles are close

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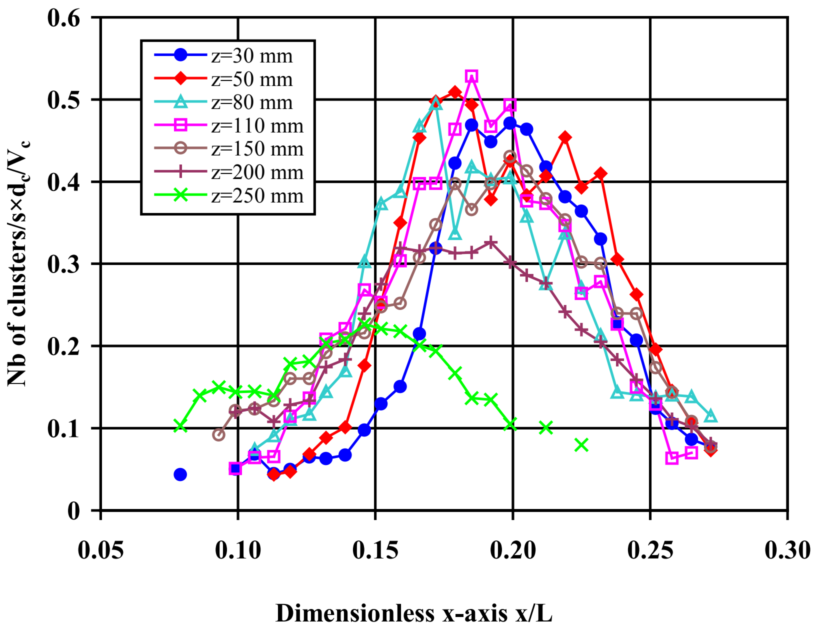
together and the packet is surrounded by a sizeable volume of water. In the present study, a cluster was identified when the water pseudo-chord length was smaller than one-tenth of the mean water pseudo-chord size at that measurement point [12]. Alternative approaches have been proposed but it is believed that selected is more appropriate to bubbly flow. Importantly this study was a streamwise analysis and did not include bubbles travelling side by side.
Figure 3 shows the distribution of clusters along the dimensionless horizontal axis x/L for different depths, where L=0.755 m was dropshaft length, d_c and V_c were the critical flow depth and velocity at the inflow channel brink. In Figure 3, the vertical axis is the number of clusters per seconds times the ratio d_c/V_c. With increasing depth z beneath the free-surface, the location where the number of clusters is maximum tended to follow that of the jet trajectory. Further the average number of clusters was maximum at about 0.05 m beneath the free-surface and decreased with increasing depths (Table 2).

Fig.3 - Number of clusters



The percentage of bubbles that were associated with clusters ranged from 14% to 60% for all considered depths, although it was in average about one third (Table 2). This result was consistent with an earlier dropshaft study with different flow rates in the same facility [11]. Interestingly the percentage of bubbles associated with cluster structures was the smallest along the jet trajectory (Fig. 4). In Figure 4, the red diamonds are the locations where the minimum percentage of clustered

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bubbles was observed at each depth, while the empty triangles represent the points with minimum ratio of number of clusters to number of detected bubbles. Both data set were very close, but for z=250 mm. They are compared with the theoretical trajectory of the jet, which was computed using Chanson's method [6].

Table 2 – Clustering analysis data

Depth – z - mm	Average cluster Number	Clustered bubbles – %		
		Minimum	Mean	Maximum
30	338.0	18.73	35.44	47.07
50	**445.8**	15.79	34.12	57.06
80	401.4	14.03	33.68	47.43
110	409.9	21.62	36.29	60.04
150	390.5	22.83	37.41	55.94
200	335.1	23.73	35.50	51.95
250	255.4	30.23	37.77	50.23

Fig.4 - Jet trajectory

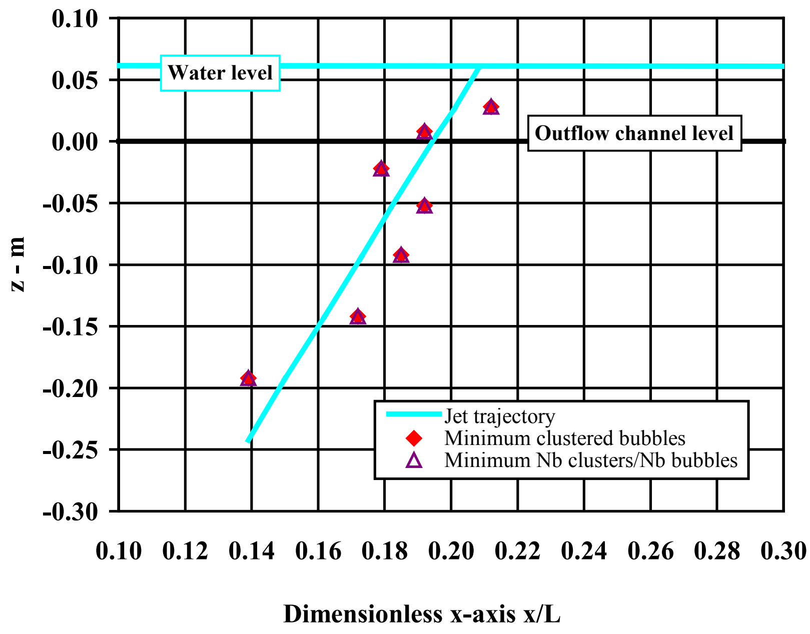

Figure 5 presents distributions of the ratio of number of clusters to number of detected bubbles. The data were minimum for z=80 mm along the jet centreline

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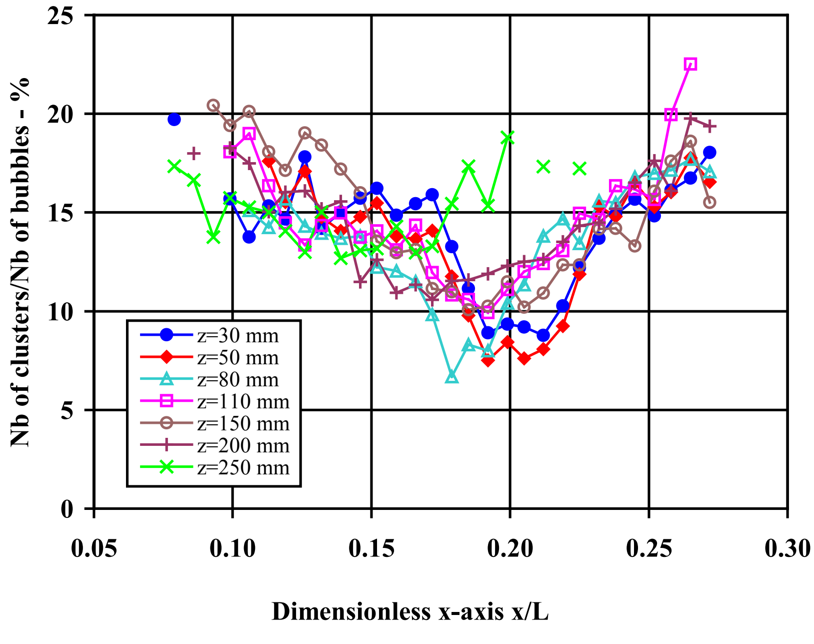
and they showed a decrease in that ratio with increasing depth.
The existence of clusters is related to break-up, coalescence, bubble wake interference and to other processes. As the bubble response time is significantly smaller than the characteristic time of the flow, it is believed that bubble clustering is caused primarily by bubble trapping in vortical structures. In plunging jet flows, such large-scale vortices are generated in the developing shear layers. As vortical structures are advected downstream, they grow up in size by vortex pairing and contribute to further clustering. Overall about 70 to 95% of all clusters comprised 2 bubbles only. This result is consistent with the results obtained in stepped chutes, where for skimming flow and transition flow the cluster made of two bubbles were nearly 68% and about 78%, respectively [12]. Overall the average number of bubbles per cluster was about 2.50 for all depths. Along the jet centreline, a slight trend could be also observed with the maximum percentage around z=30-50 mm, i.e. near impingement.
In summary, the data demonstrated that a large proportion of bubbles travelled as a part of cluster structure, consisting typically of two particles only.

Fig.5 - Ratio Nb of clusters/Nb of bubbles



4 Interfacial area calculation. Results. Discussion

The interfacial area is a parameter of paramount importance in air-water gas-transfer. This process occurs if a non-equilibrium condition between the air

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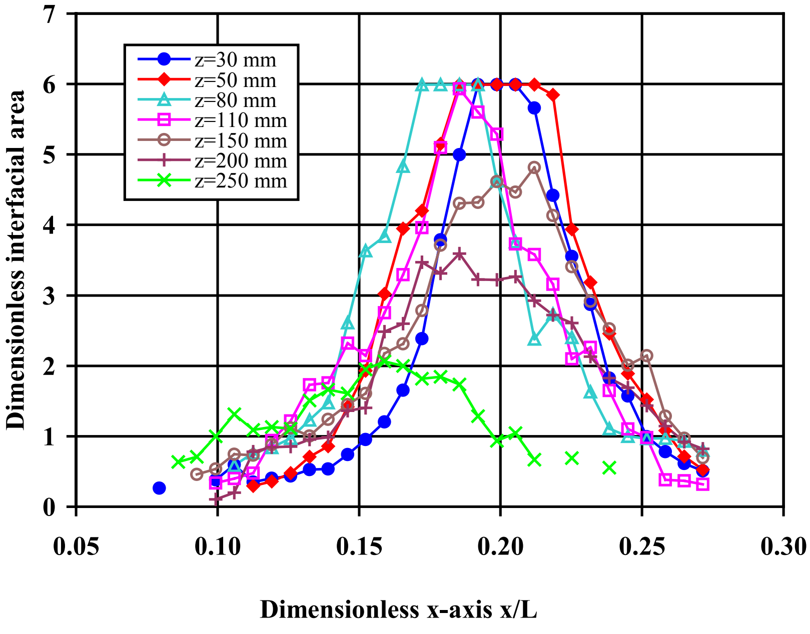
phase and water phase exists for a chemical. For sparingly soluble gases, such as oxygen, the gas-transfer is controlled by the liquid side. If the gas flux through the air-water interface equals the time rate of change of gas concentration in the bulk water assuming complete mixing, mass balance is:

$$V \cdot \frac{\partial C}{\partial t} = K_L \cdot A \cdot (C_{sat} - C_w) \qquad (2)$$

where K_L [$L \cdot T^{-1}$], is the gas-transfer coefficient, V is the water volume [L^3], A is the area of air-water interface [L^2], and C_{sat} and C_w are gas concentrations at saturation and within the bulk water, respectively [$M\ L^{-3}$]. If the oxygen is the transferred gas, K_L is usually termed *reaeration coefficient*, which in stream and rivers depends both on the hydrodynamics and on the channel characteristics [13]. If in a river at low velocity oxygen is transferred to the water column through the water surface, in plunging jets, the surface crossed by the oxygen is represented by the overall surface of the bubbles produced by the falling nappe.

Fig.6 - Dimensionless interfacial area



Thus, eq. (2) could be rewritten as:

$$\frac{\partial C}{\partial t} = K_L \cdot a \cdot (C_{sat} - C_w) \qquad (3)$$

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where a is the interfacial area [L^2/L^3], i.e. the specific surface area defined as the air-water interface area per unit volume of air and water. Experimental measurements in supercritical flows down a flat chute, hydraulic jumps and plunging jet flows [14] [15] recorded local specific interface area of up to 550 m^2/m^3 demonstrating the significant role of air bubble entrainment on the mass-transfer process.
Estimates of the air-water interfacial area are based upon measured air-water flow properties such as void fraction, velocity, bubble size, and bubble count.
In the present study, the specific air-water interface area *a* was calculated as:

$$a = \frac{4\,F}{V_i} \qquad (4)$$

where F is the measured bubble count rate and the impingement velocity V_i was equal to 5.77 m/s. Experimental results are presented in Figure 6. The data indicated specific interfacial areas of up to 150 m^2/m^3 next to the jet centreline, and some decays in interfacial areas was observed with increasing depths (Fig. 6). Overall the data demonstrated very strong aeration of the shaft pool.

5 Concluding remarks

This study presents new experimental results obtained in a large-size rectangular dropshaft structure. The facility was a nearly full-scale shaft comparable to sewer structures and stormwater systems. That is, these results are little affected by scale effects. The study demonstrated strong air bubble entrainment in the shaft pool (Fig. 2). Bubble cluster analysis results were consistent with earlier results obtained with different flow rates in the same facility. The new data demonstrated that the percentage of bubbles associated with cluster structures was the smallest along the jet trajectory. Also, typical cluster structure comprised of 2 bubbles only. Finally, interfacial area estimates confirmed the strong aeration potential of the shaft pool.

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