Bubble clustering in a large-size dropshaft. Comparative analysis of different cluster criteria

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Abstract: *The study of clustering processes is fundamentally significant in hydraulic engineering to comprehend the interactions between turbulence and particles. Previous studies on bubble clustering were carried out in plunging jets, hydraulic jumps and dropshafts. The present paper focuses on the bubble clustering process in a large-size dropshaft, and three criteria for cluster identification were applied. They were based upon the analysis of water chord between two adjacent air particles. When two bubbles are closer than a characteristic length scale, they can be considered as a cluster. The characteristic water length scale may be related to the water chord statistics, such as the mean or the median water chord, or to the air chord length of the preceding bubble. The results highlighted some significant patterns in clusters production both over the depth and the distance from the underwater jet trajectory. The comparison pointed out some features of the clustering process.*

Keywords: *Dropshaft, air bubble entrainment, bubble clustering process, experimental work*

1. INTRODUCTION

A dropshaft is an energy dissipator connecting two channels with different invert elevations. This type of structure is commonly used in sewers (Merlein *et al.* 2002) and storm water systems. Small dropshafts are also used upstream and downstream of culverts (Apelt 1984), while large dam spillway shafts were built (Vischer & Hager 1998). The dropshaft is an ancient design since Roman aqueducts (Chanson 2002). Despite their long usage, the studies of dropshaft hydraulics are limited (Apelt 1984, Rajaratnam *et al.* 1997, Merlein *et al.* 2002). Some experimental works (Chanson 2002, 2007, Gualtieri & Chanson 2004b) studied the hydraulics including the air-water flow properties. A typical characteristic of the complicated interactions between the entrained air and turbulence is bubble clustering. In a bubbly flow, a cluster may be defined as a group of two or more bubbles with a distinct separation from other bubbles before and after the cluster. A clustering analysis is believed to provide some relevant insights about the interaction between turbulence and bubbly flow because the clusters influence the surrounding flow field, introducing enhanced velocity fluctuations and hydrodynamic interactions (Chanson & Toombes 2002, Figueroa-Espinoza & Zenit 2005). In the area of hydraulic engineering, some previous investigations studied the clustering process in plunging jets (Chanson *et al.* 2006), in stepped chutes (Chanson & Toombes 2002), in the hydraulic jump (Chanson 2007, Gualtieri & Chanson 2010) and in a dropshaft (Chanson 2002, Gualtieri & Chanson 2004a, 2007).
In this paper, three criteria were applied to assess the occurrence of bubble clusters in the air-water flow in a large-size rectangular dropshaft. The comparative results highlighted some significant patterns in the cluster production both over the depth and the distance from the underwater jet trajectory. This comparison is believed to point out some basic features of the clustering process.

2. EXPERIMENTAL SETUP. DROPSHAFT AND INSTRUMENTATION

The experiments 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 0.755 long. The drop in invert was h=1.7 m and the shaft pool was P=1.0 m deep. The inflow and outflow channels were both horizontal, their width and depth were b=0.5 m and D=0.30 m, respectively. The upstream channel was open while the downstream conduit was covered and ended with a free overfall (Figs. 1 and 2, after Gualtieri & Chanson, 2004a). This was a near full-scale industrial facility in which the flow conditions were carefully controlled.
A flow rate of 12 L/s was used, for which the free-falling jet impacted into the shaft pool (Fig. 2). This flow pattern is called the R1 regime (Chanson 2002). Detailed air-water flow properties were measured with a single-tip conductivity probe (needle probe design). The probe output signal was scanned at 25 kHz for 100 seconds. Note that the single-tip probe design is a robust measurement device particularly suited in the full-scale industrial facility, while the highly turbulent flows with large void fractions required some sturdy probes (Chanson 1997, Crowe *et al.* 1998). The probe consisted of a sharpened rod (platinum wire Ø=0.35 mm) 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 with a response time less than 10 µs.

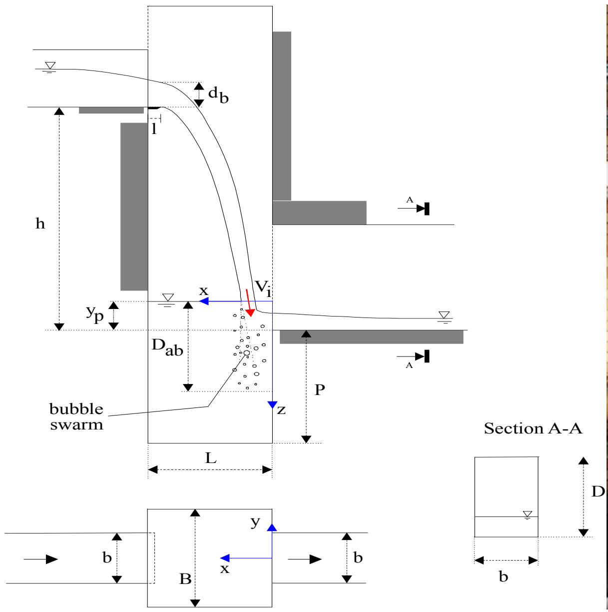


Fig. 1 – Sketch of a rectangular dropshaft

Fig. 2 – Dropshaft in operation with Q=12 L/s

The probe data processing yielded the air concentration or void fraction C, the bubble count rate F and the 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 (Chanson 2002). 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 per second. 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 chord time t_{ch} is defined as the time spent by the air (or water) on the probe tip. The bubble chord times were transformed into pseudo-bubble chord length ch_{ab} as:

$$ch_{ab} = V_i \; t_{ch-ab} \qquad (1)$$

where V_i is the jet impingement velocity, which was equal to 5.77 m/s, and $t_{ch\text{-}ab}$ is the measured bubble chord time. Using Eq. (1), the water chord length ch_w was also derived from the measured water chord time $t_{ch\text{-}w}$. Chanson *et al.* (2006) compared Eq. (1) with the measured chord length distributions for the experiments of Chanson & Brattberg (1996) and Cummings & Chanson (1997a, 1997b). In both studies, the velocity were recorded with a 2-tip probe and a comparison between the bubble chord size and pseudo-chord size data demonstrated that Eq. (1) predicted the exact shape of bubble size probability distribution functions although it overestimates the bubble chord lengths by about 10 to 30%. Furthermore, the jet velocity decay along the underwater trajectory was estimated using the empirical correlations proposed by Bohrer *et al.* (1998). Velocity decay can affect significantly the measurement of air/water chord length according to Eq. (1), but has no effect on clustering analysis carried out with the proposed approaches.

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 present 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, where *x* is the horizontal distance measured from the downstream shaft wall and *z* is vertical direction positive downwards with *z*=0 at the pool free-surface.

3. CLUSTERING ANALYSIS. DEFINITIONS AND CRITERIA

A *cluster* of bubbles was above defined as a group of two or more bubbles with a distinct separation from other bubbles before and after the cluster (Chanson & Toombes 2002, Chanson 2007, Gualtieri & Chanson 2004, 2010). In a cluster, the bubbles are close together and the packet is surrounded by a sizeable volume of water. 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, bubble clustering tends to be caused primarily by bubble trapping in vortical structures. As vortical structures are advected downstream, they grow up in size by vortex pairing contributing to further clustering. Different approaches have been proposed to identify a cluster structure within the air-water flow. One approach is based upon the analysis of water chord between two adjacent air particles If two bubbles are closer than a characteristic time/length scale, they can be considered as a cluster (Chanson 2007, Gualtieri & Chanson 2004, 2010). This time/length scale may be related to the water chord statistics or to the bubble size itself, since bubbles within that distance are in the near-wake and may be influenced by the leading particle (Chanson 2007, Gualtieri & Chanson 2004, 2010). In the present study, three criteria were applied to reveal the occurrence of clusters in the air-water flow inside the dropshaft. Namely they were:

- the water chord between two adjacent air particles was compared with the mean ch_w recorded in the point of measurement. Thus, according to the Criterion No. 1 a cluster was detected if:

  $$ch_w < \frac{1}{10}\,ch_{w\text{-}avg} \tag{2}$$

  where $ch_{w\text{-}avg}$ is the mean water chord;
- the water chord between two adjacent air particles was compared with the median ch_w recorded in the measurement point. Following the Criterion No. 2 a cluster was identified if:

  $$ch_w < \frac{1}{10}\,ch_{w\text{-}median} \tag{3}$$

  where $ch_{w\text{-}median}$ is the median water chord;
- the water chord between two adjacent air particles was compared with the air chord of the preceding bubble recorded in the point of measurement. Thus, according to the Criterion No. 3 a cluster was detected if:

  $$ch_w < \eta\, ch_{ab} \tag{4}$$

  where ch_{ab} is the air chord of the leading bubble and η is a parameter characterizing the wake length of the leading bubble. It is believed that for pseudo-spherical particles η should be in the range from 0.5 to 2.0 . In the present study η was set equal to 1.

The results of the clustering analysis were expressed by using the following parameters:

- number of clusters N_c;
- percentage of clustered bubbles on the total number of detected bubbles;
- percentage of clusters formed by two bubbles.

Further analysis was devoted to compare the locations where maximum clustering was found with the theoretical jet trajectory, and with the locations were the local void fraction and bubble count rate maxima, C_{max} and F_{max}, respectively, were recorded.

4. CLUSTERING ANALYSIS. RESULTS AND DISCUSSION

The instantaneous air and water chord times were recorded in the bubbly flow region of the shaft pool, in addition to the void fraction and bubble count rate data. The data were post-processed to study the air-water flow structure using the above outlined three clustering criteria.

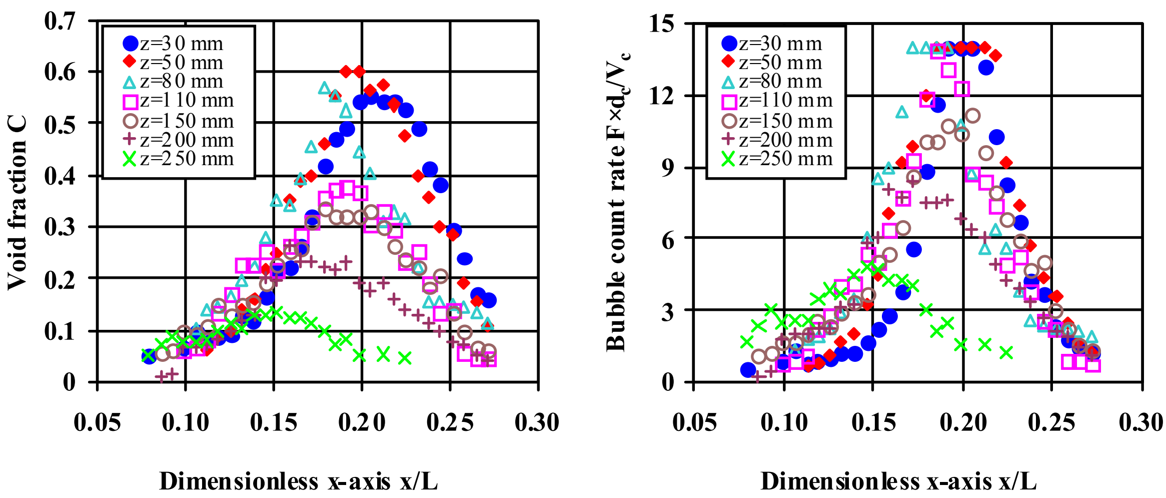


Fig.3a/3b – Void fraction and bubble count rate in the dropshaft

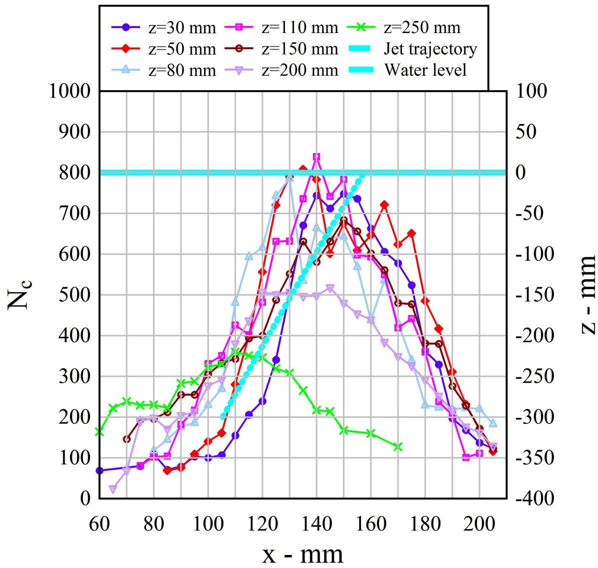
Figure 3a shows some typical distribution of void fraction C along the dimensionless horizontal axis x/L for different depths, where x in the horizontal distance from the outer wall and L=0.755 m was dropshaft length (Fig. 1). At each depth z, the maximum void fraction C_{max} ranged from 0.60 down to 0.13 for $0.03 \leq z \leq 0.25$ m. The experiments demonstrated a very high void fraction next to the free-surface. Particularly, void fractions larger than 50% were observed at z=30 mm, z=50 mm and z=80 mm, with the largest void fraction observed at z=50 mm. Figure 3b presents some distribution of dimensionless bubble count rate $F \times d_c/V_c$ along the dimensionless horizontal axis x/L for different depths. In the present study, i.e. for Q=12 L/s, the critical flow velocity V_c and depth d_c in the inflow channel were 0.617 m/s and 0.0389 m, respectively. The bubble count rate distributions exhibited a marked peak and the maximum dimensionless bubble count rate $F_{max} \times d_c/V_c$ ranged from 14.0 down to 4.82. In dimensional terms, the observed value of maximum bubble count rate decreased from 222 down to 77 Hz for $0.03 \leq z \leq 0.25$ m. Note also that the location of the maximum bubble count rate shifted toward the outflow channel with increasing depths.

Figs.4, 5 and 6 present the distribution of the number of clusters N_c along the horizontal axis x for different depths for the three considered criteria. Herein N_c is the number of clusters detected for the whole sampling duration of 100 s. The graph includes the theoretical trajectory of the underwater jet (Gualtieri & Chanson, 2004b) as well as the location of the water free-surface in the shaft pool.

The number of detected clusters N_c was different among the three considered criteria. It was ranging from 25 and 839, from 11 and 312 and from 11 and 1862 for the criteria No. 1, 2 and 3, respectively. Independently of the cluster criterion, the average N_c was maximum at about 0.05 m beneath the free-surface and decreased with increasing depths (Table 4). With increasing depth z beneath the free-surface, the location where N_c was maximum tended to follow that of the jet trajectory. It is noteworthy that the criterion No. 3, based upon the near-wake, provided N_c values higher than the remaining criteria, especially along the underwater jet trajectory and close to the water surface. The difference decreased moving far from the jet and the water surface and it might be related to the ratio ch_w/ch_{ab} inside the shaft pool.

Table 4 – Average N_c and average clustered bubbles for Criterion No. 1, No. 2 and No. 3

	Average N_c			Average clustered bubbles – %		
Depth z – mm	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3
30	338	116	619	35.44	14.36	49.91
50	446	159	858	34.12	12.62	55.54
80	401	141	727	33.68	12.05	51.70
110	410	138	635	36.29	11.85	46.16
150	390	158	570	37.41	15.14	44.27
200	335	110	387	35.96	10.48	34.34
250	255	81	224	37.77	10.19	28.39



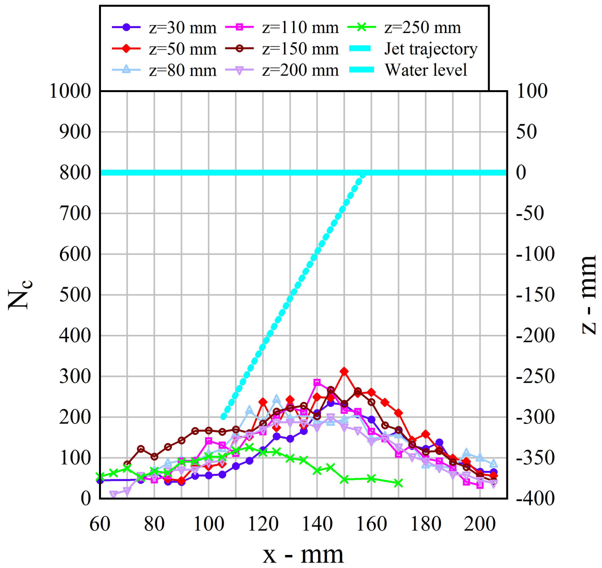
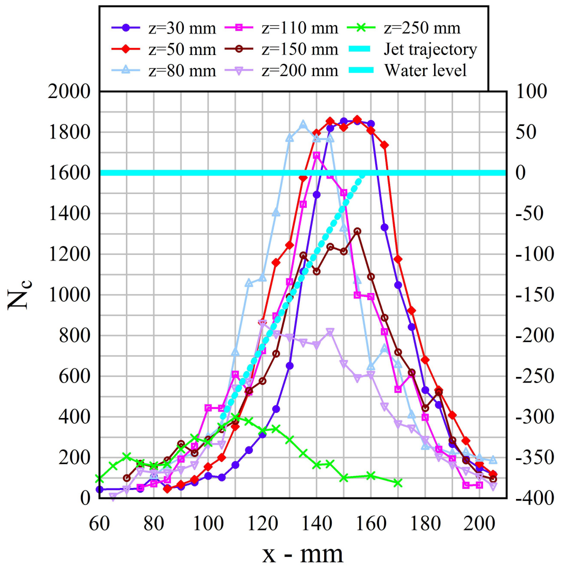


Fig.4 - Distribution of N_c along the dropshaft length and jet trajectory. Criterion No. 1 (left)
Fig.5 – Distribution of N_c along the dropshaft length and jet trajectory. Criterion No. 2 (right)

Figs.7, 8 and 9 present the distribution of the percentage of clustered bubbles along the horizontal axis *x* for different depths for the three considered criteria. The figures also include the trajectory of the underwater jet. The percentage of bubbles that were associated with clusters was in average about one third for the Criterion No. 1. The lowest and highest percentages were observed with the criterion No. 2 and 3 respectively (Table 4). Interestingly, the percentage of bubbles associated with cluster structures was the smallest along the jet trajectory for Criteria No. 1 and 2, whereas it was the highest for Criterion No. 3. The latter was expected because the clustering process is believed to be more intense at the locations where the turbulent shear is the highest, i.e. along the jet trajectory. Also, the results for Criterion No. 3 showed that the percentage of clustered bubbles was maximum at z=0.05 m and decreased with the increasing depths (Table 4).
Notably the results for Criterion No. 2 were consistent with some results obtained by Gualtieri & Chanson (2007) in a hydraulic jump flow, using the same criterion, where the percentage of clustered bubbles was in average of about 21%. In that study, the averaged percentage of clustered bubbles was 32%, 22% and 14% for inflow Froude number Fr_1=6.5, 10.8 and 14.3, respectively. The result implied some effects of the inflow Froude number on the clustering structure (Gualtieri & Chanson, 2010). Finally the percentage of clusters formed by two bubbles (only) was calculated. For Criterion No. 1, the percentage of cluster formed by two bubbles ranged from 53% to 95% and was in average 86%. For Criterion No. 2, it was in the range from 76% to 100% and in average 92%. For Criterion No. 3 the percentage ranged from 64% to 96%, with an average 80% (Table 5).



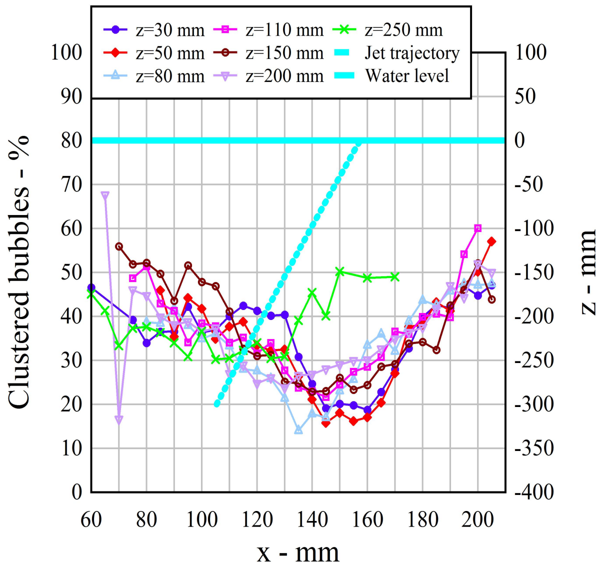
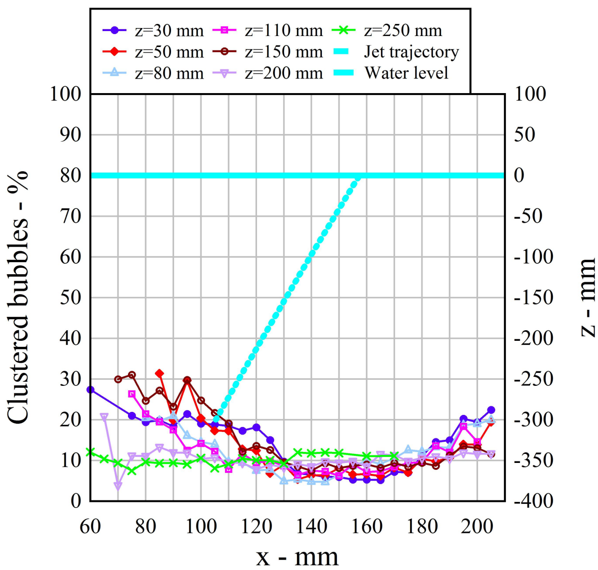


Fig.6 – Distribution of N_c along the dropshaft length and jet trajectory. Criterion No. 3 (left)
Fig.7 – Distribution of clustered bubbles in the dropshaft and jet trajectory. Criterion No.1 (right)

The results were consistent with the results obtained in stepped chutes, where, for skimming flow and transition flow, the clusters made of two bubbles were nearly 68% and about 78% of all clusters, respectively (Chanson & Toombes, 2002). In a hydraulic jump, this percentage was about 80 to 94% with an overall average value of 88% for Criterion 1 and from 70 to 91% with an overall average value of 81% for Criterion 3 (Gualtieri & Chanson, 2007, 2010). Lower values were observed at lower Fr_1. Overall, the average number of bubbles per cluster in the dropshaft was for all depths about 2.48, 2.19 and 2.54 for criteria No. 1, 2 and 3, respectively.



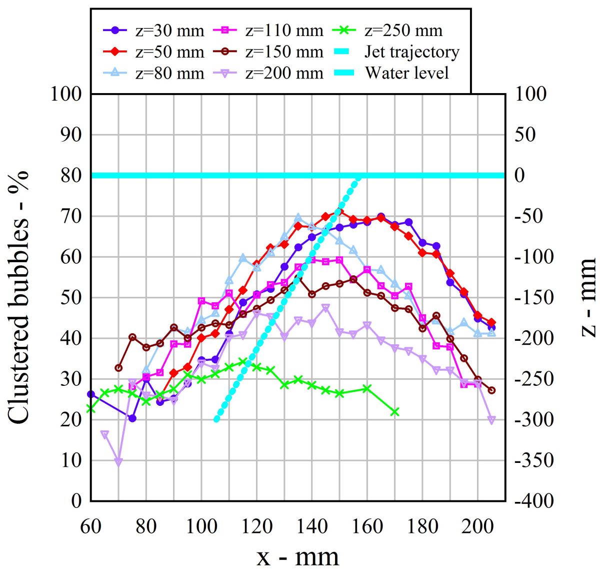


Fig.8 – Distribution of clustered bubbles inside the dropshaft and jet trajectory. Criterion No. 2
Fig.9 – Distribution of clustered bubbles inside the dropshaft and jet trajectory. Criterion No. 3

Finally, Table 6 lists the locations along the *x*-axis where the maximum void fraction C_{max}, the maximum bubble count rate F_{max} and the maximum number of clusters $N_{c\text{-}max}$ were recorded at each depth. The *x*-locations where $N_{c\text{-}max}$ were recorded following Criterion No. 3 are much closer to the F_{max} locations than to the C_{max} locations than for the other criteria.
After all, the comparison among the three considered criteria pointed out that the formation of cluster structures was a frequent feature of the air-water flow in the dropshaft pool and a significant proportion of bubbles travelled inside a cluster structure. Furthermore, the Criterion No. 3, based upon the near-wake concept, may be considered as the most effective to describe the close interaction between flow

dynamics and clustering process. First, it relies on a comparison between the *local* characteristic flow lengths, namely the water chord and the air chord of the preceding bubble. The other criteria provide a comparison between a *local* characteristic length, such as the water chord, and a *time-averaged* characteristic length of the flow, such as the average or the median value of the water chord recorded in the measurement point. Second, the locations for N_{c-max} provided by Criterion No. 3 were very close to the theoretical jet trajectory and might imply that the clustering process is most intense there, suggesting that the main mechanism responsible for clustering in the dropshaft was turbulent break-up. Third, the Criterion No. 3 yielded a decay of clustering process with the increasing depth, while the other criteria provided similar values of the percentage of clustered bubbles over the pool depth (Table 5). Finally, all the criteria confirmed that most of cluster structures were formed by only two bubbles.

Table 5 – Clustering analysis data. Clusters formed by two bubbles

	Average clusters formed by two bubbles – %		
Depth z – mm	Criterion No. 1	Criterion No. 2	Criterion No. 3
30	81.67	90.57	76.93
50	82.02	92.71	73.58
80	81.93	91.57	75.66
110	81.49	92.41	78.85
150	80.83	89.11	80.03
200	81.08	93.13	84.34
250	80.58	80.58	87.16

Table 6 – Clustering analysis data. Locations with maximum *C*, *F* and N_c

			x_{Nc-max}		
Depth z – mm	x_{Cmax} – mm	x_{Fmax} – mm	Criterion No. 1	Criterion No. 2	Criterion No. 3
30	155	155	150	145	150
50	145	145	135	150	155
80	135	135	130	125	135
110	145	140	140	140	140
150	135	145	150	145	155
200	120	130	145	145	120
250	115	110	110	115	110

5. CONCLUSION

The cluster structures are believed to a characteristic feature of the interactions between turbulence and particles in multiphase turbulent flows. The paper presented the results of a comparative clustering analysis of the turbulent flow in a large-size dropshaft corresponding to a near full-scale industrial facility. The facility was characterized by highly turbulent flows and large void fractions requiring the usage of sturdy probes, herein a single-tip probe design. Three criteria were applied to identify the presence of bubble cluster structures within the temporal series of air bubbles and water particle recorded at each measurement point. Two criteria were based upon a comparison of the water chord length with a time-averaged characteristic water length scale, i.e., the mean water chord length for the first criterion and the median water chord length for the second criterion. A third criterion identified a cluster when the water chord length was smaller than the air chord length of the preceding bubble: i.e. the bubble was in the near-wake of the preceding bubble.
The comparative results highlighted some significant patterns in bubble cluster production at all the locations. The formation of cluster structures was a common characteristic of the air-water flow in the shaft pool and a large proportion of the bubbles travelled within some cluster structures. The Criterion No. 3, based upon the near-wake concept, appears to be the most effective to describe the close interaction between flow dynamics and clustering process. First it relies on a comparison between the *local* characteristic flow lengths: the water chord and air chord of the preceding bubble. Second the locations where the cluster rate was maximum according to this criterion was very close to the theoretical jet trajectory, implying that the clustering process is most intense in the regions of large turbulent shear stresses. This suggests that the main mechanism responsible for clustering in the

dropshaft was turbulent break-up. Third the Criterion No. 3 yielded some decay of clustering process with the increasing depth in the pool. Finally, all the criteria indicated that a large majority of cluster structures were formed by only two bubbles, although the criterion definition is solely defined in terms of a longitudinal bubbly flow structure.

6. ACKNOWLEDGEMENTS

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