Effect of Froude number on bubble clustering in a hydraulic jump

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ABSTRACT

The study of bubble clustering processes may provide significant insights about the turbulent air-water flows in the hydraulic engineering field. Previous studies investigated these processes in plunging jets, in a dropshaft and in the hydraulic jump. The present technical note develops an analysis of the bubble clustering process in the hydraulic jump using experimental data collected in a rectangular horizontal flume with partially-developed inflow conditions for inflow Froude number F_1 in the range from 6.5 to 14.3. Two criteria for cluster identification were applied. One criterion was based upon a comparison of the local instantaneous water chord time with the median water chord time. The second criterion identified a cluster when the water chord time was smaller than the air chord time of the preceding bubble: i.e. a bubble was in the near-wake of the leading bubble. The results highlighted some significant patterns in clusters production both over the depth and the distance from the jump toe.

KEYWORDS

Hydraulic jump, air entrainment, laboratory experiments, bubble clustering process, Froude number.

1. Introduction.

A hydraulic jump is a sudden rapid transition from a super- to sub-critical flow (Long et al., 1991; Mossa, 1999; Chanson, 2007). It is characterised by a significant amount of energy dissipation and air entrainment. The jump roller is characterised by two distinct air-water regions: an air-water shear region and a recirculation region above. The air-water shear layer is characterised by a transfer of momentum from the high-velocity jet flow to the recirculation region above, as well as by very significant interactions between the entrained air and turbulence. These interactions lead to some complicated processes including bubble breakup, coalescence and clustering. The clustering process is related to the inhomogeneous distribution of the bubbles, which tend to have some preferential concentration forming coherent structures termed “clusters”. In a bubbly flow, a cluster of bubbles may be defined as a group of two or more bubbles with a distinct separation from other bubbles before and after the cluster. In the area of hydraulic engineering, some previous investigations studied the clustering process in plunging jets (Chanson et al. 2006), in stepped chutes (Chanson and Toombes 2002), in a dropshaft (Chanson 2002; Gualtieri and Chanson 2004, 2007b), and in the hydraulic jump (Chanson 2007, Gualtieri and Chanson 2007b).

In this note, two criteria were applied to assess the occurrence of bubble clusters in hydraulic jumps with inflow Froude numbers F_1 ranging from 6.5 to 14.3. The comparative results highlighted some significant patterns in the cluster production both over the depth and the distance from the jump toe. The influence of inflow Froude number on clustering process was also discussed.

2. Experimental setup. Channel and instrumentation.

The laboratory experiments were performed at the University of Queensland in a horizontal channel, 3.2 m long and 0.25 m wide (Fig.1). Both bottom and sidewalls were made of 3.2 m long glass panels. This channel was fed by a constant head tank. The flow rate in the flume was measured with a 90º V-notch weir which was calibrated on-site with a volume-per-time technique. The percentage of error was expected to be less than 2%. The water depths were measured using rail mounted pointer gauges with an accuracy of 0.2 mm. The experiments were carried out for an inflow Froude number F_1 in the range from 6.5 to 14.3, while the inflow depth d_1 and the inflow velocity V_1 were from 0.0119 to 0.0128 m and from 2.23 to 4.87 m/s, respectively. The 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. It was excited by an electronic system designed with a response time less than 10 μs and calibrated with a square wave generator. The probe vertical position was capable of being adjusted in 0.1 mm increments. All the measurements were conducted on the channel centreline (z=0).

Fig.1 – The hydraulic jump at Fr_1=14.3

The experiments yielded the void fraction C and the bubble count rare F over the depth at different distances from the jump toe (Gualtieri and Chanson, 2007a). The air concentration or void fraction C is the proportion of time that the probe tip is in the air, whereas the bubble count rate F is the number of bubbles impacting the probe tip per second. In the present study, the probe tip was horizontal and aligned with the main flow direction. With the single-tip conductivity probe, the error on void fraction measurements was estimated as: $\Delta C/C$ =4 % for $0.05 < C < 0.95$, $\Delta C/C \approx 0.002/(1 - C)$ for $C > 0.95$, and $\Delta C/C \approx 0.005/C$ for $C < 0.05$. The probe was scanned at F_{scan}=20 kHz for T_{scan}=45 s at each sampling location. Preliminary clear water velocity measurements were performed in the flume using a Prandtl-Pitot tube (Ø=3.3 mm). The results showed that the supercritical inflow was partially-developed for all investigated flow conditions. The relative boundary layer thickness δ/d_1 varied from 0.5 to 0.6 depending upon the inflow conditions (Fig.2).

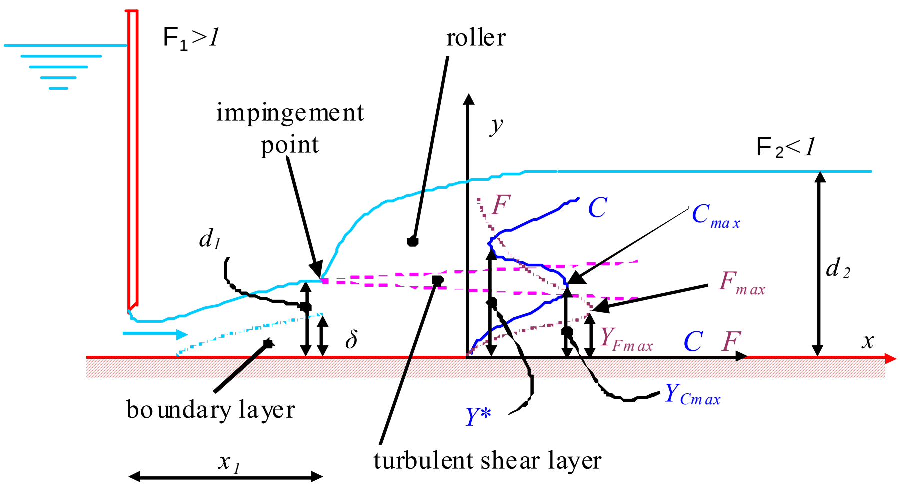

Fig.2 - Sketch of hydraulic jump flow with partially-developed inflow conditions

3. Clustering analysis. Criteria, results and discussion.

Different approaches were proposed to identify a cluster structure within the air-water flow. One approach is based upon the analysis of water chord between two subsequent air particles. If two bubbles are closer than a characteristic time/length scale, they can be considered a group of bubbles that is a cluster (Chanson and Toombes 2002; Gualtieri and Chanson 2004, 2007b). 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 and Toombes 2002; Chanson et al. 2006; Gualtieri and Chanson 2007b). In the hydraulic jump, it is difficult to ascertain the direction of motion of each individual bubbles, and the analysis must be conducted in terms of chord times.

In the present study, two criteria were applied to detect the occurrence of clusters in the air-water flow. Namely they were:

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

$$t_{ch-w} < \frac{1}{10} t_{ch\text{-}w\text{-}median} \tag{1}$$

  where $t_{ch\text{-}w\text{-}median}$ is the median water chord time;

- the water chord time between two subsequent air particles was compared with the air chord of the preceding bubble recorded in the point of measurement. Thus, according to the Criterion No. 2 a cluster was detected if:

$$t_{ch\text{-}w} < \eta\, t_{ch\text{-}ab} \tag{2}$$

  where $t_{ch\text{-}ab}$ is the air chord time of the leading bubble and η is a parameter characterizing the wake timescale of the leading bubble. It is believed from literature 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:

- dimensionless number of clusters per second $(N_c/s)\times(d_1/V_1)$, where N_c is the number of clusters detected in the measurement point over the sampling time s;
- percentage of clustered bubbles relative to the total number of detected bubbles;
- number of bubbles per cluster.

Further analysis was devoted to compare the locations where maximum clustering was found in terms of these properties as well as at locations where the local void fraction and bubble count rate maxima, C_{max} and F_{max}, respectively, were recorded.

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. In plunging jet and hydraulic jumps, such large-scale vortices are generated in the developing shear layers. As the vortical, coherent structures are advected downstream, they grow up in size by vortex pairing and contribute to further clustering.

Details about the air-water flow properties were provided by Gualtieri and Chanson (2007a).

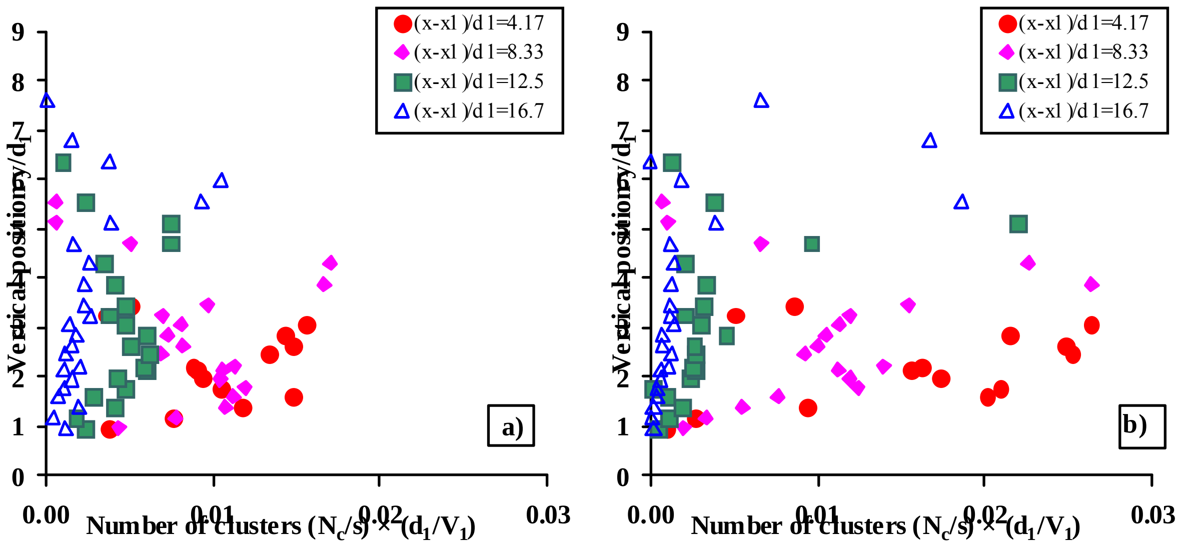

Fig. 3 – Number of clusters for F_1=6.51. Criterion No .1 (Fig. 3a) and No. 2 (Fig. 3b)

Figures 3a and 3b present some vertical distributions of the number of clusters per second N_c in the hydraulic jump for F_1=6.51 for the two cluster criteria (Eq. (1) and (2)) where y is the vertical elevation above the invert and d_1 is the inflow depth. In Figs.3a and 3b, the horizontal axis is the dimensionless number of clusters per second $(N_c/s)\times(d_1/V_1)$. Figures 4a, 4b, 5a and 5b present the results of the clustering analysis for F_1=10.8 and 14.3 for both criteria. Overall, the clustering analysis regrouped 269 records from 18 vertical profiles (Table 1).

Earlier studies demonstrated that an air diffusion region exists in which the void fraction distributions follow an analytical solution of the classical advection-diffusion equation (Chanson, 1995; Murzyn et al., 2007). Above this air diffusion layer, for $y > Y^*$, there is the upper free-surface region where the void fraction increases rapidly to the unity as illustrated in Figure 2.

The dimensionless number of clusters per seconds was different between the two considered criteria. For F_1=6.5, it ranged from 0.0026 to 0.0102 and from 0.0025 to 0.0153 for the criteria No. 1 and 2, respectively. For F_1=10.8, it was ranging from 0.0031 to 0.0116 and from 0.0023 to 0.0355 for the criteria No. 1 and 2, respectively. Finally, for F_1=14.3, it was ranging from 0.0035 to 0.0103 and from 0.0037 to 0.0383 for the criteria No. 1 and 2, respectively.

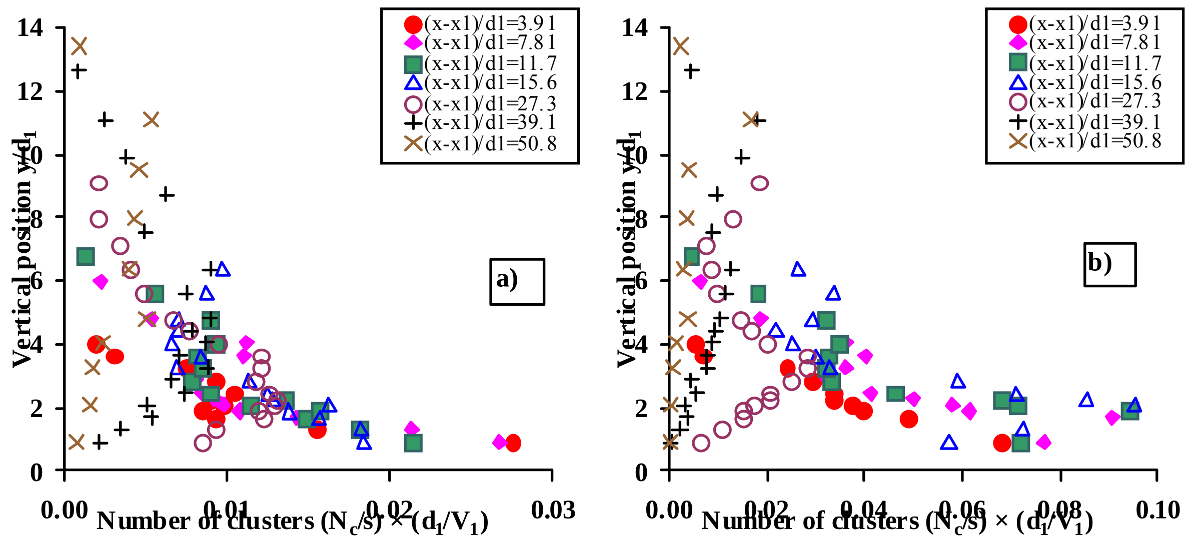

Fig. 4 – Number of clusters for F_1=10.8. Criterion No .1 (Fig. 4a) and No. 2 (Fig. 4b)

Generally, the lowest values were observed at the largest distance from the jump toe for all Froude numbers F_1 and for both cluster criteria. The lowest values were quite similar for both criteria. In average, the dimensionless number of clusters per seconds was for criterion No. 1 about 0.0065, 0.0088 and 0.0086 for F_1=6.5, 10.8 and 14.3, respectively. For criterion No. 2, it was 0.0079, 0.0207 and 0.0223 for F_1=6.5, 10.8 and 14.3, respectively. The criterion No. 2 showed that the clustering process tended to increase with increasing F_1.

For the criterion No. 2, the location of the maximum dimensionless number of clusters per second Y_{Nc-max} was mostly close to the location of maximum bubble count rate in the shear region, i.e. Y_{Fmax}/d_1 (Table 1). Usually, this location is higher than that of the maximum void fraction, i.e. Y_{Cmax}/d_1 (Gualtieri and Chanson, 2007a; Murzyn et al., 2007).

Figures 6a and 6b show the dimensionless longitudinal profiles of the maximum dimensionless number of clusters per seconds in the hydraulic jump flows. The values from criterion No. 2 were always larger than those from criterion No. 1 . Independently of the clustering criterion, the maximum number of clusters per second decreased with increasing distance from the jump toe and decreased with decreasing inflow Froude number F_1 at a given dimensionless distance $(x-x_1)/d_1$.

Table 1 – Comparison between Y_{Nc-max}/d_1, Y_{Cmax}/d_1, Y_{Fmax}/d_1 and Y^*/d_1

					Y_{Nc-max}/d_1	
F_1	$(x-x_1)/d_1$	Y_{Cmax}/d_1	Y_{Fmax}/d_1	Y^*/d_1	*Criterion No. 1*	*Criterion No. 2*
6.51	4.17	---	1.60	---	3.05	3.05
	8.33	2.85	1.97	3.47	4.30	4.30
	12.5	2.85	2.85	4.30	4.72	5.14
	16.7	3.26	3.26	4.72	5.97	5.55
10.8	3.91	---	0.91	---	0.91	1.30
	7.81	2.08	1.30	2.86	0.91	1.30
	11.7	1.69	1.30	3.25	0.91	1.30
	15.6	2.86	1.69	4.43	0.91	1.69
	27.3	3.65	3.25	6.38	2.28	3.25
	39.1	4.82	4.82	8.72	4.82	11.1
	50.8	---	11.1	9.50	11.1	11.1
14.3	4.20	1.40	0.98	2.24	0.98	0.98
	8.40	1.40	1.40	3.08	0.98	1.40
	16.8	2.24	1.82	4.76	0.98	1.82
	29.4	3.92	2.24	7.28	1.82	2.66
	42.0	6.02	3.50	9.38	1.82	4.34
	54.6	5.60	5.60	9.38	4.34	5.60
	67.2	8.12	8.12	9.38	11.1	16.11

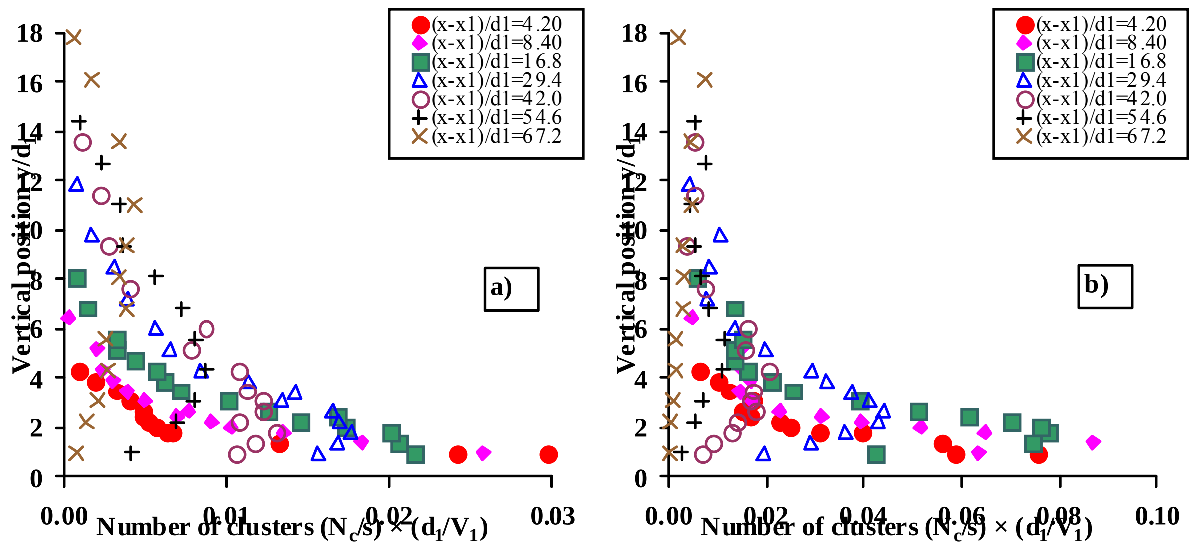

Fig. 5 – Number of clusters for F_1=14.3. Criterion No .1 (Fig. 5a) and No. 2 (Fig. 5b)

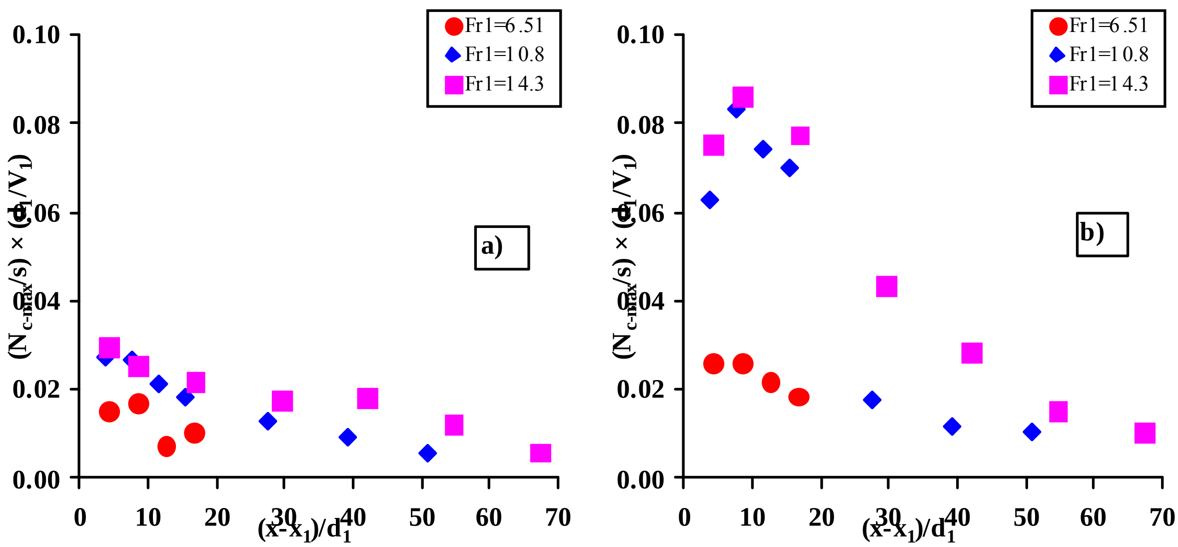

Fig. 6 – N_{c-max} for F_1=6.51 10.8 & 14.3. Criterion No .1 (Fig. 6a) and No. 2 (Fig. 6b)

The results included further the percentage of clustered bubbles. The averaged percentage of clustered bubbles for criterion No. 1 was about 32%, 20% and 14% for F_1=6.5, 10.8 and 14.3, respectively. For criterion No. 2 it was 35%, 41% and 41% for F_1=6.5, 10.8 and 14.3, respectively. Overall the results showed that the percentage of clustered bubbles was in average of about 20% and 39% for criteria No.1 and No. 2 , respectively. Furthermore, the average number of bubbles per cluster was about 2.3 and 2.5 for criteria No.1 and No. 2 , respectively, demonstrating that cluster structures were mostly formed by 2 bubbles. The percentage of clusters made of two bubbles was from about 79 to 94% with an overall average value of 88% for criterion No. 1, and from about 70 to 91% with an overall average value of 81% for criterion No. 2 . These results were consistent with the results obtained in dropshafts and stepped chutes. In a dropshaft, the percentage of clusters formed by two bubbles ranged 76% to 100% with an average of 92% for criterion No. 1, whereas for criterion No. 2 was in the range from 64% to 96%, with an average 80% . For skimming flows and transition flows, the clusters made of two bubbles accounted for nearly 68% and 78% of all clusters respectively (Chanson and Toombes, 2002), and for between 79 and 84% of all clusters in circular plunging jet flows (Chanson et al., 2006).

Overall the comparison between the two cluster criteria pointed out that the formation of cluster structures was a frequent feature of the air-water flow in the hydraulic jump flows and a significant proportion of bubbles travelled inside a cluster structure. The criterion No. 2, based upon the near-wake concept, may be considered as more effective because it relies on a comparison between the *local* characteristic flow scales, namely the water chord and the air chord of the preceding bubble. The criterion No 1 provides a comparison between a *local* characteristic time, such as the water chord time, and a *time-averaged* characteristic time of the flow, such as the median value of the water chord time recorded in the measurement point. The locations for N_{c-max} provided by criterion No. 2 are inside the turbulent shear layer implying that the clustering process is most intense where maximum turbulent shear exists. Finally, both criteria confirmed that a significant proportion of cluster structures were formed by only two bubbles.

4. Conclusion.

The cluster structures are believed to be a characteristic feature of the interactions between turbulence and particles and bubbles in hydraulic jumps, because the clusters influence the surrounding flow field, introducing enhanced velocity fluctuations and hydrodynamic interactions that could affect the overall flow structure. Thus, the study of clustering process may provide some significant insights into the air-water flows in the hydraulic engineering field.

The objective of this note was to present the results of a comprehensive clustering analysis in which two criteria were applied to identify the presence of bubble cluster structures within the temporal series of air bubbles and water particles recorded at each measurement point. One criterion was based upon a comparison of the *local*, instantaneous water chord time with a *time-averaged* characteristic water time scale, i.e., the median water chord time. The second criterion identified a cluster when the water chord time was smaller than the air chord time of the preceding bubble: i.e. a bubble was in the *near-wake* of the preceding bubble.

The results highlighted that the formation of cluster structures was a common characteristic in the hydraulic jumps and that a large proportion of the bubbles travelled within some cluster structures. Moreover, independently of the clustering criterion, the maximum number of clusters per second decreased with increasing distance from the jump toe and it decreased with decreasing inflow Froude number F_1 at a given distance. This demonstrated some effect of the Froude number on clustering process in the hydraulic jump.

The second cluster criterion, based upon the near-wake concept, appears to be most effective because it relies on a comparison between the local, instantaneous characteristic flow times. The location where the cluster rate was maximum was within the turbulent shear layer, suggesting that the clustering process is most intense in the regions of large turbulent shear stresses. Both cluster criteria showed 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. Finally, the results herein presented were consistent with earlier results obtained in different air-water flows. Future studies will be addressed to investigate scale effects on the clustering process in the hydraulic jump.

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