VELOCITY AND CONCENTRATION OF BUBBLES IN OZONIZATION COLUMNS WITH CROSS SECTIONS OF DIFFERENT SIZES

VELOCIDAD Y CONCENTRACIÓN DE BURBUJAS EN COLUMNAS DE OZONIZACIÓN CON SECCIÓN TRANSVERSAL DE TAMAÑOS DIVERSOS

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RESUMEN

La sección transversal de una columna de ozonización posee influencia directa sobre las características hidrodinámicas de esa columna, lo que se refleja en los fenómenos que dependen de la transferencia de masa en la interfase gas-líquido. En este estudio se utilizaron dos columnas con secciones transversales diferentes cuanto a la forma y al tamaño. La primera con sección transversal cuadrada de 0,19 m y la segunda con sección transversal circular de 0,10 m de diámetro. Se midieron las velocidades ascensionales de las burbujas y su concentración. Los resultados obtenidos muestran que el aumento de la sección transversal en la proporción aquí estudiada no conlleva un aumento semejante de la sección transversal de la pluma ascendentes de burbujas, cuando son computadas las velocidades y concentraciones medias. Los resultados de velocidad media y de concentración media para la columna de sección más pequeña se mostraron independientes de la altura del líquido, mientras que los resultados de velocidad media y de concentración media obtenidos para la columna de sección más grande mostraron dependencia con la altura del líquido. La evolución de la razón de las áreas de la pluma a lo largo del eje longitudinal de las columnas se presenta y muestra que esta razón disminuye en la dirección del tope de las columnas.

Palabras clave: Ozono, velocidad a láser no intrusiva, transferencia de masa gas-líquido, columna de burbujas, difusor.

ABSTRACT

The size of the cross section of an ozonization column influences its hydrodynamic characteristics, which, on its turn, has effects on phenomena that depend on the relative movement between gas bubbles and liquid. To observe the influence of the cross sectional area on gas concentration and bubbles velocity, two columns were used. The first column had a square cross section with side of 0.19 m and the second had a circular cross section with diameter of 0.10 m. The ascendant velocities of the bubbles and their concentration were measured in both columns and compared. The transversal spread of the plumes of bubbles was also quantified. The results show that the increase of the cross section of the column, in the proportion studied here, does not result in a similar increase of the cross section of the ascending plume of bubbles. Furthermore, the results of average velocities and concentrations obtained for the smallest cross section resulted independent of the liquid level in the column, while the results for the largest cross section showed to be dependent of this level. The ratio between the cross sectional areas of the larger and the smaller plumes of bubbles decreases for higher distances to the bottom of the columns.

Keywords: Ozone, non-intrusive laser velocimetry, gas-liquid mass transfer, bubble columns, diffuser.

INTRODUCTION

Research studies carried out at the Department of Hydraulic and Sanitary Engineering of the Escola de Engenharia de São Carlos, Universidade de São Paulo, using ozone to oxydize organic matter and to inactivate indicative microorganisms, are revealing situations of decrease of efficiency, possibly associated to the mass transfer across the ozone-water interface of the bubbles of ozone. The geometric characteristics of the used equipments are easily controlled, and different dimensions of the columns were tested to obtain different hydrodinamic conditions.

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Evidently, the choice of the micro porous diffuser was also of major importance, because it determined the diameter of the released bubbles, which must be small.

The literature shows that the liquid level in the column should not be too low or too high. In the first case, ozone can be released to the atmosphere, without reacting with chemicals or microorganisms contained in the liquid. In the second case, the ozone is thoroughly consumed in the inferior part of the column, turning superfluous the superior part. The liquid level affects, for instance, the quantification of parameters such as the global mass transfer coefficient, which depends on the specific interfacial area, inversely proportional to the liquid volume [8]. The optimum level of the liquid depends upon a large number of variables, among which can be mentioned the diameter of the bubbles, the cross section of the column, the discharge of ozone and the velocity of the bubbles [8]. The quantification of mass transfer coefficients may be found, for instance, in [1-7], [9-12], among others.

Considering the relevance of the mentioned parameters, a set of data of bubble velocities and concentrations was obtained for two different ozonization columns, permitting comparation of the results. One column had a square cross section and the other a circular cross section. Non-intrusive methods were used for the measurement of velocities and bubble concentrations, using PIV velocimetry and a Cesium 137 probe, respectively. The results for larger cross sections showed to be more sensitive to the level of the liquid in the column. The increase of the cross section of the column did not imply in a proportional increase of the cross section of the plumes of bubbles.

MATERIALS AND METHODS

Ozonization columns

The column with larger square cross section, named “column 1” in this study, had sides of 0.19 m and height of 2.00 m. Two parallel walls were built on Perspex and two parallel walls were built on glass, both materials with thicknesses of 15 mm. The column with smaller circular cross section, named “column 2” in this study, had an internal diameter of 0.10 m, height also of 2.00 m, and was built using a tube of Perspex with wall thickness of 5.00 mm. Diffusers were installed at the bottom of both columns, with pores of 20 µm, permitting air flows up to of 3.0 m^3/h. Both diffusers had diameters of 75 mm and height of 70 mm, providing bubble diameters between 1 and 3 mm.

The top of both columns was covered with a lid of Perspex, convenientely perforated to allow the release of gases into the atmosphere. The elimination of residues of non-reacted ozone from those gases was performed bubbling the gas flow into a solution of potassium iodide 2%. The saturation by ozone implies in a strong golden-yellow color, which indicates the need to replace the solution. However, routinely the solution of potassium iodide was replaced after each day of experiments.

Ozone generator

The ozone generator used in this study can be ajusted to produce 20%, 40%, 60%, 80% or 100% of its maximum generation capacity. In the working conditions, the generation of ozone oscillated weakly around 3.0 gO_3/h, with the equipment set at 100% of its capacity and the oxygen flow rate set at 300 L/h (5 L/min). The contact time between liquid and gas bubbles (ozone+oxygen) was fixed in 5 minutes. The flow rate was controlled using a stainless steel flowmeter fixed to the ozone generator.

Velocimetry technique and laser equipment

The PIV (Particle Image Velocimetry) method was used to measure instantaneous velocity fields of the plumes of bubbles within the columns. The PIV method uses a light beam to illuminate moving particles in the fluid, recording their successive positions with the aid of photographic equipment. In the present study, the particles of interest were the bubbles of gas (ozone+oxygen) with ascending movement. Their positions were recorded with a CCD camera (1024 vs 1024 pixels) and their velocities calculated with proper softwares, using auto-correlation algoritmes and interrogation areas of 64 vs 64 pixels with 75% of overlapping. Fifteen frames were recorded per second and a total of 200 frames were obtained for each run, which permitted to obtain the mean velocity values. The main advantage of the PIV method is its non-intrusive characteristic. In other words, the method does not modify the flow that is being measured.

The light source was a copper gas Laser, with a mean power of 20 W and pulses at 10 kHz. The pulse power lied between 60 and 140 kW. Generated wavelengths were 510.6 nm (green) and 578.2 nm (yellow). The light was conducted to the measurement section through optic fibers and converted to a light sheet using a set of converging and diverging lenses.

Translucid environments, like the liquids that compose home sewers, are not adequate for the PIV technique. So, water of public provisioning was used for the measurement of the velocities of the bubbles. Eventual velocity differences related to the liquid used in the coluns (although small) occur equally in both columns, still allowing comparisons. Instantaneous and averaged velocity profiles were obtained along the whole columns of water. Figure 1 shows a scheme of the equipment used in this study. The measurements in column 2 were taken along the central vertical plane (which accompanies the longitudinal axis), so that no deviations of the light sheet occurred due to the curvature of the surface. The measurements in column 1 were also taken along the the central vertical plane, with the light sheet being introduced parallel to the Perspex faces, as schematized in figure 1.

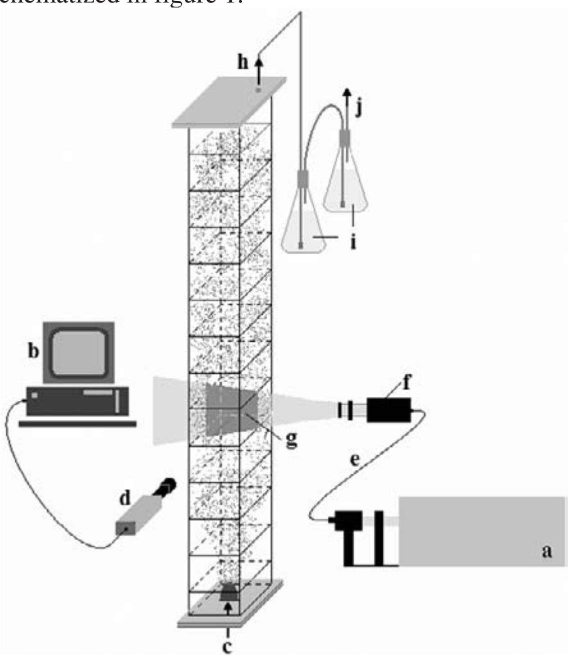

Figure 1. (a) laser source; (b) micro-computer; (c) ozone inlet in the column; (d) CCD camera; (e) optic fiber; (f) converging and diverging lenses; (g) light sheet; (h) gas outlet; (i) potassium iodide 2%; (j) release of oxygen into the atmosphere.

The sequence of steps in each run was: to fix the water level, to focus the CCD camera, to establish the air discharge and to obtain the successive images for each flow condition.

Concentration records and Cesium 137 probe

A Cesium 137 probe was used for the bubble concentration measurements, as shown in figure 3. Calibration was made with the columns full with water and empty. The Cesium 137 radiation was projected across the columns and a counter registered the remaining radiation, after passing the mixture of gas bubbles (ozone+oxygen) and water. The obtained concentrations consider the entire width of the columns (side or diameter). Bubbles concentrations were thus means transverse to the gas flow direction. The concentration is quantified as the percentage of bubbles in the liquid medium (void ratio). Radiation attenuations produced by the different materials were considered in the quantification of the concentrations. The measurements were conducted with the ozone generator set to 20% of its maximum capacity. The Cesium probe was positioned at distances of 0.15 m, 0.55 m, 0.95 m and 1.45 m from the bottom of both columns. The radiation always intercepted the central axis of the column. In column 1 the radiation was emitted parallel to the Perspex walls and in column 2 it was emitted along the diameter. Three water levels in the columns were studied: 1.00 m, 1.50 m and 1.90 m. For the level of 1.00 m only the first three positions of the probe could be used. The gas discharges were adjusted in the range from 37 L/h to 300 L/h. Concentrations were recorded in 20 sequences of 20 seconds for each run (fixed liquid level and gas discharge), furnishing mean concentration values. The mean values obtained for the four probe positions showed to be very close to each other and a global mean value (arithmetic average) was then calculated for each run.

Table 1. Control parameters: gas discharge, applied dose of ozone and liquid level. Ci designate the experiments conducted in column 1 and Di designate the experiments conducted in column 2.

	Column 1 – Square section						Column 2 – Circular section						h (m)
Run	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4			
Flow (L/h)	50	100	150	200	250	300	63	76	220	298			1.0
Dose (mg/L)	11.2	15.9	19.6	22.8	22.5	28.0	10	20	20	10			
Run	C7	C8	C9	C10	C11	C12	D5	D6	D7	D8	D9	D10	
Flow (L/h)	50	100	150	200	250	300	37	45	67	129	157	232	1.5
Dose (mg/L)	11.2	15.9	19.6	22.8	22.5	28.0	10	10	20	10	20	10	
Run	C13	C14	C15	C16	C17	C18	D11	D12	D13	D14	D15	D16	
Flow (L/h)	50	100	150	200	250	300	56	68	106	197	239	284	1.9
Dose (mg/L)	11.2	15.9	19.6	22.8	22.5	28.0	10	10	20	10	20	10	

CONTROL PARAMETERS

Table 1 presents the variables that were controlled at each run (control parameters). They are: water level (h, which determines the volume of liquid used), gas discharge (ozone+oxygen), and the dose of ozone applied, obtained from the calibration curves of the ozone generator.

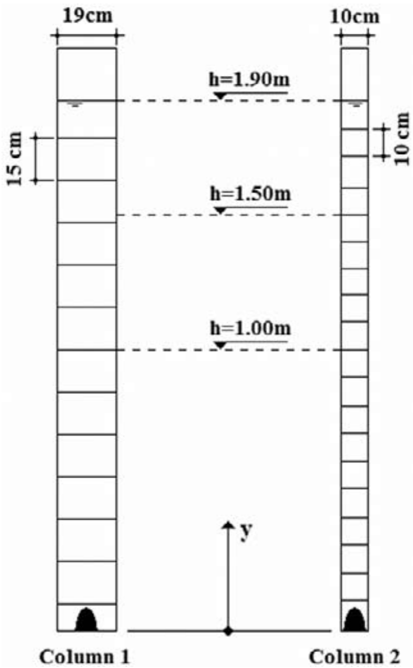

Figure 2. Measurement sections in both columns. The water levels were 1.0; 1.5 and 1.9 m. The dimensions of the columns and the longitudinal axis (y) are also shown.

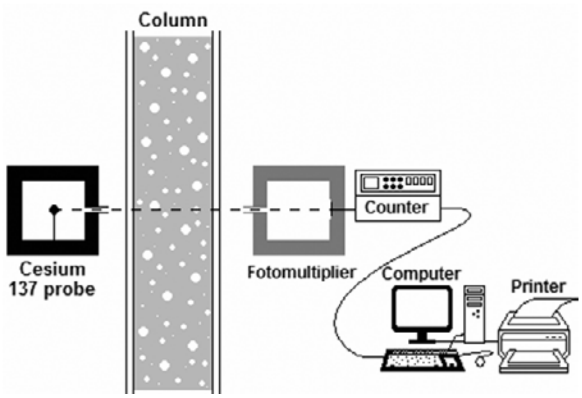

Figure 3. Cesium probe, column, photomultiplier, particle counter and computer used to measure the concentration of bubbles in the different sections of the column.

RESULTS AND DISCUSSION

Velocity results

The measured velocity fields reproduced evidently the movement of the ascending bubbles. However, they also captured the movement of the fluid in regions of the flows without bubbles, mainly close to the walls of the columns, where the water presented a preferential descending movement. These regions were not considered in the calculations of bubbles velocities. The descending movement was more evident in column 1 than in column 2.

The area occupied by the diffuser in the bottom of the column influences the spread of the plume of bubbles close to the bottom. Volumes of water without bubbles in this region were more evident in column 1. The diffusers occupied about 56% and 12% of the cross sectional areas of columns 2 and 1, respectively. The measurements in column 1 were taken in cross sections apart 15.0 cm from each other, while the measurements in column 2 were taken in sections apart 10.0 cm from each other. The positions of the sections are shown in figure 2.

Figure 4a presents the velocity data obtained for the water level of 1.0 m in both columns. As expected, the general trend is to increase the bubble velocity when increasing the gas discharge (the relative position of the curves for each flow are the same for the different sections). An evident influence of the geometry of the section is observed, for the range of discharges used in this study (from 50 to 300 L/s in column 1 and from 37 to 298 L/s in column 2). The mean velocities of the bubbles in column 1 are about twice the corresponding mean velocities in column 2. In the present study, the equivalent diameter of column 1 is 21.4 cm, also about twice the diameter of column 2 (10 cm). As the comparisons are made for same water levels and gas discharges in both columns, the different velocities are due only to the different geometrical characteristics.

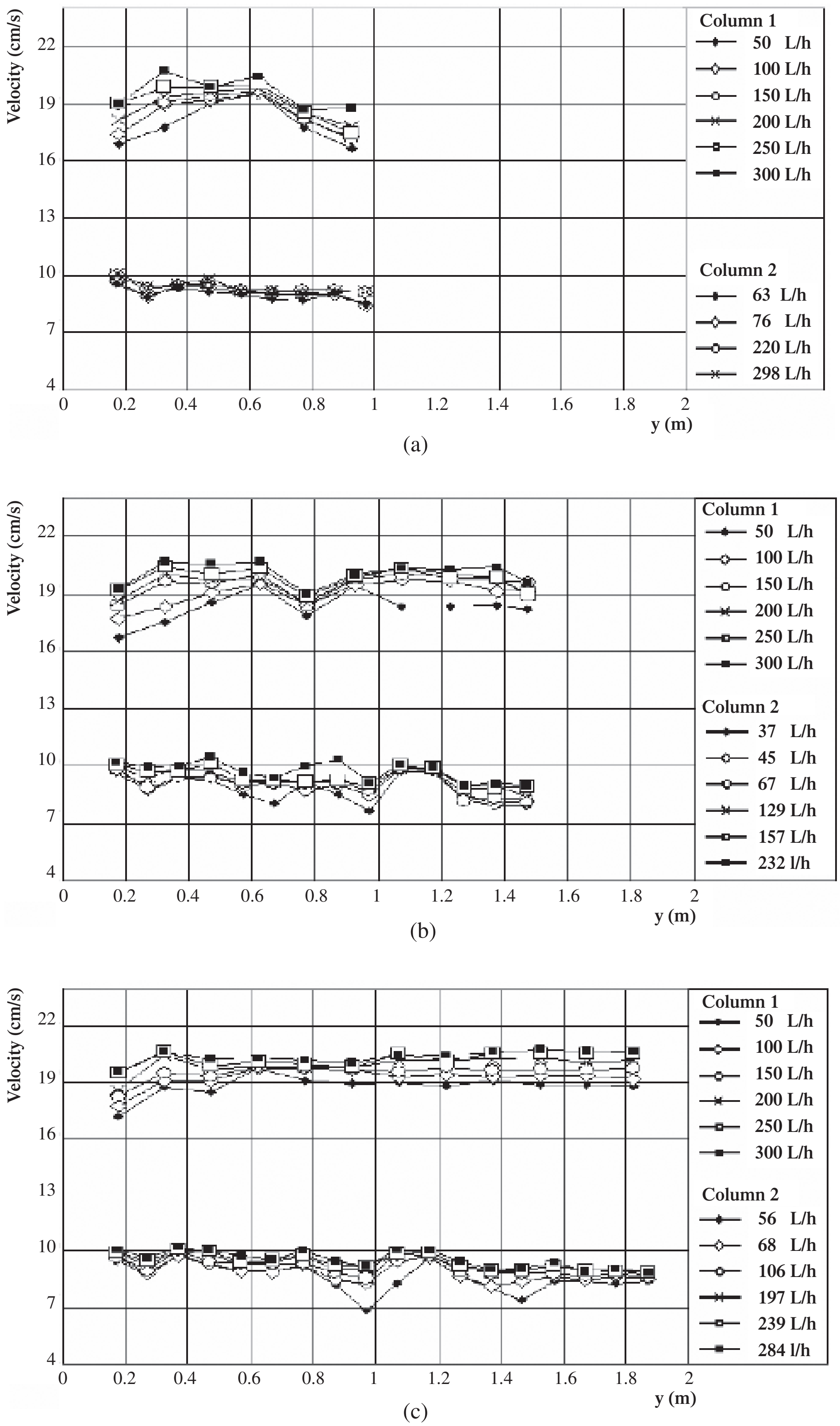

Figure 4. Velocity of the ascending bubbles of gas along y; (a) water level = 1.0 m; (b) water level = 1.5 m; (c) water level = 1.9 m.

Figures 4b and 4c, with velocity data obtained for water levels of 1.50 m and 1.90 m in both columns, show general trends similar to those of Figure 4a.

Figures 4a, 4b and 4c show that, for column 2, the velocities stayed reasonably constant along the measurement sections, slightly decreasing for higher y. For column 1, a region of acceleration is observed close to the bottom of the column, which is more evident for the lower discharges. Still considering column 1, figure 4a shows an acceleration region followed by a deceleration region for all gas discharges, when the water level is 1.0 m. Figure 4c also shows the acceleration region close to the bottom, but now followed by a general trend of stabilization (or constancy) of the velocity, while Figure 4b shows an intermediate behavior between the two previous situations. The general behaviors of acceleration, deceleration or constancy can be evidenced defining a mean value for the velocities, which uses all discharges at each cross section. Figure 5 shows the evolution of these mean values, obtained for both columns.

A second set of average values is obtained considering each discharge separately and calculating the mean value of the corresponding velocities at all the cross sections. Table 2 and figure 6 show the evolution of these mean velocities. In this case, the influence of the water level in the column is evidenced. Figure 6 shows that the data of column 2 are not segregated by the water level, while the data of column 1 show higher mean velocities for higher liquid levels. Prediction equations 1 and 2 are furnished, based on regression analyses, valid for experimental conditions similar to those of the present study.

Table 2. Mean velocities according to the gas discharge and the water level in each column.

	Column 1						Column 2						h (m)
Flow (L/h)	50	100	150	200	250	300	63	76	220	298			1.0
Vel. (cm/s)	17.9	18.4	18.7	18.8	19.1	19.5	8.9	9.1	9.3	9.4			
Flow (L/h)	50	100	150	200	250	300	37	45	67	129	157	232	1.5
Vel. (cm/s)	18.2	19.0	19.4	19.5	19.7	20.0	8.7	9.0	9.1	9.3	9.4	9.7	
Flow (L/h)	50	100	150	200	250	300	56	68	106	197	239	284	1.9
Vel. (cm/s)	18.7	19.2	19.5	19.9	20.2	20.3	8.5	8.8	9.1	9.3	9.4	9.5	

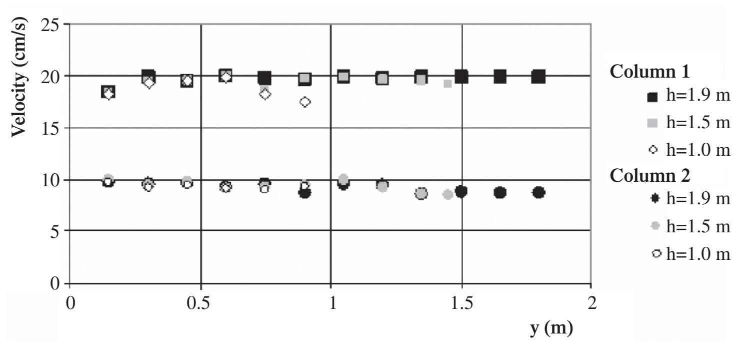

Figure 5. Mean velocities in both columns. The velocities increase in column 1 for y < 0.50 m. For column 2 there is a slight decrease of the velocity for higher values of y.

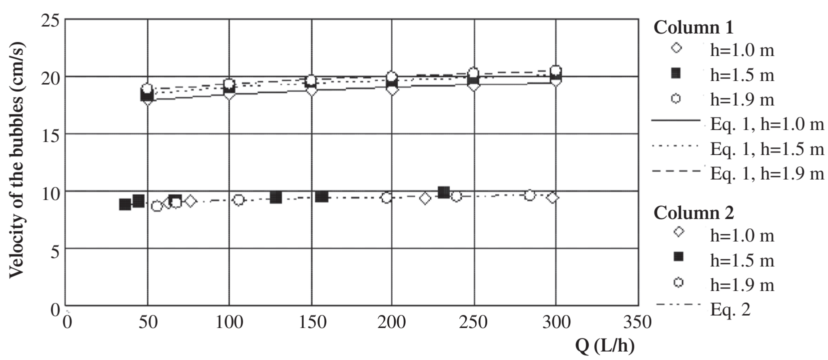

Figure 6. Ascending velocity of the bubbles as a function of the gas discharge for both columns. Effect of the water level is observed in column 1.

$$V_1=14.8.h^{0.0730}.Q^{0.0469} \quad (1)$$

$$V_2=7.56.Q^{0.0412} \quad (2)$$

Where: V_1 and V_2 are the mean velocities in columns 1 and 2 (cm/s), respectively; Q is the applied gas discharge (L/h); h is the water level (m).

Concentration Results

Table 3 presents the results of the mean concentrations (mean values for the four positions of the Cesium probe), for the different gas discharges and water levels in the columns. Figure 7 shows these concentrations plotted against the applied discharge. The results of column 2 does not present segregation related to the liquid level, while the results of column 1 show that the data obtained for the level of 1.0 m are preferentially positioned above the data of the other levels. Similarly to the velocity results, the water level affects the results of bubbles concentration in column 1.

Figure 7 consideres so called "homogenized concentrations", obtained as follows. Ideally, concentrations can be understood as a macroscopic volume of gas (ozone+oxygen) divided by the macroscopic volume of the mixture gas+liquid, which lead to the expression:

$$C = [\text{Volume of gas}]/[\text{Volume of mixture}] \quad (3)$$

Considering two columns with the same expanded water level and the same volume of ozone being provided, the ideal relation between the concentrations is:

$$\frac{\bar{C}_1}{\bar{C}_2} = \left(\frac{D_2}{D_1}\right)^2 \quad (4)$$

In the present case, the concentrations are obtained along well defined linear dimensions. For column 1 this dimension is the side of 0.19 m and for column 2 this dimension is the diameter of 0.10 m. Using these values in equation 4, the ideal ratio between the concentrations in both columns is obtained as:

$$3.61\,\bar{C}_1 = \bar{C}_2 \quad (5)$$

In other words, multiplying the concentrations measured in column 1 by 3.61 would lead to a superimposition with the concentrations measured in column 2 (operation which was named "concentration homogenization").

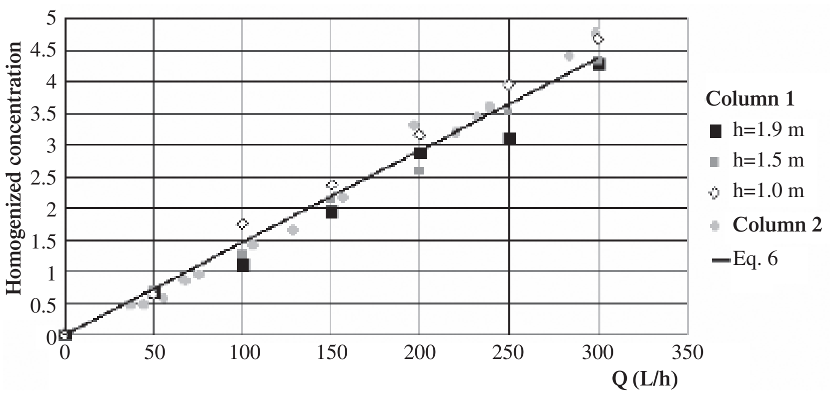

Figure 7. Homogenized concentration as a function of the gas discharge. Column 2 does not present segregation caused by the water level. Column 1, however, shows the points of h=1.0 m above the other data. Equation 5 was used for homogenization.

Table 3. Mean concentrations obtained in both columns, according to the gas discharge and the water level.

	Column 1						Column 2						h (m)
Flow (L/h)	50	100	150	200	250	300	63	76	220	298			1.0
Conc. (%)	0.18	0.48	0.65	0.87	1.09	1.29	0.80	0.94	3.18	4.75			
Flow (L/h)	50	100	150	200	250	300	37	45	67	129	157	232	1.5
Conc. (%)	0.19	0.35	0.59	0.71	0.97	1.20	0.47	0.47	0.86	1.64	2.16	3.43	
Flow (L/h)	50	100	150	200	250	300	56	68	106	197	239	284	1.9
Conc. (%)	0.19	0.31	0.54	0.80	0.86	1.18	0.59	0.86	1.41	3.30	3.57	4.37	

Figure 7 shows that equation 5 holds well for the experimental conditions of this study, permitting to present jointly all the data. Equation 5 does not consider any secondary effect, as the dependence of bubbles properties on the pressure (water level). As the bubble concentrations in column 1 do depend on the water level, its effect may be well observed in figure 7. Considering all results together, the graph shows that the bubble concentration may be expressed as a linear function of the discharge, for the present experimental conditions. Equation 6 is the best linear adjustment, also represented in figure 7.

$$\bar{C} = 0.0146\ Q \qquad (6)$$

$\bar{C}$ is the homogenized concentration (factor 3.61 for column 1 and of 1.0 for column 2), without dimension, and Q is the flow in L/h.

The effect of the water level on equation 6, for the homogenized bubble concentrations of column 1, is a change in the coefficient of Q. The coefficient is changed to 0.0157, 0.0139 and 0.0135 for water levels of 1.0, 1.5 and 1.9 m, respectively.

Ratio A_1/A_2 of the plumes

The mean values of concentrations and velocities allow to evaluate the relative transversal spread of the plumes of bubbles along the columns. The relative spread is obtained from the ratio between the cross seccional areas of the plumes. As already mentioned, the mean velocities were evaluated only for the ascendant bubbles, excluding volumes of fluid with descendent velocities (close to the walls). The ratio between the areas is calculated as shown in equation 8. For the same gas discharge in both columns, equations 7 are valid, from which equation 8 is straightforward.

$$Q_{Bubbles}=V_1.A_1.C_1 \qquad (7a)$$

$$Q_{Bubbles} = V_2.A_2.C_2 \qquad (7b)$$

$$A_1/A_2=[(V_2.C_2)]/[(V_1.C_1)] \qquad (8)$$

$Q_{Bubbles}$ is the flow of gas furnished to the columns (L/h); V_i is the mean velocity of the bubbles (cm/s); C_i is the void ratio (concentration) of the bubbles (%) and A_i is the area of the cross sections of the plumes (m^2). Indexes i=1 and 2 correspond to columns 1 and 2, respectively. In this case, the areas are defined as those crossed by the mean concentration of bubbles moving with the mean velocity.

Although the cross sectional area of column 1 is 4.59 times larger than the cross sectional area of column 2, the plumes of bubbles do not follow equivalent transversal increase. This can be seen in figures 8 and 9, which show the evolution of the ratio A_1/A_2 along y and for different gas discharges, respectively, considering different levels of the liquid. A_1/A_2 varies in the range from about 1.5 to 2.3, and figure 8 shows that it attains the lower values for higher y.

Although the data of figure 9 are sparser, it is still possible to observe some influence of the liquid level on the relative spread of the plumes, since the results referring to the level of 1.0 m are located preferably below the other results.

Figure 8 uses the mean velocity defined for figure 5 and the ratio between concentrations given by equation 5. Figure 9 uses the mean velocities defined for Figure 6 and the concentrations presented in Figure 7. The differences observed between the plotted values in Figures 8 and 9 are consequence of the different definitions for the average operations (averaging over the discharges or over the cross sections).

In figure 8, linear interpolations were performed between two successive velocities of column 2, when the position of the measurement sections did not coincide with those of column 1. In figure 9, equations 2 and 6 furnished V_2 and C_2 for gas discharges with values equal of those of column 1, while the values of V_1 and C_1 were taken from tables 2 and 3.

The combined results of concentration and velocity may be so sumarized: In column 1, with the larger cross section, the transversal spread of bubbles is also larger (but not following the relative increasing of the area of the column). This leads to lower bubble mean concentrations; but keeping the bubbles in a central nucleus, which moves upwards with less resistance than the plume of column 2, attaining, thus, higher velocities.

In column 2, with the smaller cross section, the transversal spread is contained by the proximity of the walls, imposing a higher concentration of bubbles in the water and a consequent higher resistance to the relative movement between bubbles and water, attaining lower velocities than in column 1. The relative values of velocities, concentrations and transversal spread of the plumes of bubbles, obtained for the present experimental conditions, are summarized in table 4.

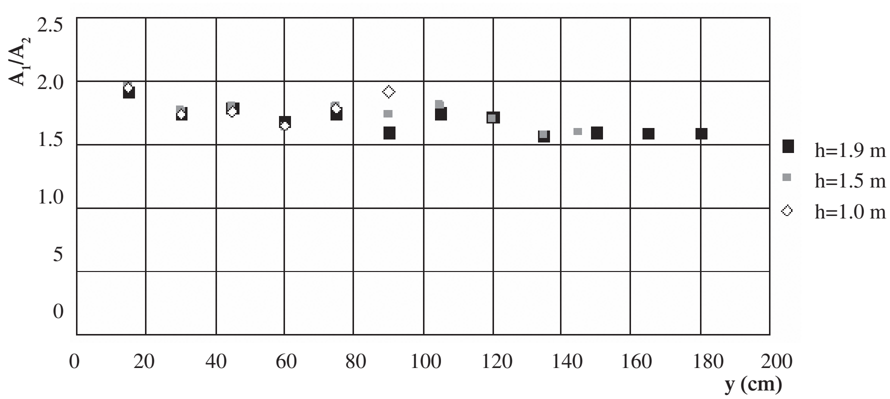

Figure 8. Evolution of the relative transversal spread A_1/A_2 along y, evidencing the decrease of the ratio for higher y.

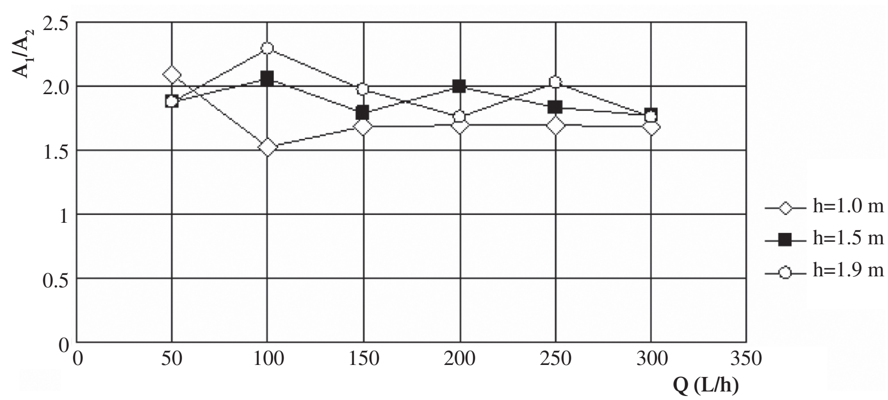

Figure 9. The influence of the level of the liquid upon A_1/A_2. The values obtained for h=1.0 m are preferably below the other data.

Table 4. Summary of the present results.

Experimental conditions	Dimensions: Column 1: Side = 0.19 m Column 2: Diameter = 0.10 m Water depths: 1.0; 1.5 and 1.9 m Bubble diameter at diffuser: 2 to 3 mm Gas discharge: 37 L/h ≤ Q ≤ 300 L/h
Velocities ratio	$2.00 \leq \frac{V_1}{V_2} \leq 2.12$
Concetrations ratio	$\frac{C_1}{C_2} \cong \frac{1}{3.61}$
Transversal spread ratio	$1.5 \leq \frac{A_1}{A_2} \leq 2.3$

CONCLUSIONS

Velocity and concentration values of gas bubbles (ozone+oxygen) were measured along the vertical axes of two ozonization columns with different cross sections, for different levels of liquid in their interior.

- Column 1 (with larger cross section) showed more evidently regions with absence of bubbles (close to the bottom and near to the walls), which may be related to the lower percentage of the cross sectional area occupied by the diffuser in the bottom of the column. In the present study, the diffusers installed in both columns were the same (dimension relatively smaller for the larger cross section), which influences this result.

- The usual behavior of increase of the mean velocity with the gas discharge was observed in both columns. The ratio between the mean velocities measured in column 1 and 2 (V_1/V_2) presented a value around 2.0 for all experimental conditions.

- The ratio between the mean concentrations measured in columns 1 and 2 was shown to be related to the dimensions along which the mean values were taken (side of column 1 and diameter of column 2), following equation 4. Without considering pressure effects (water level effects), the bubble concentrations in column 2 showed to be around 3.61 times higher than in column 1.

- The values of velocities and concentrations obtained for column 1 (larger cross section) showed to be dependent on the water level in the column (pressure). Higher mean velocities and lower mean concentrations were obtained for the higher water levels. No segregation caused by the water lever was observed in the results of column 2 (smaller cross section).

- The velocities presented different behaviors along the vertical axes of the columns (y). For column 2, the velocity decreased for higher values of y, regardless of the water level. For column 1, the plumes of bubbles accelerate close to the bottom of the column ($y < 50$ cm) in all experiments. For the water level of 1.0 m, the plumes decelerate for $y > 50$ cm. For the water level of 1.90 m, the plumes stabilized the velocity for $y > 50$ cm. For the water level of 1.50 m, oscillations on the velocity evolution along y were observed, characterizing an intermediate situation between the previous ones.

- The increase in the concentration of bubbles with the increase of the gas discharge can be approached adequately by a linear equation, for the experimental conditions of the present study.

- The values of mean concentrations and velocities allowed to evaluate the ratio A_1/A_2 between the areas crossed by the plumes of bubbles (the so called relative spread). It was observed that A_1/A_2 decreases for higher values of y. The values obtained for A_1/A_2, considering two different average operations for velocities and concentrations, varied between 1.5 and 2.3, showing that the increase of the available cross sectional area of the column (4.84 times in this study) is not followed by a similar increase of the cross section of the plume.

- The points of A_1/A_2 for the water level of 1.0 m, were preferentially located below the other data, showing that the influences of the water level on the results of column 1 also influences the relative spread of the plumes. In this case, the data for the water levels of 1.50 and 1.90 m are not segregated.

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