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The hydrodynamic parameter optimisation in design of drinking-water ozonation contactors

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ABSTRACT: The hydrodynamic characteristics in three pilot scale bubble-diffuser contactors have been investigated using the Residence Time Distribution method in order to achieve a better understanding of ozonation contactors and their optimum operational conditions. Two mathematical models for two types of contactor have been proposed and the experiments show a good correlation with the models. The optimisation of some important hydrodynamic parameters has been carried out.

INTRODUCTION

At the present time, ozone is widely used as an effective oxide agent for preoxidation and disinfection. Ozone contactors have been installed in almost every drinking water treatment plant in Europe and North America, and the corresponding standards for ozonation process have been formulated and perfected. In our home country Korea, despite the fact that the application of ozone to drinking water treatment is still in its initial stages, it is a fast developing field. Recently, the Korean Environmental Protection Administration commenced the installation of the pioneer ozonation systems at two drinking water treatment plants, Pu-Pyung and Mun-Mak. Under this set of circumstances, the study and characterisation of the new ozone contactor taken on a more important and interesting perspective.

The most commonly used contactor is the bubble-diffuser system, on which our studies were based. The design of a contactor of this type is fairly complicated, because of too many performance variables. For a better understanding of the performance of our contactors, the hydrodynamic nature of fluid in the contactors has been studied. The hydrodynamics of water flow within a contactor is determined by the contactor's geometry, operating modes and operating conditions, such as contact time, mixing state, mean superficial velocity of gas and liquid, and so on. Typically, the most common criterion for quantifying disinfection, and therefore the efficiency of a contactor, is the CT approach, proposed by USEPA 1989 [1]. The CT value is a numerical product of the residual disinfectant concentration C (mg/L) and the time interval T (min) during which the disinfectant is present. It appears that various ozone contactors with different hydraulic characteristics have different disinfection efficiencies, which can be characterised using a classical approach, based on the Tracer Test studies and the Residence Time Distribution (RTD) curves. From a RTD curve, the effective detention time T_{10} can be measured to evaluate the CT_{10} value. A higher CT_{10} value, required for the better disinfecting creditability, can be obtained by either increasing the amount of ozone or the detention time.

The effective detention time T_{10} depends on the hydraulic efficiency of both gas and liquid phases and should be determined by tracer studies. For a certain ozone residual concentration C, the higher CT_{10}, or the higher hydraulic efficiency, is achieved only by longer T_{10}. Hence, the optimisation of a contactor is equivalent to the optimisation of the contactor's geometry and operating conditions by a criterion of the maximum T_{10}.

Full scale tracer tests were performed at the two water treatment plants for the pioneer project. The operating conditions, such as liquid-flow rate, the gas/liquid ratio and different RTD were studied. In addition, using experimental data, we can evaluate the fluid-flow at a given condition and optimise the hydraulic characteristics of the future ozone contactors.

OZONE CONTACTORS AND TRACER TEST

Characteristics of the contactors

Two typical types of contractor were designed and installed for the hydraulic studies: the tank-in-series type and the column type.

At the Pu-Pyung plant, two contactors of tank-in-series were designed for preozonation and post-ozonation, respectively, where the capacity of water treatment is 200 m^3/day with a liquid-flow rate fixed to 140 L/min. The volume of preozonation/post-ozonation contactor was 1.3458/2.716 m^3 with the mean contact time of 9.82/19.63 min. Each of the contactors consisted of four chambers in series. Ozone gas could be

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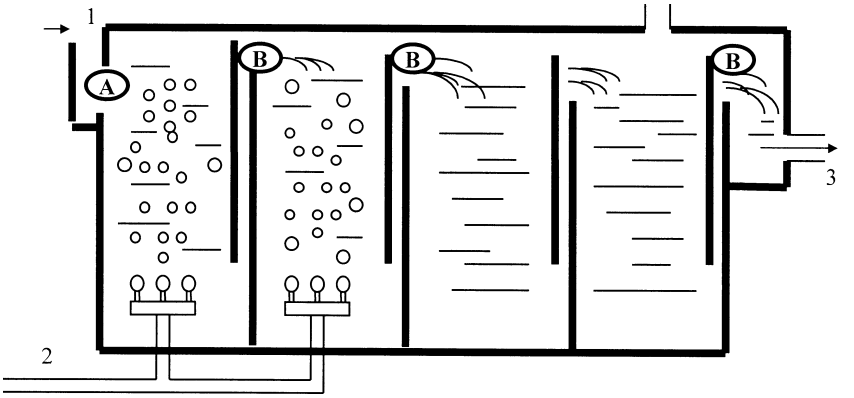

Fig. 1 Schematic diagram of an ozone contactor at the Pu-Pyung drinking water treatment plant. (1) Inlet of water, (2) Inlet of ozone gas, (3) Outlet of water (A) Injection point, (B) Detection point.

introduced into the first two chambers as a counter-current flow from the bottom of contactor, where the fine bubble distributors were mounted. The other two chambers were used for ozone dissipation. A schematic diagram of the contactors is shown in Fig. 1.

At Mun-Mak plant, a column contactor was designed, with a diameter of 0.15 m, a height of 3 m and a volume of 60 L. A ceramic porous distributor was mounted at the bottom of the column for introducing the gas with a varying rate from 0 to 10 L/min. Water was introduced from the top of column, reverse of the gas flow, as the counter-current mode. The water-flow rate ranged from 3.5 to 11.3 L/min and the mean contact time was measured within 6–19 min. The operating conditions and the details of the contactor scales are summarised in Table 1.

Tracer tests

Tracer tests were performed in each of these three contractors, using NaCl solution as the tracer agent, and the conductometer was used to detect tracer sample at different flow regime and gas/liquid ratio [1–5]. For the two tanks-in-series contactors, the tracer solution was injected in a pulse-input mode at the point A (for the column contactor, at the top of column) and it was detected at the point B as shown in Fig. 1 (at the bottom for

Table 1 The main characteristics of contactors

	No. of chamber	Height (m)	Useful volume (m^3)	Contact time (min)	
Pu-Pyung plant					
Preozonation					
	1	2	0.35	2.53	
	2	1.96	0.343	2.48	
	3	1.92	0.336	2.43	
	4	1.88	0.329	2.38	
	Total water volume (m^3)	1.3458	Total contact time (min)	9.82	
Post-ozonation					
	1	2	0.7	5.06	
	2	1.96	0.686	4.96	
	3	1.92	0.674	4.86	
	4	1.88	0.658	4.75	
	Total water volume (m^3)	2.716	Total mean contact time (min)	19.63	
Mun-Mak plant					
	Contact time (min)	Gas flow rate (L/min)	Liquid flow rate (L/min)	Diameter (m)	Height (m)
	6–19	0–10	3.5–11.3	0.15	3

the column contactor). From these tests, the Residence Time Distribution curves or $E(\theta)$ curves were obtained [6].

A computer program was used to simulate the RTD curves and, accordingly, the hydraulic conditions of the contactors were optimised.

Hydraulic modelling

Many investigators have studied the theoretical and experimental influence of various hydraulic parameters on the performance of a contactor, and several models have been proposed to describe the fluid-flow through a vessel [7–10]. Among these models, some have been widely applied and extended to the ozone contactors for predicting fluid-flow profiles [3,11–14]. Principally, the axial dispersion model and the tanks-in-series model are typical and are widely utilised to characterise the fluid flow in real contactors. The main parameter of the axial dispersion model is the axial dispersion coefficient E_s, and the principal parameter of the tanks-in-series model is the number of tanks, J, in the chain. The tank-in-series model assimilates to a real contactor with a volume of $V_L = V_j \cdot J$, with V_j the volume of one tank. The tanks-in-series model was chosen to simulate our experimental data because not only it is simple but also it allows introducing many new parameters, such as the dead zone, the short-circuit or the recycle existing within a real contactor.

Based on the tank-in-series, the following two mathematical models have been employed for data analysis and simulation:

(i) J mixing tanks in series with equal size:

$$E(\theta) = \frac{J^J}{(J-1)!} \cdot \theta^{(J-1)} \cdot e^{(-J\theta)} \tag{1}$$

(ii) J mixing tanks in series with dead zone:

$$E(\theta) = \frac{1}{m^J} \cdot \frac{J^J}{(J-1)!} \cdot \theta^{(J-1)} \cdot e^{\frac{-J \cdot \theta}{m}} \tag{2}$$

Here, $\iota = V_L/Q_L$ is the mean residence time, $\theta = t/\iota$ is the reduction time and m is the fraction of well mixing volume. The mean-root-square error between the experimental and the theoretical curves, ΔE, can be calculated as:

$$\cdot \quad E = \frac{\sqrt{\sum[E(\theta)_{\text{cal.}} - E(\theta)_{\text{exp.}}]^2}}{N-1} \tag{3}$$

with N = the number of experiments.

Tracer curve $E(\theta)$ obtained from the tests can be mathematically manipulated for calculating the J number, the fraction of dead zone, T_{10} and T_{90}, which are the time when 10% and 90% of the total tracer material leave the contactor, respectively. A discussion of the information obtained from the RTD curve is presented below.

RESULTS AND DISCUSSION

Comparison of experiment and simulation

The RTD curves have been obtained after tracer tests in three contactors installed in the Mun-Mak and Pu-Pyung drinking water treatment plants.

Table 2 summarises the tracer test conditions and the results from the RTD at the Mun-Mak plant. It appears that:

1. The experimental data show that the ratio of μ/ι is close unity, which implies that no dead zone exists within the contactor. Here, μ is the mean average of $E(\theta)$-curve.
2. The tracer test indicates that the tank-in-series is a good model and that the J number depends on the ratio of gas-flow and liquid-flow rate. When gas flow rate is equal to zero, **j** number already is above 15, it means the ozone contactor can be considered as a plug flow reactor independent on liquid flow rate, As soon as the air is introduced, included with small flow rates, the model of fluid flow was immediately changed, **j** decreases very rapidly below 9, indicating that the ozone contactor can be considered as a perfect mixing reactor in series. Figure 2 shows a comparison between E-curves of the experiment and the tank-in-series model, and Fig. 3 indicates the effect of the gas-flow on the E-curve. Generally, there is a good consistency between experimental and theoretical curves.

As yet, there is no widely accepted way to estimate the J number for a given bubble column up to now. Thus tracer tests should be performed on pilot or full scale plants in order to describe the liquid-flow by a mathematical model.

According to the tracer tests, the J mixing tanks-in-series with dead zone model fits the hydrodynamic behaviour of the

Table 2 Summary of tracer tests for the operation conditions and values of the number J (at Mun-Mak drinking water treatment plant)

Number	ι (min)	Q_L (L/min)	U_L (m/h)	G (L/min)	Ug (m/h)	J
1	19	3.5	12	0	0	15
2				2	6.8	9
3				6	20.4	7
4				10	34	5
1	9.2	6.3	21.4	0	0	20
2				2	6.8	7
3				6	20.4	5
4				10	34	6
1	6	11.3	38.4	0	0	30
2				2	6.8	9
3				6	20.4	9
4				10	34	7

Q_L and G: flow rate of liquid and gas, U_L are U_g: superficial velocity of liquid and gas.

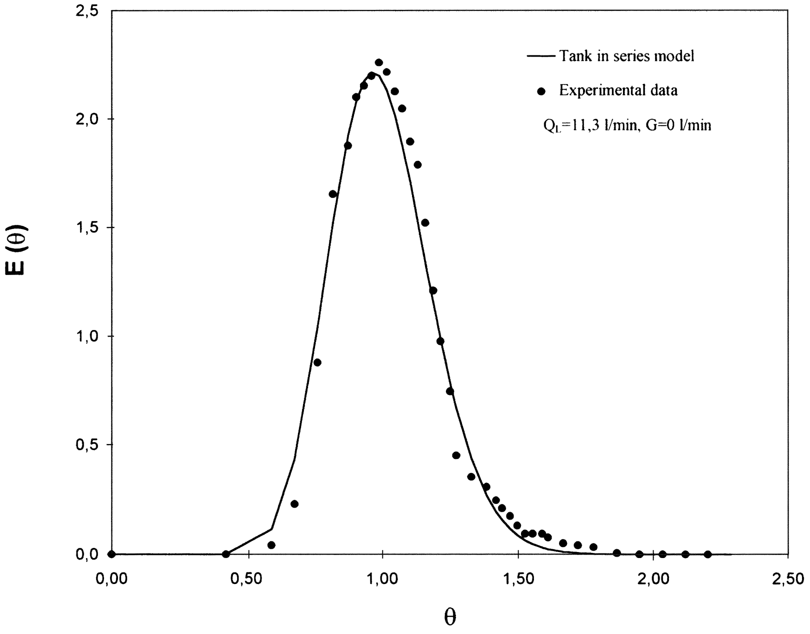

Fig. 2 Comparison of experimental *E*-curve and tank in series model.

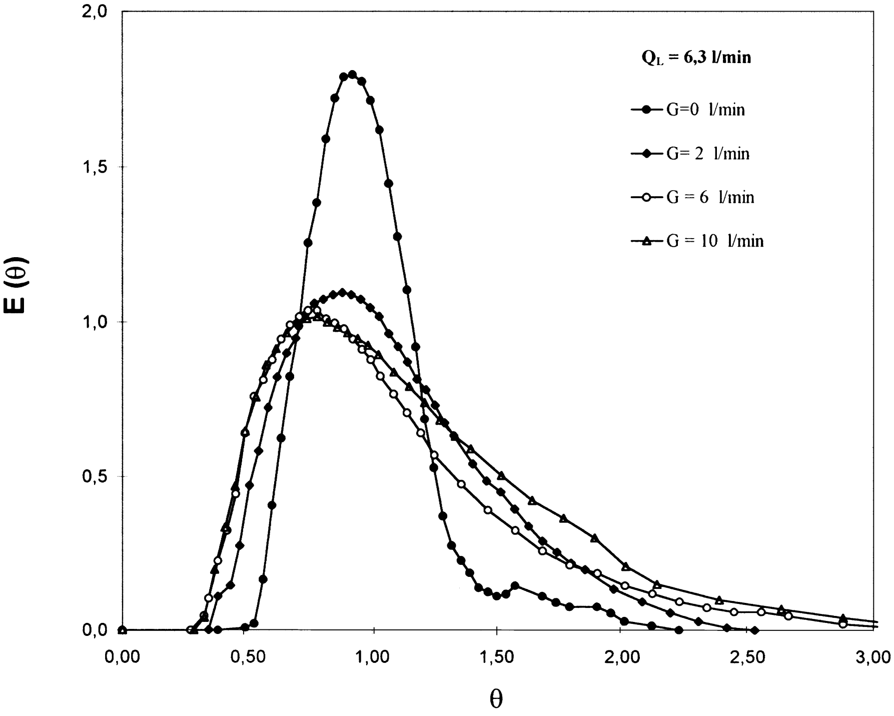

Fig. 3 Effect of gas flow rates on *E*-curves.

liquid-flow inside the contactors at the Pu-Pyung plant. Table 3 lists the main experimental results, with α the fraction of the dead zone. Figure 4 compares the experimental E-curve and the theoretical model; Fig. 5 shows the variation of the *E*-curve in each chamber at a given condition.

The best model to describe the two contactors, according to Table 3, is the model of J (J = 2–13) mixing tanks-in-series with a dead zone fraction of 3–15%. For the post-ozonation contactor, the gas-flow rate does not affect the J number, although in the first two chambers the dead zone fraction decreases with the increase of the gas-flow rate. It indicates that the gas plays a role of stirrer, improves the mixing and reduces the dead zone. Hence, the contactor has a better performance than without gas. For the preozonation contactor, the additional gas also improves the mixing and reduces a little bit dead zone, but the J number decreases with the increase of gas amount. A low gas-flow rate, perhaps, is better for the contactor performance. (Tables 2 and 3; Figs 2–5)

Table 3 The main experimental results for model predictions (for the Pu-Pyung plant)

	G	Chamber 1			Chamber 1 + 2			Chamber 1–4		
Contractors	(L/min)	*J*	α	Δ*E*	*J*	α	Δ*E*	*J*	α	Δ*E*
Post- ozonation										
	0	2	0.15	0.0309	5	0.10	0.0146	7	0.03	0.0106
	2	2	0.10	0.0159	4	0.07	0.0125	7	0.03	0.0189
	5	2	0.07	0.0168	4	0.05	0.0123	7	0.03	0.0204
Pre-ozonation										
	0	7	0.15	0.0140	10	0.15	0.0146	13	0.05	0.0178
	1	4	0.10	0.0212	6	0.10	0.0150	12	0.05	0.0161
	2	4	0.10	0.0189	6	0.10	0.0137	12	0.05	0.0086

α: fraction of dead zone.

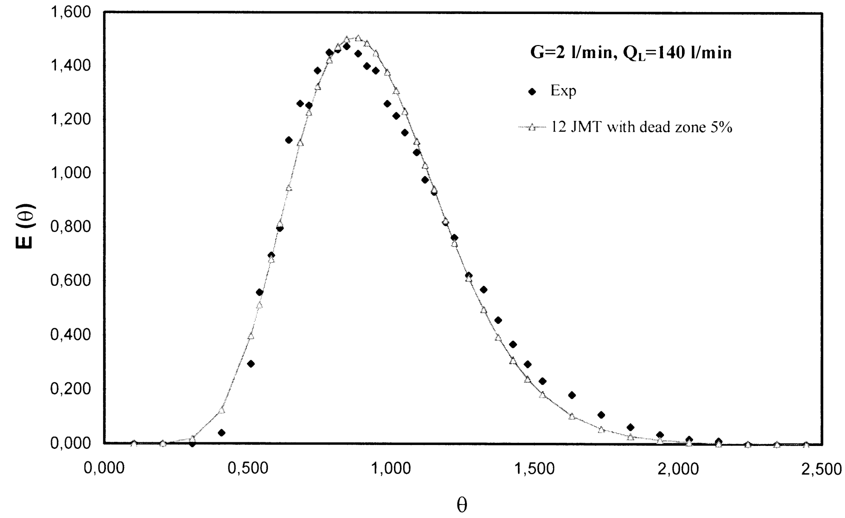

Fig. 4 Comparison of experimental *E*-curve and model prediction for preozonation contactor-chambers 1–4.

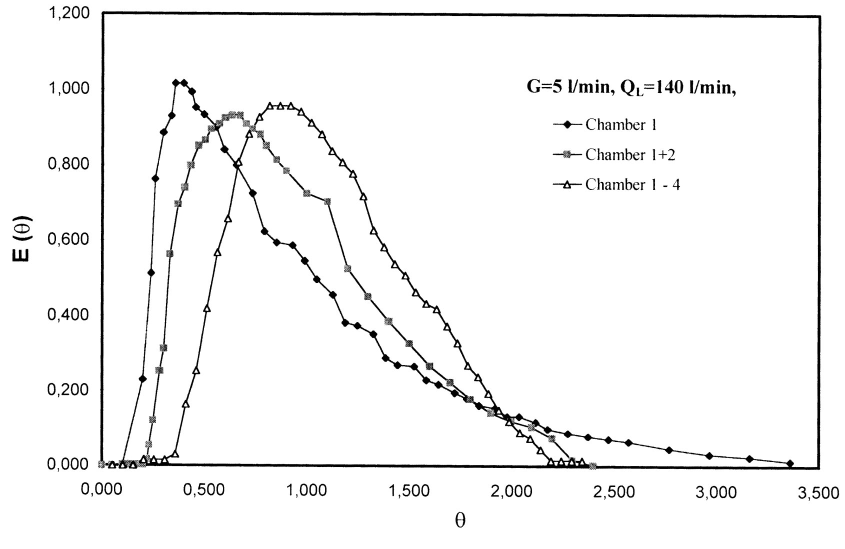

Fig. 5 Evolution of E-curves vs. mean contact time θ at the given condition for the post-ozonation contactor.

Table 4 Comparison of model prediction for T/ι at different conditions

Plants	Contactors	Q_L (L/min)	G (L/min)	τ (min)	T_{10}/ι	J
Mun-Mak						
	Column	3.5	0	19.1	0.46	15
		3.5	2	19.1	0.30	9
		3.5	6	19.1	0.26	7
		3.5	10	19.1	0.23	5
		6.3	0	9.2	0.58	20
		6.3	2	9.2	0.43	7
		6.3	6	9.2	0.40	5
		6.3	10	9.2	0.36	6
		11.3	0	6	0.62	30
		11.3	2	6	0.50	9
		11.3	6	6	0.38	9
		11.3	10	6	0.38	7
Pu-Pyung postozonation						
	Chamber 1	140	0	5.06	0.24	2
		140	2	5.06	0.24	2
		140	5	5.06	0.26	2
	Chambers 1 + 2	140	0	10.02	0.37	5
		140	2	10.02	0.35	4
		140	5	10.02	0.36	4
	Chambers 1–4	140	0	19.63	0.53	7
		140	2	19.63	0.58	7
		140	5	19.63	0.55	7
Pu-Pyung preozonation						
	Chamber 1	140	0	2.53	0.40	7
		140	1	2.53	0.32	4
		140	2	2.53	0.36	4
	Chambers 1 + 2	140	0	5.01	0.42	10
		140	1	5.01	0.40	6
		140	2	5.01	0.42	6
	Chambers 1–4	140	0	9.82	0.60	13
		140	1	9.82	>0.60	12
		140	2	9.82	>0.60	12

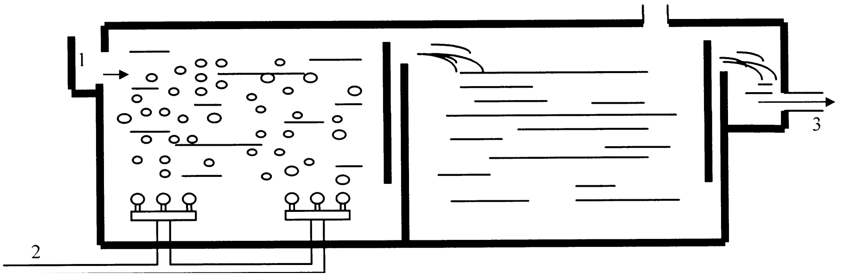

Fig. 6 Proposed modification for preozonation contactor at Pu-Pyung plant. (1) Inlet of water, (2) Inlet of ozone gas, (3) Outlet of water.

Effect of the liquid and the gas-flow on T/ι

The results obtained from the above E-curve analysis are easy to apply to the improvement of the hydraulic condition in a contactor. Table 4 shows a comparison of T_{10}/ι at different conditions.

For the column contactor at the Mun-Mak plant, T_{10}/ι shows a better performance of the contactor under a greater liquid-flow such as $Q_L = 11.3$ L/min and $\iota = 6$ min, because at a higher liquid-flow rate, the plug-flow character seems stronger. The increase of the liquid-flow improves the hydraulic behaviour of the contactor as T_{10}/ι increases from 35% (at $G = 0$ L/min) to 65% (at $G = 10$ L/min), comparing with the liquid flow rate between $Q_L = 3.5$ L/min and $Q_L = 11.3$ L/min. On the other hand, the low gas-flow rate also results in a bigger T_{10}/ι, such as G = 0–10 L/min, T_{10}/ι = 0.62–0.38 under Q_L = 11.3 L/min. (Table 4)

In case of a contactor with different chambers in series, the geometry configuration of the contactor, such as the ratio between its length, width and depth, plays a very important role. For the post-ozonation contactor, two chambers in series have an increased T_{10}/ι value from 24 to 36% and for four chambers in series, a total of 55% can be reached. It seemed that gas played the role of stirring, so with a higher flow rate of gas, the dead zone can be improved. However, as regards the preozonation contactor, the second chamber does not seem to be as efficient, the $T_{10}/\iota x$-value only increased a little, by about 5% on the base of first chamber. Besides, a bigger dead zone always exists when comparing with post-ozonation contactor, maybe this is a caused by its geometry configuration. Based on this experiment, it is proposed to modify the contactor geometry for the preozonation contactor, as shown in Fig. 6, or, using a contactor the same as the post-ozonation contactor.

Design of a better contactor

The three important parameters for designing an ozone bubble-diffuser contactor are the hydrodynamic behaviour of fluid, the kinetic aspect and the mass transfer efficiency between gas and liquid. An ozonation process depends not only on the mass transfer, but also on the kinetic reaction. On the other hand, the efficiency of the ozone mass transfer depends strongly on the hydraulics of the contactor. Using the information provided by the hydrodynamic behaviour of fluid and the kinetic reaction, the performance of an existing ozone contactor can be predicted, or a new type of reactor with optimal operating parameters can be designed. First of all, it is necessary to understand the hydrodynamic behaviour of both gas and liquid within a contactor, either it is a pilot plant or a full scale plant. Consequently, the best model to describe it has to be selected [15,16].

In a full scale plant, the contactor's geometric ratio varies greatly. Often, the height is between 3 and 6 m, the width and the length can be similar. The hydrodynamic behaviour of a contactor can be modelled by a closed perfect mixing tank in series with some modifications, such as dead zone, short-circulation, etc. If the J number is high, the hydraulics of contactor is close to a plug-flow. However, it is difficult to determine the J number and the fraction of dead ozone for a given bubble-diffuser contactor. Alternatively, the tracer test must be performed on pilot or full scale plants, in order to obtain a description of the real behaviour of liquid. Meanwhile, the tracer test must be followed by an ozonation test, to establish a model taking into account the hydrodynamics and kinetics.

In conclusion, the hydraulics of a contactor can have a strong effect on the quantity of the treated water. For any type of kinetic reaction, whether it is very slow, slow or fast, the hydraulics of a contactor play a predominant role. Consequently, the reactor with closed plug-flow hydraulics is always better than conventional contactors, if 90% of the pollutant is to be eliminated [17].

CONCLUSIONS

For a better understanding of the hydrodynamic behaviour of the fluid-flow within an ozone contactor and for optimising the operation conditions of the contactor, the tracer tests have been performed in three contactors at various gas and liquid flow rates. Two fluid-flow models have been investigated and a good consistency between the experimental datum and the theoretical prediction has been obtained. The flow rate of liquid seems to be very important: at a high liquid-flow rate, the fluid-flow mode can be modified towards the plug-flow mode with an increasing T_{10}/ι from 0.46 to 0.62 for a column contactor. For the tank-in-series contactor, the increase of the gas-flow rate enhances the mixing and reduces the fraction of dead zone.

With the help of the *CT* curve, the quantification of the disinfection and the performances of contactor can be estimated and improved to cater for the industrial demand. Future development will include establishing a new model for the simulation of gas phase flow and bubble size distribution, applying the Computational Fluid Dynamics Modelling (CFDM) for obtaining more precise information concerning the nature of the flow and the distribution of the disinfectant residual.

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