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A study on the hydraulics of waste stabilization pond

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Abstract—In this study, tracer tests and organic removal tests were conducted on three different ponds in the purpose of evaluating the influence of the flow velocity and dispersion on the hydraulic efficiency of the pond. The authors have compared the hydraulic flow patterns among ponds with different configurations. Experimental and theoretical analyses were performed. This study indicated that the flow characteristics of square ponds are different from that of baffled ponds; the flow velocity and dispersion are equally important factors which affect the pond hydraulics; the number of inserting baffles can be optimized; and the hydraulic efficiency of multistage ponds is superior to that of baffled ponds.

Keywords: stabilization pond; hydraulic characteristic; hydraulic efficiency; tracer test.

BACKGROUND

Waste stabilization ponds have been proved to be an economical and appropriate remedy for waste treatment. It has been employed for over 3000 years and has been widely employed in China in recent years.

To sum up the previous studies, it is found that the hydraulic characteristics obviously have effects on the dispersion processes as well as the average detention time of the gross flow in pond, therefore have ultimate effects on the biological transformation as well as the organic removal efficiency of the pond. Unfortunately, less attention has been given to the hydraulic design of the ponds than the reaction kinetics. This study attempts to evaluate the influence of flow velocity and dispersion on the pond efficiency; to compare the flow patterns in ponds with different configurations and different sizes.

Stabilization pond can be referred to a continuous-flow reactor. The flow pattern in a continuous-flow reactor can be predicated by the residence time distribution curve obtained from tracer tests. Plug flow reactor(PFR) and complete mix flow reactor (CMER) are the two extreme ideal flow patterns. Various models have been proposed to characterize the general flow in real reactors. One of those models is axial dispersion model. Others are the equal-sized CMFR in-series model and unequal-sized CMFR in-series and so on.

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The dispersion model for first-order reaction kinetics appears as:

$$\frac{c_e}{c_o} = \frac{4ae^{1/2d}}{(1+a^2)^2 e^{a/2d} - (1-a)^2 e^{a/2d}}, \tag{1}$$

where: $a = 1 + 4K\theta d$, dimensionless
$d = D/(UL)$, dimensionless dispersion factor
L= reactor length, m
θ=hydraulic detention time, h
K= reaction rate, L/h
c_e and c_o= initial and final substrate concentration, respectively, mg/L

With the limits $d = 0$ and $d = \infty$, Equation (1) can be simplified to two basic equations for the first order reaction of plug flow and complete mix flow reactors.

Equation (1) was recommended as the most appropriate approach to the design of waste stabilization pond (Thirumurthi, 1967; 1969; 1974; 1979; Murphy, 1974; Ferrara, 1981). The dimensionless dispersion factor, d, in this equation is as important a design parameter as the reaction rate K. The larger d is, the more similar to the complete mix flow the flow pattern is. Therefore, d can be used as a parameter for comparing and evaluating the flow patterns in different ponds.

It must be emphasized that the dimensionless dispersion factor in Equation (1) is quite different from its original meaning. It is a comprehensive parameter used to describe various hydraulic characteristics in pond.

EXPERIMENT DESCRIPTION

Three experimental ponds were employed in this study. One is the last two stages of a pilot scale concrete stabilization pond on the campus of Tsinghua University named outdoor pond. The others are laboratory scale apparatus which are made of PVC sheets, called contrast pond and multistage pond. The contrast ponds M and B were designed for simulating the CMFR and PFR, respectively. The dimensions of the three models are listed in Table 1 and illustrated with Fig.1, Fig.2 and Fig.3.

Table 1 Properties of experimental ponds

Type of pond	Dimensions	Comment
Outdoor pond	2:2.8×2.0×1.0m^3	Three baffles
	3:2.6×2.0×1.0m^3	
Contrast pond	M: 0.8×0.8×0.5m^3	
	B: 0.8×0.8×0.5m^3	Three baffles
Multistage pond	1, 2, 4: 1.4×0.194×0.5m^3	
	3:1.6×0.194×0.5m^3	

Tracer tests was performed on three ponds. In contrast ponds M and B, the tracer tests were conducted under identical control factors. The control factors and results are listed in

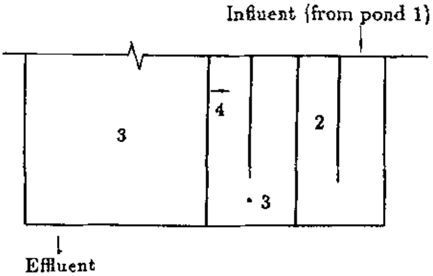

Fig.1 Plan of the outdoor pond

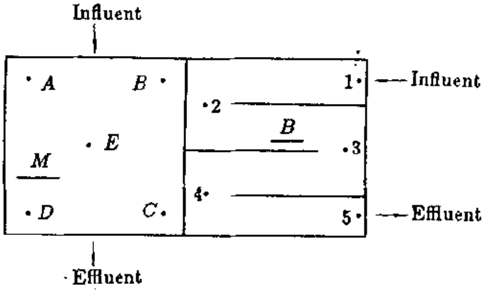

Fig.2 Plan of the contrast pond

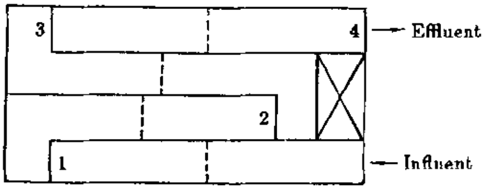

Fig.3 Plan of the multistage pond

Table 2. The conditions and results of outdoor ponds are listed in Table 3. The tracer test results of multistage pond are illustrated in Table 4.

Impulse tracer inputs were used to obtain residence time distributions of the systems. Bromophenol blue was used as tracer. This study was to deal with several parameters especially d and θ obtained from the residence time distributions and some other data measured from tests, and to regard them as criteria for analysing the flow patterns in ponds.

Table 2 Tracer test results of contrast ponds

Q ml/min	θ_0 h	Pond name	U, mm/s	d	$\bar{\theta}$, h	t_p, h	δ^2	$\frac{\bar{\theta}-\theta_0}{\theta_0}100\%$
72	69.0	B	0.0124	0.6594	49.57	10.0	0.6400	−28.1
		M	0.0030	0.5028	56.20	8.0	0.5692	−18.5
222	22.5	B	0.0381	0.2969	20.17	4.0	0.4236	−10.4
		M	0.0092	0.3860	18.81	4.0	0.4963	−16.5
1170	4.27	B	0.2010	/	/	0.33	/	/
		M	0.0487	0.4355	3.00	0.33	0.5299	−29.7
2610	1.91	B	0.448	0.6230	1.10	0.50	0.6257	−42.4
		M	0.109	0.4570	1.28	0.17	0.5431	−32.6

Table 3 Tracer test results of outdoor ponds

Q, ml/s	θ_0 h	Pond name	U, mm/s	d	$\bar{\theta}$, h	δ^2	$\frac{\bar{\theta}-\theta_0}{\theta_0}100\%$
3600	24.26	3	0.030	0.04574	18075	0.5434	−22.7
3600	19.44	2(3)	0.0857	0.4481	13.46	0.5377	−30.8
3600	25.92	2(4)	0.0857	0.3599	17.74	0.4768	−31.6

Table 4 Tracer test results of multistage ponds

Q, ml/s	θ_0 h	Pond name	U, mm/s	d	$\bar{\theta}$, h	δ^2	$\frac{\bar{\theta}-\theta_0}{\theta_0}100\%$
146	17.12	1	0.024	0.1231	15.28	0.2159	−10.7
146	34.25	2	0.024	0.0778	32.56	0.1434	−4.9
146	51.37	3	0.024	0.0438	53.92	0.0832	5.0
146	68.50	4	0.024	0.0512	71.20	0.0512	3.9

The parameter d and θ are calculated from the following equations with an electric computer.

Dimensionless dispersion factor,

$$d = D/(UL), \tag{2}$$

Mean hydraulic residence time,

$$\bar{\theta} = \frac{\int_0^2 (c\theta/c_0)d\theta}{\int_0^2 (c/c_0)d\theta}, \tag{3}$$

where c_0= tracer concentration if the input tracer was mixed uniformly with the entire reactor volume;

c= actual tracer concentration of sample taken at θ;

θ= time between sampling and addition.

Variance,

$$\sigma_t^2 = \Sigma\theta^2 c/\Sigma c - (\Sigma\theta c/\Sigma c)^2, \tag{4}$$

Variance in terms of dimensionless time,

$$\sigma^2 = \sigma_t^2/\bar{\theta}^2 = 2(D/(UL)) - 2(D/UL))^2(1 - e^{-\frac{UL}{D}}). \qquad (5)$$

Six sets of test were conducted, each with a different combination of hydraulic and organic loads. The influent was synthesized with industrial glucose, urea and phosphate and so on in proper ratio to simulate the composition of general domestic wastewater.

RESULTS AND DISCUSSION

Contrast ponds results

Comparison of the residence time distribution

Four tracer tests were performed in the contrast ponds M and B. Fig.4–7 show the residence time distribution curves obtained from each tests. It is obvious in Fig.4–7 that all the time distribution curve of M appear flat with lower peak concentrations. In contrast, the curve of B look steep with higher peak concentrations. When the theoretical detention time was controlled to be 69.0, 22.5, 4.27, 1.91h, the corresponding time which the peak concentration occurred was 8.0, 4.0, 0.33 and 0.17 for M while 10.0, 4.0, 0.33 and 0.50 for B, separately. It demonstrates the difference in flow patterns between M and B. M shows more complete mix flow characteristics than B. The flow pattern in B is more close to plug flow than that in M. The difference in flow patterns between pond M and B is not very distinct, however, it is because the design of these two ponds is not typical enough.

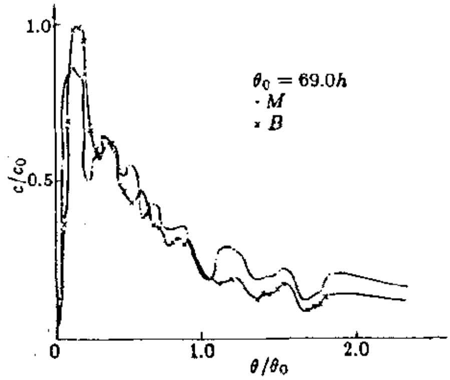

Fig.4 Detention time distribution curve for contrast pond

Analysis of the presence of dead space and short-circuiting

According to the principle of the "reactor theory", the major factors which cause the flow pattern in stabilization pond to deviate from plug flow include the axial backmixing which is created by turbulence; nonuniform distribution of cross-section velocity because of laminar flow patterns; dead spaces and short-circuiting in pond.

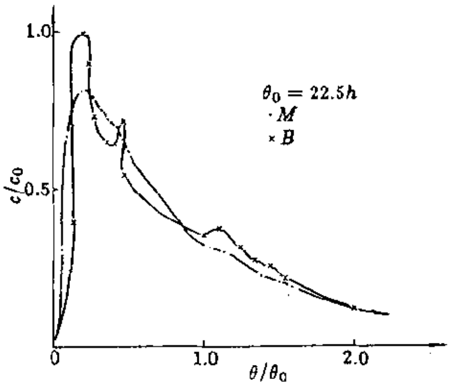

Fig.5 Detention time distribution curve for contrast pond

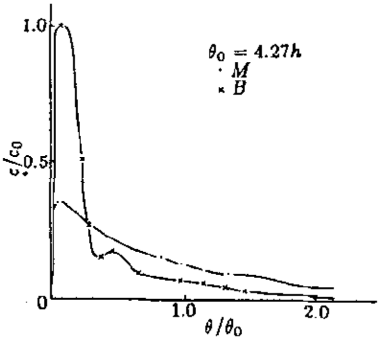

Fig.6 Detention time distribution curve for contrast pond

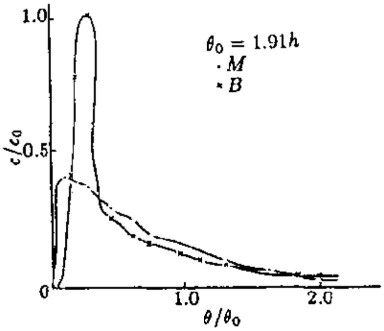

Fig.7 Detention time distribution curve for contrast pond

It is shown by the analysis results listed in Table 2 that there is no regular differences in the dispersion factor d and in the mean residence time θ between pond M and B, with different inflow rate (Q). But it should not be proved that there is not any difference of hydraulic characteristics between M and B.

For exploring the difference of hydraulic characteristics between the contrast ponds M and B, the magnitudes of COD in different positions (Fig.2) of the contrast ponds M and B were measured and are shown in Table 5 and Table 6. No matter how large the organic loads are, the COD values of M are smaller in pond corner than in the center of the pond. It shows that the dead spaces occur in the corner and the short-circuiting occurs in the path from the inlet directly to the outlet in pond M. In contrast, the COD values measured from several points (Fig.2) in pond B are almost equal. There are also dead spaces in pond B, however. First, according to the analysis of flow stream, the dead spaces occur round the turn of the baffles. Second, from distributions of cross-section velocity, it can be seen that the velocity near the baffles is much lower than in the axis of the pond. The laminas close to the surface of the baffles are very similar to a dead space. Kilani's experimental results, reported in 1984, also demonstrated that with the increasing number of the baffles inserted, the values of dead space parameters increased and the indexes of short-circuiting decreased. Therefore, the hydraulic characteristics of M and B are different, even though the parameters of d and $\bar{\theta}$ of them are similar to each other in this study. There are different causes which make the flow in pond M and B deviate from ideal flow pattern. With the method of inserting baffles, the short-circuiting can be reduced but the dead space may be increased meanwhile. Although the effects of baffles on the hydraulic characteristics of ponds have not been shown clearly in this study, it can not be concluded that there are not effects of inserting baffles at all.

Table 5 COD vaules of pond M

Influent load,	COD values, mg/L				
g COD/m^{3}d	A	B	E	C	D
44.56	26.75	/	32.92	/	24.69
66.06	85.42	/	124.99	/	87.50
79.13	57.65	/	84.12	/	55.76
46.83	28.99	25.36	34.42	25.36	25.36

Table 6 COD vaules of pond B

Influent load,	COD values, mg/L				
g COD/m^{3}d	1	2	3	4	5
44.56	28.39	32.92	21.81	28.81	43.21
66.06	79.17	79.17	99.99	83.33	83.33
79.13	57.65	61.44	57.65	60.49	57.65
46.93	28.99	25.36	34.42	25.36	25.36

Outdoor ponds results

The results of tracer tests for outdoor ponds are listed in Table 3. Pond 2 is similar to pond *B* and pond 3 is similar to pond *M* in configuration, but of large sizes. The size of pond 2 is nearly equal to pond 3. The dispersion factor *d* is 0.3599 for pond 2 and 0.4574 for pond 3 when the flow rate is 3600 ml/min. This implies that the hydraulic efficiency of pond 2 is higher than that of pond 3. It is shown that ponds which have baffles inserted serve better flow patterns and higher hydraulic efficiency as well(Fig.8).

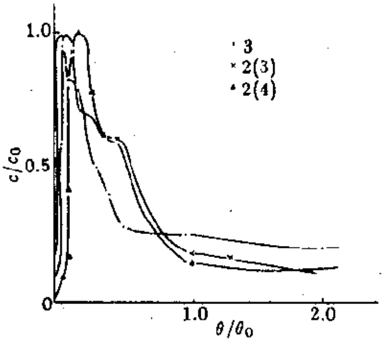

Fig.8 Detention time distribution curve for outdoor pond

The influence of velocity on flow patterns

Plug flow pattern is originally used to describe the flow characteristics in tubular vessels with high flow velocity. In reactors with high flow velocity, the distribution of velocity in the cross-section approaches uniform. Thus, the backmixing caused by the nonuniform substrate concentrations in cross-section diminishes. The dead spaces close to the surface of baffles diminish comparatively. The backmixing created by nonuniform distribution of cross-section velocity can not be ignored in the flow with lower velocity which always happens in small scale model experiment, however, and this is just the condition of stabilization pond study. For making some conclusions about the influence of slow velocity, following analysis has been carried out, and the deduction of the residence time distributions are made for one-dimensional lamina flow in open channel as an example of low velocity flow.

Although a real flow is in three dimensions, it is difficult to obtain the flow velocity functions, which is still a research subject in hydraulics. The hypothesis of one-dimensional lamina flow is taken in this study. The influence of lateral boards is ignored and the bottom effects are considered only. From this, a simple expressions of flow velocity can be written as Equation (6). The distribution of cross-section flow velocity in open channel is explained in Fig.9 and Fig.10.

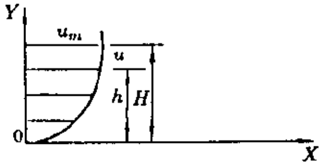

Fig.9 Distribution of the cross-section flow velocity

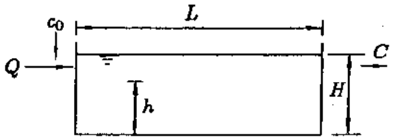

Fig.10 Diagram of the reactor

$$\begin{cases} u\dfrac{\partial u}{\partial x}+v\dfrac{\partial u}{\partial y}=-\dfrac{1}{\rho}\dfrac{\partial P}{\partial x}+\gamma\dfrac{\partial u}{\partial y} \\ \dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial y}=0 \end{cases} \tag{6}$$

where, u= flow velocity in x direction, m/s

v= flow velocity in y direction, m/s

x= coordinate in main flow direction

y= coordinate representing depth of water

γ= viscosity of water, m^2/s

ρ= density of water, kg/m^3

P= pressure intensity, N/m^2

For one-dimensional lamina flow,

$$V=0 \quad \frac{\partial v}{\partial y}=0 \longrightarrow \frac{\partial u}{\partial x}=0$$

with boundary conditions as,

$$\begin{cases} y=0, & u=0 \\ y=H, & \dfrac{\partial u}{\partial y}=0 \\ \int_0^H u dy=Q_w \end{cases} \tag{7}$$

where, Q_w= flow rate of a unit width, m^2/s.

The solution for Equation (6) is

$$u = -3Q_w h^2/(2H^3) + 3Q_w h/H^2 \tag{8}$$

where, h= depth of water, m

H= the maximum depth of water, m

Hence, mean velocity of the cross section is

$$\bar{u} = \int_0^H \frac{udh}{H} = \int_0^H \frac{1}{H}(-\frac{3Q_w h^2}{2H^3} + \frac{3Q_w h}{H^2})dh \tag{9}$$

while, maximum velocity of the cross section is

$$u_m = 3Q_w/(2H) \tag{10}$$

when $y = H$.

Supposing the step input of tracer, the input signal can be expressed as follows:

$$c = \begin{cases} 0 & t \leq 0 \\ C_0 & t > 0, \end{cases} \text{ when } 1 = 0 \tag{11}$$

Receiving signal is

$$c = \begin{cases} 0 & t \leq L/u_m \\ c_t & t > L/u_m \end{cases} \tag{12}$$

Effluent tracer concentration at any depth is

$$c_{t,h} = \begin{cases} 0 & t \leq L/u \\ C_0 & t > L/u \end{cases} \tag{13}$$

Total tracer concentration in effluent is

$$\begin{aligned} c_t &= \int_0^H (c_{t,h/H})dh \\ &= \int_0^{h_t} 0dh + \int_{ht}^H (c_0/H)dh, \end{aligned} \tag{14}$$

where, h= height at time t where the tracer first appear in effluent.

The velocity at height h is

$$U_h = L/t. \tag{15}$$

Form Equation (8),

$$U_h = -3Q_w h_t^2/H^3 + 3Q_w h_t/H^2. \tag{16}$$

From Equation (15) and (16)

$$L/t = -3Q_w h_t^2/H^3 + 3Q_w h_t/H^2. \tag{17}$$

Neglecting minus value, solution for (17) is

$$h_t = [3Q_w H + \sqrt{(3Q_w)^2 - 12Q_w.LH/t}]/(6Q_w). \tag{18}$$

Let $K_1 = (3Q_w)^2$, $K_2 = 12Q_w LH$,

thus,

$$h_t = (\sqrt{K_1} \cdot H + H\sqrt{K_1 - K_2/t})/(2\sqrt{K_1}). \tag{19}$$

From (14) and (19),

$$c_t = c_0(\sqrt{K_1} + \sqrt{K_1 - K_2/t})/(2\sqrt{K_1}) \tag{20}$$

while, $u_m/\bar{u} = 3/2$.

Theoretical detention time is

$$\theta_0 = L/\bar{u},$$

therefore, the concentration of tracer in effluent is

$$c_t = \begin{cases} 0 & t \leq L/u_m = 2\theta_0/3 \\ c_0(\sqrt{K_1} + \sqrt{K_1 - K_2/t})/(2\sqrt{K_1}), & t > L/u_m = 2\theta_0/3. \end{cases} \tag{21}$$

In accordance with (21) the distribution curve of one-dimensional flow in an open-channel is drawn in Fig.11.

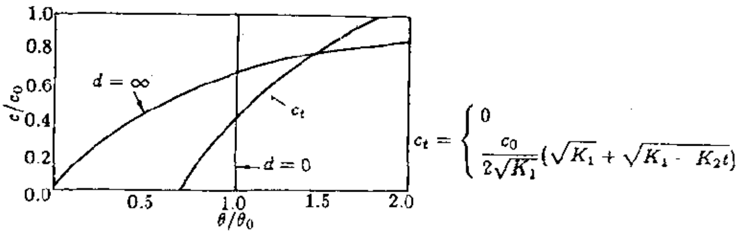

Fig.11 Distribution curve for one-dimensional flow in an open channel

Both Equation (21) and Fig.11 indicate the deviation from plug flow in the open-channel because of lower flow velocity.

Equation (2) shows that the dispersion factor d is inversely proportional to flow velocity U. Hence, theoretically speaking, with the increasing of flow velocity, the hydraulic efficiency rises.

If conducting a step input tracer test in a tubular reactor, the residence time distribution function will appear in the following form.

$$c_t = \begin{cases} 0 & t \leq \theta_0/2 \\ 1 - (t/\bar{\theta})/4 & t > \theta_0/2. \end{cases} \tag{22}$$

It can be seen from Equation (21) and (22) that the tracer appears earlier in the effluent in tubular reactor than in the open-channel. The tracer can be first detected in the effluent at half of the theory detention time in the tubular reactor, but it will need two-thirds of the theory detention time in the open-channel. It demonstrates that the flow pattern in the open-channel is more close to plug flow than the tubular reactor. Equation (22) takes all side affections in consideration while only the bottom effects is considered in Equation (21). Therefore, with the increasing of the interface area of water and boundary, the distribution of flow velocity becomes nonuniform. It means that the difference between the maximum velocity u_m and mean velocity $\bar{u}$ increase, this will cause the tracer arrives outlet earlier and the deviation of the flow from plug flow increases as a result.

Low flow velocity is an important hydraulic characteristics of waste stabilization pond. Inserting baffles can speed up the flow of water in ponds and enlarge the length to width ratio and improve the pond hydraulic efficiency as well. But it causes the increase of interface area of water and baffles, and creats more turns at the end of baffles, these will result to further nonuniform of flow velocity distribution and lower the pond hydraulic efficiency ultimately. Therefore, inserting baffles has both positive and negative effects on the pond hydraulic efficiency. In this regard, it can be concluded that the number of the baffles inserted can be optimized. There is an optimum for it.

The test results can be full proof of the aforesaid analysis. The results from contrast ponds (Table 2) show that as the flow velocity increases from 0.0124 mm/s to 0.0381 mm/s, *d* decrease from 0.6494 to 0.2969 and the corresponding relative error of detention time decreases from 28.1% to 10.4%. In contrast with this, as the flow velocity continuously increase to 0.448 mm/s, *d* increases to 0.6340. It demonstrates that when the flow velocity is less than a limit the hydraulic efficiency rises with the increasing of flow velocity. But if the flow velocity is over the limit the hydraulic efficiency declines with the increasing of flow velocity probably due to the effects of inlet jet and other factors discussed above. The characteristics of a real flow depend on various factors. There must be a different main factor in different conditions. In accordance with this study, the flow velocity is an important factor which affects the hydraulic characteristics in ponds. The hydraulic efficiency can be improved by properly increasing the flow velocity.

Because of the small size of experimental model ponds, the negative effects caused by the boundary and the jet influence appear very obviously. Based on the principle of geometric simulation, the flow velocity of a real pond with the size *K* times of a model is *K* time of that in the model, when the same detention time is maintained. Thus, the hydraulic efficiency in the real pond must be better than that in the model pond. Besides, increase of flow velocity with the inserting of baffles in a real pond will be larger than that in a model pond because the original flow velocity is large. Therefore, the advantages of inserting baffles in a real pond will be more obvious than the test results. The above predication is also proven by the experimental results. From Table 2 and Table 3, it can be found that d equals 0.4236 in pond B and 0.3599 in outdoor pond 2 while both ponds are in the similar hydraulic conditions. That is the hydraulic characteristics are better in outdoor pond than in the model pond. Also more advantages of inserting baffles are shown in outdoor pond.

Through the above theoretical and experimental analyses, it is suggested that inserting baffles with proper numbers is beneficial to improve the performance of stabilization ponds and advanced study on it is needed.

Multistage ponds results

After the tracer had been injected into the multistage pond, it went through the ponds stage by stage. There are no backmixing and dispersion among stages. The residence time distribution curves (Fig.12) obtained from the tracer test on multistage ponds show consistency with the theoretical curves of multistage ponds and possess the characteristics of plug flow pattern.

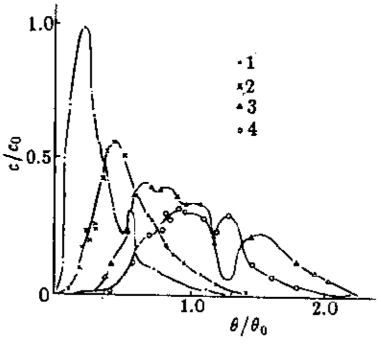

Fig.12 Detention time distribution curve for multistage pond

The cross-section flow velocity in multistage pond is 0.024 mm/s (Table 4). The dispersion factors of four stages are 0.1231, 0.0778, 0.0438 and 0.0512, respectively. The relative errors of their detention time are −10.7, −4.9, 5.0 and 3.0. It can be seen that with the increasing of the stages, the dispersion factor d as well as the relative errors of the detention time decrease. This indicates that the hydraulic efficiency in multistage pond can be arose by the increasing of the stage numbers. This is consistent with the theoretical conclusion.

Pond B has the dispersion factors of 0.6400 and 0.4236 when the flow velocity was controlled to be 0.0124 and 0.0381 mm/s, respectively. Comparing these with the value d of multistage pond, it is seen that the hydraulic characteristics of multistage ponds are superior to that of a baffled ponds. The influences of inlet jet, boundary especially dispersion are declined in multistage ponds. It can be concluded that dispersion is so important a factor as velocity for pond hydraulic characteristics.

CONCLUSIONS

To summarize the results of this study, the following conclusions can be drawn:

1. The flow characteristics of square pond is different from that of baffled pond. There are dead spaces in the corner and short circuiting along the path from inlet to outlet in a square pond. In contrast, the dead spaces in baffled pond appear at the turns of the baffles and near the surface of baffles. Baffled pond has less short circuiting than square pond. The flow pattern in baffled pond is more approaching plug flow than that in square pond.

2. The flow velocity is an important factor which affects the pond hydraulic characteristics. Its influences are very complicated. The hydraulic efficiency can be improved by speeding the flow velocity within a limit.

3. The hydraulic efficiency can be improved by inserting baffles in general. The number of inserting baffles can be optimized. There is a optimum number. In some conditions, for example, in a small scale pond, the hydraulic efficiency may not be improved by inserting baffles.

4. The hydraulic efficiency of multistage pond is superior to that of baffled pond. Dispersion is so important a factor as the flow velocity which affects the pond hydraulic efficiency.

The main method used in this experiment is tracer test. The pond hydraulic efficiency is evaluated by analyzing the parameters obtained from the tracer test information. It is found that pond hydraulic characteristics can not be described in detail only by a tracer test. The tracer test demonstrates a macroscopic influence only. Some basic equations and methods of hydraulics should be introduced to the future study of pond hydraulic characteristics. Finding solutions for these equations is very difficult, which requires a lots of computer work. But this work has profound significance for the study of flow patterns.

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