Prediction of the pollutant concentration field in oxidation ditches

A.I. Stamou
Department of Civil Engineering, National Technical University of Athens, Iroon Polytechniou 5, 15773 Zografou-Athens, Greece

ABSTRACT

The paper reports on the application of a water quality model for the prediction of the concentration field of a soluble organic substrate in a typical oxidation ditch. Calculations show that the concentration field is not affected by the use of guiding walls. Concentration profiles in the inlet region are skewed due to the effect of inlet, being strongly affected by the initial dilution. Downstream of the inlet region concentration profiles tend to be uniform. Decreasing the average flow velocity or increasing the bacterial population results to lower concentration values.

1. INTRODUCTION

Mathematical models are powerful tools for the design of wastewater units and the assessment of their performance under a variety of conditions. Unfortunately, due to the relatively high degree of sophistication involved with mathematical models, these have not yet been incorporated into the routine design and operation practice. Semi-empirical methods are still in use instead. These involve correlations between inlet and outlet variables (e.g. inlet and outlet BOD, COD and SS concentrations), which ignore the real biology and the hydrodynamics of the system by adopting unrealistic and crude assumptions, such as this of either complete mixed or plug flow.
Recognising the benefits from the routine use of mathematical modeling the IAWPRC in 1983 formed a task group to promote the development and facilitate the application of practical models to the design and operation of biological wastewater systems. In the summary of the report prepared by the task group, a water quality model for single sludge systems performing carbon oxidation, nitrification and denitrification was presented [1]. Although the IAWPRC model described with a relatively high degree of sophistication the biology of single sludge systems, it did not cope with the hydrodynamics of such systems.

The author has recently presented a mathematical model, which incorporates such hydrodynamic aspects [2]. The model solves the continuity and momentum equations to provide with a realistic flow field and turbulent diffusivity using the $k$-$\epsilon$ turbulence model [3]. After the flow field is determined, the equations of the water quality model are solved for the calculation of the concentration fields of the water quality variables. In the present work the simplest version of a water quality model is presented, which involves only one water quality variable, namely the concentration of organic substrate (pollutant). The organic substrate is oxidised by the aerobic growth of heterotrophic bacteria, whose population is kept constant. Dissolved oxygen is considered to be in adequate concentrations, thus not being a limiting factor. The model is applied to calculate the organic substrate concentration field in the typical oxidation ditch shown in Fig.1a, consisting of an inlet, an outlet and an aeration device (rotor).

2. MATHEMATICAL MODEL

The mathematical model consists of the flow field model and the water quality model. The flow field model (see [2] for more details) consists of the continuity and momentum equations governing the two dimensional, steady, incompressible flow in the horizontal plane of an oxidation ditch as approximated in Fig.1b. The water quality model consists of a mass balance equation for the organic substrate concentration ($S$, gCOD/m$^3$). This is derived by applying the mass conservation principle to a small but finite control element within the flow and can be written as follows

$$\frac{\partial S}{\partial x} + \frac{\partial S}{\partial y} = \frac{\partial}{\partial x} \left( \frac{v_t}{\sigma_s} \frac{\partial S}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{v_t}{\sigma_s} \frac{\partial S}{\partial y} \right) + S_S$$

(1)
where \( x \) and \( y \) are the Cartesian co-ordinates as defined in Fig. 1, \( U \) and \( V \) are the velocities in the \( x \) and \( y \) directions respectively and \( \nu_t \) is the eddy viscosity. The distribution of \( \nu_t \) is being determined with the \( k-\varepsilon \) turbulence model \([3]\). \( \nu_t/\sigma_s \) is the turbulent mass diffusivity for \( S \), which is assumed to be proportional to the eddy viscosity provided by the flow field model. The proportionality factor is the turbulent Schmidt number \( \sigma_s \), for which a value of 0.7 has been chosen in this work. The source term \( S_S \) is actually a reaction rate, which is based on the Activated Sludge Model No1 of the IAWPRC \([1]\) and has the following form:

\[
S_S = - \frac{1 - y_H}{y_H} \frac{\mu_H}{k_{SH} + x_{bH}} S + b_H S
\]

where \( x_{bH} \) (g cells COD/m\(^3\)), \( y_H \) (g cells COD formed/g COD oxidised), \( k_{SH} \) (g COD/m\(^3\)), \( \mu_H \) (day\(^{-1}\)) and \( b_H \) (day\(^{-1}\)) are respectively the concentration, maximum specific growth rate, yield, half saturation coefficient and decay coefficient for heterotrophic biomass. The following typical values are used in the present work: \( y_H = 0.666 \), \( \mu_H = 3.4 \), \( b_H = 0.24 \) and \( k_{SH} = 20.0 \) \([1]\).

The basis of the formulation of the present computer program is the TEACH-BIO code \([2]\), which is a latest version of the TEACH-SET code \([4]\).

---

Fig. 1 Geometry of the oxidation ditch

---

(a) Real geometry

(b) Approximated geometry
3. APPLICATION OF THE MODEL

The mathematical model is applied for the prediction of the organic substrate concentration field in the typical real oxidation ditch of Fig.1a having the following dimensions: length L=106.5m, depth H=3.0m and width W=10.0m (volume V=6132m^3). The ditch consists of an inlet pipe of diameter d_i=0.45m carrying a flow Q_i=0.180m^3/s, an effluent weir of length 1_e=6.0m, an inner wall, two guiding walls and a rotor located at x=20.5m. The rotor, which has a gross power of 45KW, splashes the mixed liquor to provide intensive aeration and satisfy completely the oxygen requirements, while keeping the mixed liquid particles in suspension by maintaining a minimum velocity throughout the tank.

3.1 Simplifications-boundary conditions and the grid

The following approximations and boundary conditions are applied:

(i) Inlet and outlet. The inlet pipe was approximated by a slot opening carrying a flow rate equal to Q_i and an inlet organic load equal to Q_iS_i, where S_i=400ppm is the inlet concentration of organic substrate. The effluent weir is approximated by a series of slot openings occupying a length equal to 1_e. Outlet boundary points are assumed to have no influence inside the ditch, i.e. \( \partial S/\partial x = 0 \).

(ii) Walls: The curved parts of the ditch are approximated by horizontal and vertical lines (see Fig.1a and 1b). At all solid walls, no flux of S is assumed i.e. \( \partial S/\partial x = 0 \) and \( \partial S/\partial y = 0 \) for walls perpendicular to the x and y-direction respectively.

(iii) Rotor: The rotor is assumed to provide to the mixed liquor the required quantities of oxygen to maintain the aerobic conditions throughout the tank.

The 40X22 numerical grid shown in Fig.2 is used in the computations. This grid was selected, so as to ensure grid independence.

![Fig.2 The numerical grid](image-url)
3.2 Effect of the guiding walls

Calculated velocity vectors (normalised by the average velocity in the ditch, \( U_m = 0.20 \text{m/s} \)) without and with guiding walls are shown in Figs.3a and 3b respectively (see [2], for more details). The main effects of the guiding walls are (i) the significant increase of flow velocities in the region close to the inner walls downstream of the bends and (ii) the tremendous reduction of the volumes of the recirculation regions, which are almost eliminated. These effects result to a relatively uniform flow in the largest portion of the ditch, without any regions of significant extent with low velocities or recirculating flow.

Initial dilution of the incoming liquid within the tank is a very important factor [5], which has to be taken into account in the design of oxidation ditches. In the present case dilution is calculated equal to \( D = Q_i / Q_T = 1/35 \), where \( Q_T \) is the total flow rate in the ditch \( Q_T = U_m WH + Q_i = 0.20 \times 3.0 \times 10.0 + Q_i = 6.075 + 0.180 = 6.255 \text{ m}^3/\text{s} \). The hydraulic detention time is equal to \( \theta = 6132 / (6.255 \times 60) = 16.3 \text{min.} \), i.e. the tank contents circulate 3.7 times every hour.

(a) without guiding walls

(b) with guiding walls

Fig.3 Predicted flow fields
Fig. 4a and Fig. 4b show computed concentration profiles for the flow fields of Fig. 3a and 3b respectively. In the inlet region, which is extended up to four widths (x=20-60m), concentration profiles are skewed. Average cross-sectional concentrations near the inlet (x=20.5m) are approximately 14.0ppm for both flow fields. Maximum concentrations observed near the wall are lower without guiding walls (S=31ppm), due to the higher initial dilution of the incoming liquid caused by the higher local velocities (see Figs. 3a and 3b). Downstream of the inlet region (x>60m) concentration profiles tend to be uniform and independent of the use of guiding walls, with somehow higher values lying near the inner wall. Effluent concentration is equal to $S_e=3$ ppm, corresponding to an efficiency of 99.2%.

3.3 Effect of the average flow velocity
Flow field calculations with guiding walls have been performed for higher rotor gross power figures, i.e. for 90 and 135 KW. Normalised (by $U_m$) flow fields are identical to that of Fig. 3b [2]. Average velocity is increased to 0.29m/s and 0.36m/s respectively, initial dilution is increased to 1/49 and 1/61 and thus average concentration at x=20.5m is decreased to 11.5ppm (see Fig. 3c) and 10.7ppm respectively. However, efficiency is decreased to 99.0 and 98.8% respectively due to the reduction of the detention time from 16.3min to 11.5min and 9.3min respectively. This behaviour shows that increasing the average flow velocity, results to lower efficiency.

3.4 Effect of the bacterial population
Fig. 4d presents the computed concentration field for a double bacterial population ($X_{DH}=2000$ ppm). As expected, dilution of the incoming liquid is the same as in Fig. 4b and results to similar concentration profiles in the inlet region. However, downstream of the inlet reaction rates $S_S$ are increased resulting to lower concentration values and higher efficiency (99.8%).

3.5 Computation requirements
The calculations have been performed on a PC-386, with an Intel 80387 mathematical-processor running at 33 MHz. The computational speed was 130 iterations/minute. Since 250 iterations were necessary for convergence, a computation time of approximately 2 minutes was required.
(a) Without guiding walls ($U_m=0.20\text{m/s}, X_{bH}=1000\text{ppm}$)

(b) With guiding walls ($U_m=0.20\text{m/s}, X_{bH}=1000\text{ppm}$)

(c) With guiding walls ($U_m=0.29\text{m/s}, X_{bH}=1000\text{ppm}$)

(d) With guiding walls ($U_m=0.20\text{m/s}, X_{bH}=2000\text{ppm}$)

Fig. 4 Predicted concentration fields
4. CONCLUSIONS

In the present work a simple water quality model is presented for the prediction of the concentration field of soluble organic substrate in a typical oxidation ditch. Calculations show that the concentration field is not affected by the use of guiding walls. Concentration profiles in the inlet region are skewed due to the effect of inlet, being strongly affected by the initial dilution. Downstream of the inlet region concentration profiles tend to be uniform. Decreasing the average flow velocity or increasing the bacterial population results to lower concentration values.

Research is under way to include into the model all 13 water quality parameters described in the IAWPRC model, aiming at an accurate prediction of all important characteristics, which control the biology of the system (e.g. length of anaerobic, anoxic and aerobic zones, sludge production). It is hoped that such a model, which accounts with a high degree of sophistication for both flow and biology, will be of significant practical importance for the routine design and operation practice of oxidation ditches.

5. ACKNOWLEDGEMENTS

The financial support of the Technical Chamber of Greece to the author for participation in the present Conference is acknowledged herewith.

6. REFERENCES