Calculation of peak oxygen demand in the design of full-scale nutrient removal activated sludge plants

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Abstract

The sizing of the aeration system is a very important factor in the design of activated sludge plants. An aeration system with insufficient capacity to meet the peak oxygen demand results in unaerated pockets in the aerobic reactor thus affecting the performance of the plant. In this paper, two methods of calculating oxygen demand are compared, namely, empirical design rules and computer based dynamic simulation models. A computer based nutrient removal simulation model is applied to simulate the dynamic response of four full-scale biological nutrient removal plants. The simulation results are used to assess whether one of the design rules developed for fully aerobic plants, under cyclic loading conditions, can be reasonably applied to nutrient removal plants. The results indicate that the relative damping of the maximum oxygen utilisation rate response wave of 0.5 given in the design rule, has to be reduced by an average of 44% at 20°C in order for the peak oxygen utilisation rate values calculated using the design rule to correlate with those calculated with the computer based model. A value of 0.28 for the relative damping of the maximum oxygen utilisation rate response wave at 20°C is therefore suggested for use in the design rule when applied to nutrient removal activated sludge plants. More diurnal load variation data, however, needs to be collected at other full-scale nutrient removal plants in order to provide sufficient information to calibrate the design rule. This would provide designers with a simple and quick method that can be used for the calculation of peak oxygen demand in nutrient removal activated sludge plants in a similar manner to fully aerobic activated sludge plants. In conclusion, the paper highlights the importance of accurate assessment of daily cyclic flow and load conditions to a treatment plant at design stage as well as the use of dynamic simulation models in determining the peak oxygen demand and its distribution within the aerobic reactor.

Introduction

The flow and load to a sewage treatment plant vary considerably throughout the day and the peak flow and pollutant load can be several times higher than the average. For such cyclic flow and load conditions, the mass of sludge produced and plant volume remain unchanged from the steady state values, but the oxygen demand fluctuates in response to the varying load. The peak daily oxygen demand, which can be considerably higher than the average daily oxygen demand, needs to be accurately determined at design stage in order to provide sufficient aeration capacity during peak oxygen demand periods. The variation in oxygen demand differs between plants depending on the cyclic variation of the organic and nitrogen load. This variation depends on factors such as the layout of the sewerage system, the type of and intensity of industries, etc. It is therefore not possible to predict the oxygen demand pattern for a specific plant except in general terms unless data on diurnal load variations are available.

There are a number of methods which designers can use to determine the peak oxygen demand depending on the data available to them. In the absence of diurnal load variation data, designers can apply safety factors to the average oxygen demand to estimate the peak oxygen demand. These safety factors can either be based on the designer's own experience of the performance of full-scale plants or they are recommended in design procedures. For example, MetCalf and Eddy (1991) recommend that the aeration equipment be designed with a safety factor of at least two times the average biological oxygen demand load. The Ten States Standards (1978) of the USA require that the aeration system be capable of providing oxygen to meet the diurnal peak oxygen demand or 200% of the design average, whichever is the greater.

Where diurnal load variation data are available, designers usually use design rules recommended in design procedures or computer-based dynamic simulation models to calculate the peak oxygen demand. One such rule is that developed by Ekama and Marais (1978) for estimating the peak oxygen demand in fully aerobic activated sludge systems. Ekama and Marais (1978) analysed at 14°C and 20°C the dynamic behaviour of single and four reactor in-series process configurations under sinusoidal and square wave influent loads.

The analysis was carried out for settled sewage with a total Kjeldahl nitrogen/chemical oxygen demand (TKN/COD) ratio of 0.10. They found that the relative damping of the maximum and minimum oxygen utilisation rate (OUR) response wave (i.e. the ratio of the amplitude of the OUR response wave to the amplitude of the total oxygen demand (TOD) load wave) is approximately 0.5. Based on this finding, Ekama and Marais formulated a design rule that can be applied by designers to determine the peak OUR from the amplitude of the TOD load wave and the average OUR thus;

The TOD load is calculated using the diurnal flow, COD and TKN data. The TOD load is calculated as TOD load = COD load + 4.57 x TKN load. The peak TOD load is the maximum value and the average TOD load is the area under the TOD load vs. time of day curve. The average OUR is calculated from the steady state activated sludge theory and nitrification (WRC, 1984). The peak OUR is then determined from this information as follows:

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TABLE 1
Relative damping of the maximum OUR response wave calculated from dynamic simulation. Results for the four wastewater treatment plants

Wastewater treatment plant	TKN/COD ratio	Amplitude of max. TOD load a_{Lm}	T = 14 °C		T = 20 °C		T = 22 °C	
			Amplitude of max. OUR a_{om}	Relative damping of max.OUR	Amplitude of max. OUR a_{om}	Relative damping of max.OUR	Amplitude of max. OUR a_{om}	Relative damping of max.OUR
Kraaifontein	0.09	1.08	0.16	0.14	0.25	0.23	0.39	0.36
Zandvleit	0.09	0.78	0.18	0.23	0.29	0.36	0.32	0.41
Wildevoëlvlei	0.10	1.06	0.06	0.06	0.24	0.23	0.25	0.24
Athlone	0.08	0.94	0.12	0.13	0.26	0.28	0.26	0.28

$$\text{Amplitude of maximum TOD load wave } (a_{Lm}) = (\text{Peak TOD load} \div \text{Average TOD load}) - 1 \quad (1)$$

$$\text{Amplitude of maximum OUR response wave } (a_{om}) = (\text{Peak OUR} \div \text{Average OUR}) - 1 \quad (2)$$

$$\text{Relative damping of maximum OUR response wave } (a_{om} \div a_{Lm}) = 0.5 \quad (3)$$

$$\therefore \text{Peak OUR} = (1 + 0.5a_{Lm}) \times \text{Average OUR} \quad (4)$$

The analysis of Ekama and Marais found the design rule (Eq. (4)) to be applicable at sludge ages longer than about twice the minimum sludge age for nitrification. Application of the design rule to sludge ages significantly shorter than double the minimum sludge age for nitrification was found to lead to an over-estimation of the maximum and under estimation of the minimum total oxygen demand.

There are a number of computer based simulation models available on the market which designers can also use to calculate the peak oxygen demand from diurnal load variation data e.g. UCTOLD and UCTPHO (Dold et al., 1991), ASIM 3.0 (EAWAG, 1994), SIMBA 3.3+ (*ifak*, 1998) and BIOWIN 32 (EnviroSim Associates Ltd., 1998). Although the use of computer-based dynamic simulation models remains the most accurate method for calculating peak oxygen demand, the models are usually complicated thus restricting their use to specialist and experienced designers. Also, some of the models are costly. Design rules therefore offer designers a quick simple method of estimating the peak oxygen demand.

The design rule of Ekama and Marais (1978) and the UCTOLD and UCTPHO computer-based simulation models were calibrated with data from South African conditions. The design rule of Ekama and Marais was, however, developed only for aerobic systems and its validity for nutrient removal, i.e. nitrification denitrification biological excess phosphorus removal (ND-BEPR) has not been tested. In this paper, the UCTPHO computer-based model developed at the University of Cape Town for ND-BEPR systems is applied to simulate the dynamic response of four full scale ND-BEPR activated sludge plants using diurnal load variation data collected at these plants. The simulation results are then used to assess whether the relative damping of the OUR response wave of 0.5 found by Ekama and Marais (1978) for aerobic systems can be reasonably applied to ND-BEPR systems.

The UCTPHO model has been calibrated over many years and in a multitude of circumstances covering laboratory, pilot-scale and full-scale tests.

Another important aspect in the design of the aeration system is the efficient and cost-effective distribution of the oxygen demand within the aerobic reactor. The oxygen demand is not evenly distributed within the aerobic reactor because the upstream section of the reactor receives the full COD and TKN load, which decreases as the wastewater flows through the reactor. The oxygen demand should therefore be distributed within the aerobic reactor to reflect the tapering of the load. Correct distribution of the oxygen demand is important to avoid under-aerating and over-aerating sections of the aerobic reactor. The UCTPHO model is thus also applied to simulate tapered aeration in the aerobic reactor with a four compartment in series configuration for the four plants.

The paper therefore aims to calibrate the simple design rule by Ekama and Marais (1978) so that it can be applied to ND-BEPR systems. The OUR distribution pattern for a four compartment in-series aerobic reactor configuration is also recommended.

Collection of diurnal load variation data

The four wastewater treatment plants that were investigated are Kraaifontein, Athlone, Zandvliet and Wildevoëlvlei, which are all located in Cape Town, South Africa. Kraaifontein and Athlone treat settled sewage while Zandvliet and Wildevoëlvlei treat raw sewage. Except for Kraaifontein, the other three works are currently operated as ND-BEPR systems. It is proposed that the Kraaifontein Works be upgraded to an ND-BEPR system thus the data collected was applied to the proposed upgrading. Sewage samples were collected every 2 h for 24 h and the influent sewage flow was also recorded at the time of sampling. The 24 h sampling was carried out for a minimum period of 7 d at each of the works. Samples were analysed for COD, TKN, free and saline ammonia, ortho-phosphorus and total phosphorus.

Data analyis and UCTPHO simulations

The computer-based UCTPHO model was used to simulate the dynamic behavior of the four plants under a diurnal load pattern reflected by the data collected at the plants. The simulations were carried out at 15 d sludge age, and at 14°C, 20°C and a maximum temperature of 22°C. The 15 d sludge age is the design operating sludge age for the plants. Although the plants were designed for minimum and maximum temperatures of 17°C and 22°C respectively, the simulations were carried out at 14°C and 20°C to enable comparison of the simulation results with the design rule developed by Ekama and Marais (1978). The default kinetic and stoichiometric parameters in the model were accepted for the simulations.

The amplitude of the maximum OUR response wave (a_{om}) was determined from the dynamic simulation results and the amplitude of the maximum TOD load wave (a_{Lm}) was calculated from the

TABLE 2a
Distribution of the OUR in a four compartment in series aerobic reactor configuration

Wastewater treatment plant	% peak OUR distribution in a 4 compartment in series aerobic reactor configuration											
	T = 14 °C				T = 20 °C				T = 22 °C			
	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
Kraaifontein	25	25	25	25	30	28	25	17	32	29	24	15
Zandvliet	26	26	25	23	32	29	23	15	36	31	20	13
Wildevoëlvlei	25	25	25	24	31	29	24	17	33	30	22	15
Athlone	27	25	25	24	30	28	24	17	34	30	22	14
Average	26	25	25	24	31	28	24	17	34	30	22	14

TABLE 2b
Peak OUR/Average OUR (Peak factor) in each compartment in a four compartment in series aerobic reactor configuration

Wastewater treatment plant	Peak OUR/Average OUR in a 4 compartment in series aerobic reactor configuration											
	T = 14°C				T = 20°C				T = 22°C			
	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
Kraaifontein	1.13	1.12	1.14	1.23	1.07	1.09	1.17	1.68	1.10	1.23	1.53	1.71
Zandvliet	1.07	1.09	1.16	1.41	1.09	1.31	1.62	1.39	1.13	1.44	1.53	1.18
Wildevoëlvlei	1.04	1.05	1.06	1.09	1.06	1.16	1.42	1.33	1.08	1.26	1.43	1.22
Athlone	1.06	1.06	1.12	1.38	1.09	1.27	1.62	1.55	1.12	1.38	1.62	1.43

diurnal load variation data. The relative damping of the maximum OUR response wave (i.e. a_{Om}/a_{Lm}) was then calculated from these values as outlined in Section 1, Eqs. (1) to (4). Table 1 gives the average values of the relative damping of the maximum OUR response wave for each plant. Also shown in Table 1 is the TKN/COD ratio of the influent sewage to the plants.

The UCTPHO model was also used to simulate the dynamic response of the plants with the aerobic reactor considered to be divided into four compartments in series, to provide tapered aeration. The distribution of the OUR in each compartment for the four plants is shown in Table 2a. Table 2b shows the ratio of the Peak OUR to the Average OUR (Peak Factor) for each compartment for the four plants.

Discussion

TOD load wave

The amplitude of the TOD load wave calculated from the diurnal load variation data differs between the four plants and does not display any trend (see Table 1). This is expected since the cyclic variation in COD and TKN load depends on factors like layout of the sewerage systems, intensity and type of industries as well as residential areas, etc. which are specific to each plant catchment.

Relative damping of maximum OUR response wave

To enable comparison of the relative damping of the maximum OUR response wave of 0.5 for fully aerobic systems in the design rule of Ekama and Marais (1978) and the values calculated with the results of the UCTPHO simulations for ND-BEPR systems, the conditions under which the UCTPHO simulations were carried out should be similar to the ones under which the design rule was developed. The analysis for the design rule was carried out for settled sewage with a TKN/COD ratio of 0.10. Also, the sludge age at which the value of the relative damping was 0.5 was found to be longer than about twice the minimum sludge age for nitrification. Application of the design rule at sludge ages significantly shorter than double the minimum sludge age for nitrification resulted in over-estimation of the maximum OUR and under-estimation of the minimum OUR. This is because at sludge ages closer to the minimum required for nitrification, a cyclic loading pattern has an adverse effect on nitrification (Ekama and Marais, 1978).

The TKN/COD ratio of the influent sewage to the four plants does not differ significantly even though Athlone and Kraaifontein treat settled sewage and Wildevoëlvlei and Zandvliet treat raw sewage (see Table 1). The values for the plants are between 0.08 and 0.10 and therefore do not differ significantly from the value of 0.10 for settled sewage used in the development of the design rule by Ekama and Marais (1978). The minimum sludge ages for nitrification at a maximum specific growth rate for nitrifiers of 0.45 (and taking cognizance of the unaerated mass fractions of the plants) at 14°C, 20°C and 22°C are 11, 5 and 4 d respectively. The simulations at 14 °C were thus carried out at 1.4 times the minimum sludge age for nitrification and hence the conditions are not similar to the ones under which the design rule was developed. The simulations at 20°C and 22°C, however, fall within the conditions under which the design rule was developed.

Relative damping at 14°C

The relative damping of the maximum OUR response wave at 14°C varies significantly between the plants though the values for Kraaifontein and Athlone are almost the same. Zandvliet has the highest value of 0.23 and Wildevoëlvlei has the lowest value of 0.06. The values are between 50% and 80% lower than the 0.5 calculated for aerobic systems by Ekama and Marais (1978). As outlined above, at 14°C, the operating sludge age of 15 d is only 1.4 times the required minimum sludge age for nitrification, which from the analysis of Ekama and Marais (1978) was found to reduce the maximum OUR response damping. It is therefore not possible to conclude by how much the relative damping of the maximum OUR response wave for the ND-BEPR plants at 14°C differs from the 0.5 for aerobic systems since the sludge age at which the UCTPHO simulations were performed does not fall within the criteria that were applied in the analysis by Ekama and Marais (1978).

Relative damping at 20 °C

The relative damping of the maximum OUR response wave at 20°C does not differ significantly between Kraaifontein, Athlone and Wildevoëlvlei. Zandvliet has, however, a much higher value of 0.36. The high value of the relative damping for Zandvliet is because Zandvliet has a much lower amplitude of the maximum TOD load wave compared to the other three plants. The average value for the four plants is 0.28, which is 44% lower than the 0.5 for aerobic systems. Simulations at 20°C meet the same criteria as the ones used in the development of the design rule by Ekama and Marais (1978). It therefore appears that use of the value of 0.5 for the relative damping of the maximum OUR response wave when applying the design rule to the four ND-BEPR plants at 20°C, would overestimate the peak OUR by an average of 18%.

Relative damping at 22°C

At 22°C Kraaifontein and Zandvliet have much higher values of the relative damping of the maximum OUR response wave than Wildevoëlvlei and Athlone, with Zandvliet being the highest. Zandvliet has the highest value due to its lower amplitude of the maximum TOD load wave compared to the other plants. The average relative damping of the maximum OUR response wave for the four plants is 0.32, which is 36% lower than the 0.5 for aerobic systems. Simulations at 22°C for the four ND-BEPR plants also meet the same criteria as the ones used in the development of the design rule by Ekama and Marais (1978). It therefore appears that use of 0.5 as the relative damping of the OUR response wave when applying the design rule to the four ND-BEPR plants at 22°C would overestimate the peak OUR by an average of 13%.

Distribution of the OUR in the aerobic reactor

Peak OUR distribution

The peak OUR distribution in the four compartments of the aerobic zone do not differ significantly between the four plants (see Table 2a). The average values at 14 °C are 26%, 25%, 25% and 24% in the first, second, third and fourth compartments respectively. At 20 °C, 31% of the OUR is in the first compartment, 28% in the second and 24% and 17% in the third and fourth compartments respectively. The distribution at 22°C is 34% in the first compartment, 30% in the second and 22% and 14% in the third and fourth compartments respectively. At 14°C the OUR is almost evenly distributed between the four compartments while at 20°C and 22°C the first two compartments take up almost 60% of the total OUR. The percentages in the first two compartments are slightly higher at 22°C than at 20°C.

The OUR is expected to be highest in the compartments where the COD and FSA concentrations are highest. The first compartment receives almost the full COD (except for the readily biodegradable COD which is utilised in the unaerated zones for nutrient removal) and TKN load. The COD and TKN not oxidised in the first compartment during the time period that the sewage is within the compartment flow through and get oxidised in subsequent compartments. The amount of COD and TKN oxidised in the compartments depends on the temperature and sludge age of the plant. At higher temperatures and sludge ages significantly longer than the minimum sludge age for nitrification, most of the COD and TKN are oxidised in the first three compartments with the oxygen demand in the last compartment being mostly from endogenous respiration. The OUR distribution pattern at 20°C and 22°C reflects this trend because the 15 d sludge age at which the simulations were performed is more than double the minimum sludge age for nitrification. However, at 14°C, the temperature and sludge age are not sufficiently long to enable substantial COD removal and nitrification in the first two compartments hence significant oxidation takes place in the last two compartments as well, resulting in an almost even distribution of oxygen demand throughout the aerobic reactor.

Peak factors

The peak factors (i.e. the ratio of peak OUR to average OUR) were also calculated and are shown in Table 2b. At 14°C, the peak factor increases from the first to the fourth compartment for all plants. However at 20°C and 22°C, the third compartment has the highest peak factor for all the plants except for Kraaifontein which has a similar trend as at 14°C. The peak factor is lowest in the first compartment because the organisms in the first compartment are conditioned to work at their maximum rate since the load is highest in this compartment. They are therefore conditioned to work at almost the average load. Any load that is not oxidised in the first compartment is oxidised in subsequent compartments and at average load (and sufficiently high temperatures and sludge age), the oxygen demand in the last two compartments is mostly due to endogenous respiration. At peak load, the organisms in the first compartment oxidise only their maximum load which is almost equal to the average load hence the peak factor is not very much higher than one. The extra peak load flows to downstream compartments where the organisms exert a much higher oxygen demand compared to their average oxygen demand at average load. Consequently the peak factors are higher in downstream compartments. Whether the highest peak factor is in the third or fourth compartment depends on the cyclic load pattern, the operating temperature and sludge age. Application of the peak factors to individual compartments gives the peak OUR distribution given in Table 2a and discussed above.

Conclusions

The UCTPHO computer-based simulation model has been applied to simulate the dynamic response of four full-scale nutrient removal activated sludge plants using diurnal load variation data collected from these plants. The OUR results from the model simulations have been used to assess whether the value of the relative damping of the maximum OUR response wave for fully aerobic systems, used in the design rule by Ekama and Marais (1978) can be applied to nutrient removal systems. The results have shown that the relative damping of the maximum OUR response wave of 0.5 for aerobic systems has to be reduced for ND-BEPR systems in order for the design rule to predict the peak OUR predicted by the UCTPHO model. For the four plants investigated in this paper, the relative damping has to be reduced to 0.28 (44% reduction) at 20°C and 0.32 (36% reduction) at 22°C. The reduction at 14°C could not be accurately assessed because the criteria used in the UCTPHO simulations did not fall within the conditions in which the design rule for aerobic systems was valid. The lower relative damping of the maximum OUR response wave for ND-BEPR systems compared to fully aerobic systems is because in ND-BEPR systems, the readily biodegradable COD is utilised in the unaerated reactors for nutrient removal and does not exert an oxygen demand in the aerobic reactor like in fully aerobic systems.

To provide tapered aeration in a four in-series reactor configuration, the UCTPHO simulations have shown that at a minimum temperature of 14°C and 15 d sludge age, the oxygen demand is almost evenly distributed within the aerobic reactor. At a maximum temperature of 22°C, 34% of the oxygen demand is in the first compartment, 30% in the second and 22% and 14% in the third and fourth compartments respectively.

Although the analysis for the four ND-BEPR plants in this paper has shown that the relative damping of the maximum OUR response wave needs to be reduced from 0.5 when applying the design rule developed by Ekama and Marais (1978), to calculate the peak oxygen demand for ND-BEPR systems, more data are required to calibrate the design rule so that it can be confidently applied in design. Further analysis of the data for the four plants is also required at longer sludge ages at 14°C, and the relative damping of the minimum OUR response wave needs to be determined.

Analysis of the diurnal load pattern data has confirmed that the cyclic variation in oxygen demand is different between the plants thus emphasising the importance of accurately assessing the diurnal load pattern for a plant wherever possible at design stage. Comparison of the OUR values calculated with the UCTPHO simulation model and the design rule has shown that unless properly calibrated, application of design rules can lead to errors in calculating the peak oxygen demand. In the case of the four plants investigated, the use of the design rule would lead to over-sizing the aeration capacity. It is therefore recommended that computer-based models be used in the calculation of peak oxygen demand and its distribution within the reactor when accurate diurnal load variation data are available.

Acknowledgements

The authors wish to thank the staff of the Scientific Services Department of the City of Cape Town for carrying out the sewage sampling and analysis at the plants and the City of Cape Town: CMC administration for their permission to publish this paper.

References

ASIM (1994) *Activated Sludge Simulation Program Version 3.0*. Distributed by EAWAG, 8600 Dübendorf, Switzerland.

BIOWIN 32 (1998) Distributed by EnviroSim Associates Ltd.

DOLD PL, WENTZEL MC, BILLING AE, EKAMA GA and MARAIS GvR (1991) *Activated Sludge Simulation Programs*. Published by the Water Research Commission, PO Box 824, Pretoria 001, South Africa.

EKAMA GA and MARAIS GvR (1978) The Dynamic Behavior of the Activated Sludge Process. Research Report W27, Univ. of Cape Town, Dept. of Civil Eng. Rondebosch 7701, Cape Town, South Africa.

METCALF & EDDY Inc. (1991) *Wastewater Engineering: Treatment, Disposal and Reuse.* Published by McGraw-Hill, Inc.

SIMBA 3.3+(1998) Distributed by *ifak*.

TEN STATES STANDARDS (1978) Great Lakes Upper Mississippi River Board of State Sanitary Engineers: *Recommended Standards for Sewage Works.*

WRC (1984) *Theory, Design and Operation of Nutrient Removal Activated Sludge Processes*. Published by the Water Research Commission, PO Box 824, Pretoria 001, South Africa.