EVALUATION AND VERIFICATION OF THERMAL STRATIFICATION MODELS FOR WASTE STABILIZATION PONDS

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ABSTRACT
Stratification is a usual phenomenon occurring in waste stabilization ponds which needs to be incorporated in prediction models. The occurrence of stratification in waste stabilization pond (WSP) alters the flow pattern of the pond. Hence, its study is important for complete and accurate modeling of the WSP. In this study, two mathematical models developed for prediction of the condition of thermal stratification in WSPs under different hydraulic conditions and flow regimes were compared. Also the pond depth is divided into 'N' parallel layers, each of which is considered to possess a different dispersion number and bacterial die-off coefficient. The models are verified with data collected from the full scale waste stabilization pond at Nsukka. Results of field experiments show that the same result under the plug flow and completely mixed flow condition and hence gives reliable comparison. Also the coefficient of correlation ranged from 0.992007322 to 0.939220284 for plug flow model and 0.995915575 to 0.9388977 for completely mixed flow model, showing that the two models produced almost the same results.

Keywords: stratification, waste stabilization pond, plug flow, completely mixed flow model, coli form bacteria and verification.

INTRODUCTION

Waste stabilization ponds (WSPs) are designed to provide a controlled environment for wastewater treatment. Their size is established from theoretical and empirical relationships that give, directly or indirectly and estimate of the hydraulic retention time needed to achieve a given effluent quality. However, many factors may cause disturbances in the flow pattern of a pond with consequences to the actual treatment time. One of the factors is the thermal stratification, a natural phenomenon that is usually neglected in pond design.

When a waste stabilization pond is thermally stratified, a density gradient exists and its internal vertical mixing is compromised (Chu and Soong, 1997). In this situation the pond behaves as a series of superimposed liquid layers with different densities, each layer being stables at a certain depth, with the densest layer close to the bottom.

The thermal stratification can be stable-persisting for months or intermittent, appearing for a few hours in the day (Dor et al. 1993; Pedahzur et al., 1993; Torres et al., 1997). In waste stabilization ponds the main cause for the occurrence of thermal stratification is the heating of the surface layers due to incident solar radiation; and destratification has been attributed mainly to the cooling of these surface layers. Torres et al. (1997) studied the influence of the thermal stratification on the mixing efficiency of a pond located in the campus of the University of Murcia, South-east Spain. They found that during the winter, after the temperatures, the active Zone extended from the top to the bottom of the pond. During the summer, as a stable thermo cline was formed, the active zone extended from the surface to the depth where the effluent outlet was located.

Considering the importance of the thermal stratification phenomenon, we consider in this paper the verification of two existing mathematical models developed for the study of thermal stratification in waste stabilization ponds.

Although many models exist for the processes of bacteria reduction in waste stabilization ponds, none has yet been found to describe them accurately (Bowles, et al; 1979); matcalf and Eddy 1979; Finney and Middle brook 1980; polprasert, et al; 1983; Marecos do Monte and Mara, 1987). The processes involve complex interaction among several environmental and hydrodynamic variables, some of which are usually ignored to keep the mathematical modellia tractable.

The hydraulic flow regimes usually assumed by past workers to occur in WSP are completely mixed – flow, plug – flow and dispersed – flow models. Both the completely mixed and plug – flow models describe ideal flow conditions. The former assumes that the dispersion number (8) is infinite while the letter assumes (5) to be zero. Both are conditions not normally met in practice. The dispersed-flow models, on the other hand, describe real flow conditions and is believed to be the best of the three (Thirumurthi, 1974; Uhlmnn, et al. 1983; polprasert and Bhattarai, 1985; Macrocode Monta and Maca; 1987; Agunmamba, 1990 and (1992 Juanico, 1990). However, one of the problems with the dispersed-flow model, as well as with the others, is the assumption that bacteria population does not vary with depth. This is unrealistic for some obvious reasons.

Firstly, the pond's contents are rarely homogeneous; rather they tend to stratify (Pearson, et al, 1987a). This phenomenon creates different environmental conditions and non-uniform distribution of nutrients which affect the rate of bacteria die-off. Besides, the presence of dead zones and short-circuiting result in different hydrodynamic conditions within the pond (polprasert and Bhattarai 1985). These factors in turn affect the dispersion number (5) which is an important parameter in the dispersed-flow mode (Agunwamba, 1992).

Secondly, the amount of light penetration decreases with increasing depth (Sarikaya and Saatci, 1987; Sarikaya et al; Mayo, 1989). As the rate of bacterial die-off increases with the amount of light (Sarikaya and Saatic, 1987; Sarikaya, et al; 1987; Mayo, 1989), bacteria population obviously increases with depth. This, however, may depend on some other factors like PH, dissolved oxygen, nutrients, density currents and so on.

Thirdly, flow conditions may favour sedimentation so that bacteria can settle with the pond particles (Chamberlin and Mitchell; 1978). This contributes furthers to heterogeneous conditions.

Finally, it is known experimentally that bacteria population varies with pond depth (Hosetti and patil 1987; Sarikaya and Saateh, 1987; Sarikaya, et al, 1987). Bacteria population depends strongly on dispersion and the die-off coefficient (Polprasert, et al;

1983; Polprasert and those from Bhattarai; 1985) and these parameters also vary with the pond depth (Sarikaya, et al; 1987).

Hence, this research is aimed at comparing two mathematical models based on different hydraulic flow regimes and derived from different mathematical approach.

MODELS DESCRIPTION

Two mathematical models for predicting coliform bacteria at various depths in WSP due to thermal stratification have been developed by researchers as (Agunwamba, 1997 and Ukpong, 2005) based on different hydraulic flow regimes and mathematical approach.

The model proposed by Agunwamba, (1997) assume plug flow condition under series of flow layers and the solution under this condition was obtained by lap lace transform. This model is presented in Equation and (1b) a3;

$$N_y = \lambda_y \,\text{esp}(-\alpha_y \theta)x$$

$$\left\{ \frac{2\lambda_y \delta_y [\exp(-\alpha_y \theta) - \exp(-\alpha_{y+1}\theta)]}{\theta(\alpha_{y+1} - \alpha_y)} \right\}$$

where

$$\alpha_i = K_i + \frac{\delta_{i-1}}{\theta} + \frac{\delta_i}{\theta}, \; i = 2, \cdots, n-1$$

$$= K_i + \frac{\delta_i}{\theta}, \; i = n$$

Also the model proposed by Ukpong, (2005) assume completely mixed flow condition under different flow layers and the solution was obtained by algebraic method. The model is as presented in Equation (2a) and (2b) respectively as:

$$N_i = \frac{N_{oi}(1+K_{i+1}\theta_{i+1}+\delta_i)(1+K_{i-1}\theta_{i-1}+\delta_{i-2})(1+K_{i-1}\theta_{i-1}+\delta_{i-2})+\delta_{i-1}N_{oi-1}(1+K_{i+1}\theta_{i+1}+\delta_i)+\delta_{i+1}N_{oi+1}(1+K_{i-1}\theta_{i-1}+\delta_{i-2})}{(1+K_i\theta_i+\delta_{i-1}+\delta_{i+1})(1+K_{i-1}\theta_{i-1}+\delta_{i-2})(1+K_{i+1}\theta_{i+1}+\delta_i)}$$

For $i = 1, 2, ..., n-1$ ...(2a)

and $$N_i = \frac{N_{oi}(1+K_{i-1}\theta_{i-1}+\delta_{i-2}) + \delta_{i-2}N_{oi-2}}{(1+K_i\theta_i+\delta_{i-1})(1+K_{i-1}\theta_{i-1}+\delta_{i-2})}$$ for $i = n$

MODEL PARAMETERS

The use of Equations (1) and (2) in predicting the effluent bacterial population requires the determination of θ is obtained by traces studies while by is given by (Polprasert and Bacteria, a1985) as;

$$\delta = \frac{0.362 Re^{-0.489} W^2}{LH} \quad ...(3)$$

Where Re is Reynolds number given by Webber, (1976) as:

$$Re = \frac{4UR}{\upsilon}$$

δ_i and N_{0i} are determined experimentally by sampling in the region of the pond inlet at various depths, (Mara and Pearson, 1987).

Three Models exists for the computation of k. The first is given by Mara is (1974) as;

$K = 2.6\,(1.19)^{T-20}$ … (5)

Although this model is used frequently in design, (Mara and Pearson, 1987) K does not depend on temperature alone, Silva (1982), but also on some other factors which Polprasert and others included and obtained by multiple regression analysis as;

$\exp(K) = 0.6351(1.0281)^T(1.0016)^{Cs}$ ...(4)

$(0.9994)^{OL}$ ... (6)

Since algae affects die-off of Microbial pathogens in several ways, (Pearson and others, 1987). The pond depth effect on K has been accounted for by the model, (Sarikaya and saathci, 1987) and is given as;

$$K = K_d + \frac{K_S S_O}{K_i H} \quad \dots (7)$$

In Equation (7), all the other factors except depth and Solar radiation are lumped into K_d and then represented as a constant. However, K_d has been found to vary widely, Mayo, (1989), which challenges the validity of representing it as a constant in the regression analysis.

Equation (7) also failed to incorporate the effects of humid substances, PH and dissolved oxygen which are important variables in the process by which light damages bacteria (Curtis et al; 1991). Besides, it gives only the overall effect of depth, and not point by point variation of k with depth. Each of the models above has various limitations.

MATERIALS AND METHODS

The WSP, a facility for wastewater treatment at UNN Comprises of two secondary facultative ponds in series and receives digested domestic effluent from an imhoff tank.

The first pond serves a facultative function, while the second one serves the function of a maturation pond. The final effluent is used for restricted irrigation. The pond measure 123.3m × 27.1m with a mean water depth of 0.2 and a thick sludge deposits.

The WSP Treats only domestic wastewater generated within the university campus. Data for the verification studies were collected from the second facultative pond and samples were analyzed for dissolved oxygen (Do), temperature (T), Algal concentration (Cs), organic loading rate (OL), chemical oxygen demand (COD), Hydrogen ion concentration (PH), and coliform on bacteria per 100ml. The pond system receives effluent after screening, digestion and sedimentation in an imhoff tank, and serves a population of about 30,000.

Influent and effluent samples were taken at different depths in the region of the inlet and outlet of the pond respectively using a pond column sampler specially designed to obtain water samples from discrete layers, in stratified water bodies, (Mara and Pearson 1987), and (Jorgensen et al. 1979) between 7.00 am and 8. 00 am samples for the various parameters were analyzed according to the techniques given in the standard methods for the examination of water and wastewaters APHA, (1998) and in Rodies,(1981). Dissolved oxygen (DO) measurements were conducted using titration Method PH was measured with a PH meter. The coliform counts were enumerated by the standard MPN method using the three tube dilution technique. Appropriate dilutions, prepared in buffered dilution water were inoculated into macogongare broth, presumptively tested by incubation at 35^0c for 24 hours.

The dispersion number (δ) detention tome (θ) and pond flow velocity (V) were determined by carrying out tracer experiments. The constant distance variable time method which is regarded as the conventional method was used whereby the tracer was introduced or injected at the influent flow zone of the pond.

Analytical sodium chloride (NaCL) was used as tracer for all the experiments following the procedures proposed by

(Levenspiel and smith 1957) and used by such researchers as (Thirumurthi, 1974 and Polprasert, et al, 1983). The data generated by the tracer experiments were evaluated analytically.

VERIFICATION OF MODELS RESPONSE AND COMPARISON WITH MEASURED EXPERIMENTAL VALUES

The experimental data collected from Nsukka waste stabilization pond is shown in Table 1. Based on this data the effluent bacterial various depths using the plug flow and the completely mixed flow models described in Equations (1) and (2) respectively the plot of average predicted and measured effluent bacterial concentration versus depth for 8 experiments is given in figure 1. The maximum and minimum effluent coliform bacteria were 93 $\times 10^{-6}$ per 100ml to 23 $\times 10^{-6}$ per 100ml for the experimental values, 88.992 $\times 10^{-6}$ per 100ml to 18.004 $\times 10^{-6}$ per 100ml for the predicted model based on completely mixed flow condition as in Equation (2) and 89.756 x 10^{-6} per 100ml to 14.691 x 10^{-6} per 100ml for the model based on plug flow model as in Equation (1).

Based on Equations (1) and (2) each layer was discretized into N-sub – layers with thicknesses $h_1, h_2, \ldots h_n$; bacteria numbers $N_1, N_2, \ldots, N_n$; and dispersion numbers $\delta_1, \delta_2, \ldots \delta_n$. It is assume that each layer approximates a plug flow and completely mixed flow conditions.

A correlation coefficient (r) was calculated in order to compare the validation of the two models in this study. This correlation coefficient r is defined as in equation (8) as follows:

$$r = \frac{n\sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_1}{\left\{[n\sum_{i=1}^{n} X_i^2 - (\sum_{i=1}^{n} X_i)^2][n\sum_{i=1}^{n} Y_i^2 - (\sum_{i=1}^{n} Y_i)^2]\right\}^{1/2}}$$

where

X_i = observed coli form bacteria per 100ml

Y_i = predicted coli form bacteria per 100ml

n = number of observed and predicted coli form bacteria per 100ml.

Therefore, equation (8) gives the correlation coefficient ranges from 0.992007332 to 0.939220284 for model derived under the assumption of completely mixed flow condition, while that developed under plug flow assumption gave the range of correlation coefficient from 0.995915575 to 0.93889777, showing that the two models are almost the same as shown in figure 2.

Table 1.0: Parameters Used for Computing Predicting Values of Coliform Bacteria (N) at Various Depth

Expt No.	**Depth** Below water surface (cm)	**T** °C	**C_s** Mg/l	**OL** Kg. cos/ hard	Days	**Measured** Coliform bacteria (x10^6/100ml)	**Predict** Coliform bacteria using plug flow model (x10^6/100ml)	**predicted** coliform Bacteria using CMF model(x0^{-6}/100ml)
	20	23.0	43	393		75	72	71
	15	24.0	55	393		64	61	63
1	10	24.5	55	656	3.430	39	33	34

	5	26.0	85	656		39	41	42
	0	28.0	115	393		39	40	40
	20	23.0	43	398		93	90	89
	15	24.0	63	398		64	50	52
2	10	24.5	88	646	3.390	55	48	49
	5	25.0	95	663		33	30	31
	0	26.0	123	663		30	30	31
	20	23.0	43	420		75	72	71
	15	23.0	45	395		64	60	60
3	10	24.0	55	395	3.425	39	32	32
	5	25.0	85	461		23	26	27
	0	27.0	123	671		23	16	18
	20	22.0	45	378		43	43	43
	15	24.0	50	392		39	36	36
4	10	24.5	85	456	3.453	39	33	33
	5	25.5	85	587		23	21	21
	0	26.0	118	653		23	18	19
	20	23.0	55	413		75	70	69
	15	24.5	55	452		43	37	39
	10	26.0	80	456	3.485	27	28	31
	5	26.0	85	487		27	30	31
	0	28.0	115	653		27	28	31
	20	23.0	45	386		75	70	69
	15	24.0	50	399		64	54	54
6	10	24.0	85	426	3.380	27	31	33
	5	24.0	85	246		27	29	27
	0	26.0	118	399		23	19	23
	20	24.0	55	386		64	60	61
	15	24.0	55	399		47	51	52
7	10	25.5	80	399	3.380	43	40	43
	5	27.0	85	246		43	36	40
	0	28.0	115	467		43	19	25
	20	23.0	43	405		64	53	62
	15	24.5	63	405		39	29	31
8	10	26.0	88	473	3.453	27	26	27
	5	26.0	95	675		27	34	35
	0	28.0	123	675		23	17	18

RESULTS AND DISCUSSION

The variation of algal concentration (C_5), organic loading, temperature and coliform concentration with depth are given in Table 1 and figure 1 a, b, c, d, e, f, g, h. it also gives the variation of the parameters with regard to the surface and bottom of the WSP sampling coliform bacteria is higher at the bottom than on the surface. Due to higher photosynthetic activity at the surface, more bicarbonate available is utilized in the metabolic activity of algae, causing a reduction of bacteria. Coliform concentration ranged from 93×10^{-6} per 100ml to 23×10^{-6} per 100ml for the measured experimental values 90×10^{-6} per 100ml to 17×10 per 100ml for the plug flow model and 89×10^{-6} per 100ml to 18×10^{-6} per 100ml for the completely mixed flow model as in Table 1 and figure 1. Showing that the two models relate very well with the measured values. Also at the pond surface, the dispersion number (δ) increases while the coliform bacteria decreases and then reverses their values toward the bottom of the pond, indicating that sunlight, higher photosynthetic activity and dispersion number (δ) affect the coliform bacteria in WSPs. From this study therefore, there is a linear positive correlation between the two models.

CONCLUSION AND RECOMMENDATION

1. Two mathematical models for predicting coliform bacteria at various depths in WSP due to thermal stratification based on plug flow and completely mixed flow conditions were verified, using experimental data from the UNN WSP.

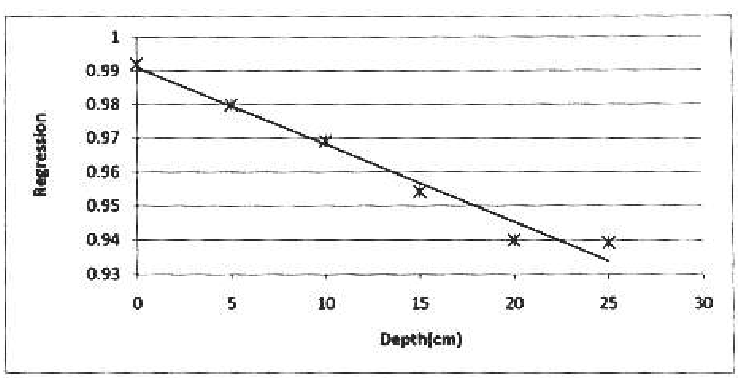
2. With data obtained from the full waste stabilization pond at Nsukka, it has been demonstrated that the two models predicts more accurate values when compared with the experimental measured values.

3. Since stratification may occur in ponds as shallow as 0.2m hence it is better to used stratification models in the design of waste stabilization pond.

4. The available K – models which could be used in conjunction with the flow modes are seriously deficient. More research is needed on the pathways of coliform bacteria/die-off so that a more accurate K – model could be formulated.

REGRESSION GRAPH FOR PLUG FLOW

REGRESSION GRAPH FOR COMPLETE MIX FLOW



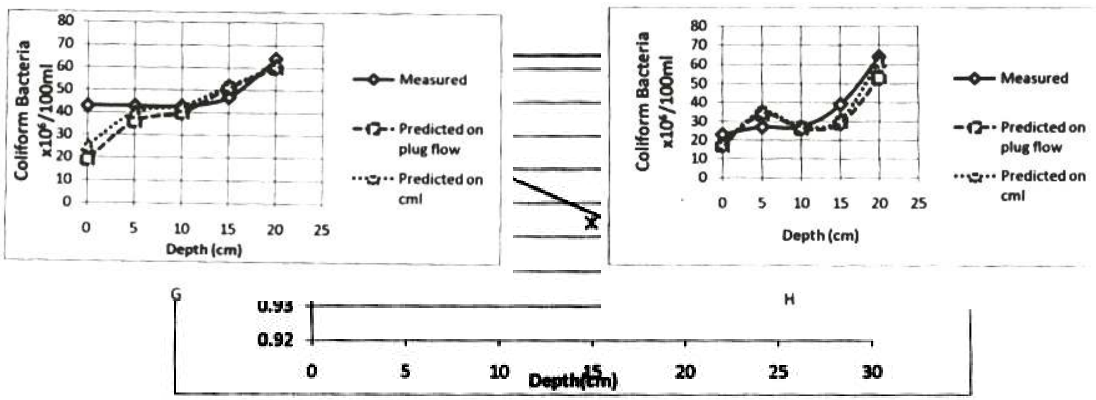


Fig. 1. Graph showing regression with between plug flow and completely mixed flow

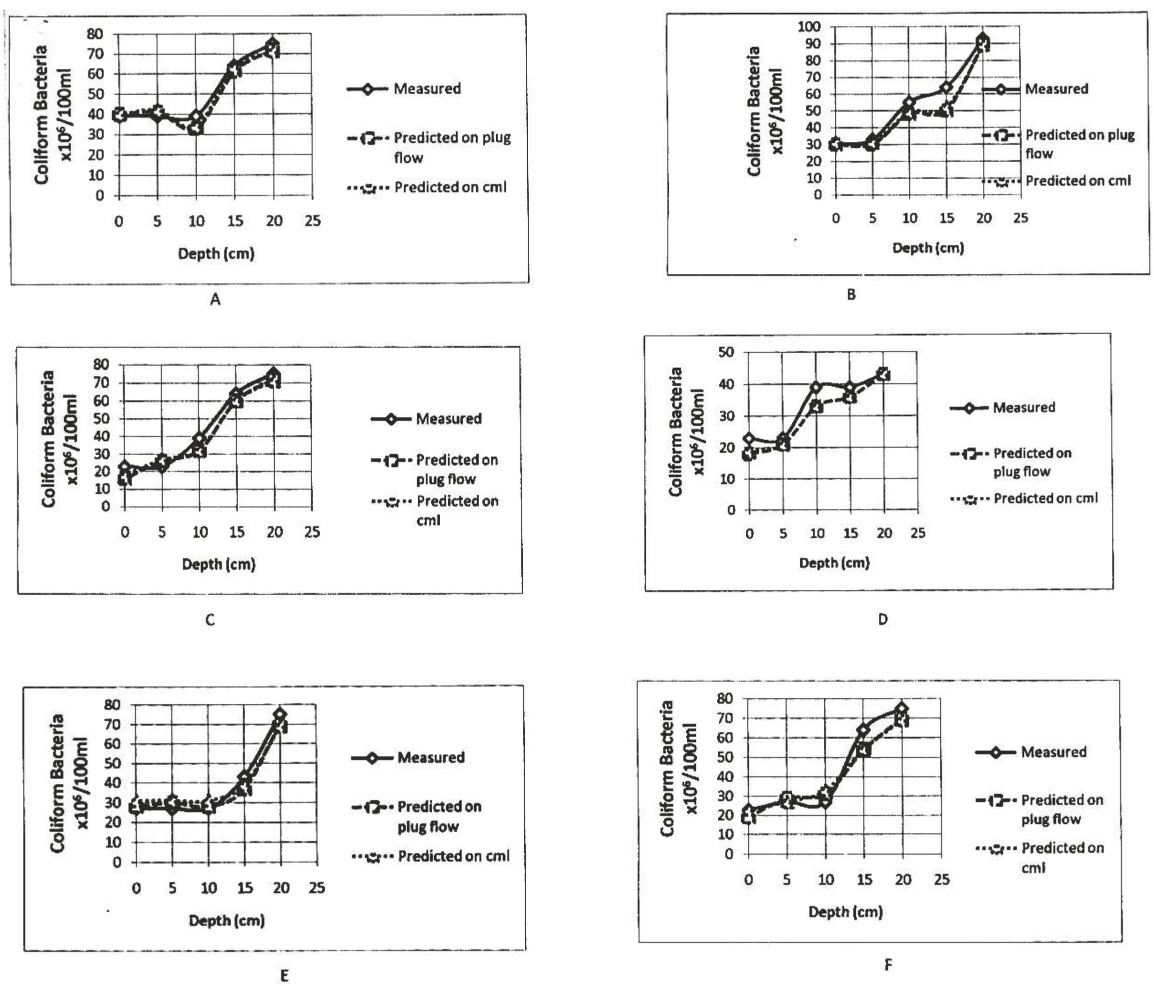


Fig. 2 Comparison of measured and predicted effluent coliform bacteria (N) againsty depth

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