The influence of thermal stratification on the hydraulic behavior of waste stabilization ponds

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Abstract Thermal stratification, which is characterized by a high vertical thermal gradient, is usually observed in deep lakes. However, although waste stabilization ponds have small depths, their high turbidity provides favorable conditions for the occurrence of this phenomenon, mainly during summer. During that time of the year, the layers nearest to the surface concentrate a larger amount of thermal energy compared to the deeper layers, which results in a temperature difference between the surface and the bottom of the pond. As a consequence a density profile appears, with the less dense layers located at the surface of the pond and the densest ones close to the bottom. This stratification in the water column induces alterations in the flow pattern and a decrease of the useful volume of the pond. This paper presents a mathematical model developed to forecast the conditions of thermal stratification in waste stabilization ponds and the volume actually used for wastewater treatment. With these values it is possible to correct the average residence time of the liquid in the pond. The theoretical results were compared with experimental observations, and maximum differences of 15% between the calculated and observed temperature profiles were found.

Keywords Waste stabilization ponds; thermal stratification; mathematical model; hydraulic detention time; pond design

Introduction

Waste stabilization ponds are designed to provide a controlled environment for wastewater treatment. Their size is established from theoretical and empirical relationships that give, directly or indirectly, an 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 stable at a certain depth, with the densest layers 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.

Among the hydrodynamic and limnological problems that thermal stratification causes, the decrease in the volume of the active zone (useful volume), with consequences on the hydraulic detention time, is of main concern for the design and operation of waste stabilization ponds. 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 temperature of the surface layer had decreased, the active zone extended from the top to the bottom of the pond. During the summer, as a stable thermocline was formed, the active zone extended from the surface to the
depth where the effluent outlet was located. The volumes of the active zones were estimated as being 70% and 20% of the total volume of the pond during the winter and the summer, respectively. The variation of the active volume caused the real hydraulic detention time to vary from 70% to 20% of the theoretical hydraulic detention time. Forero (1987), analyzing the hydraulic behavior of waste stabilization ponds, reported that the real hydraulic detention time varied from 30% to 80% of the theoretical value.

Although the dispersion number in waste stabilization ponds is influenced directly by the length-to-breadth ratio, the decrease in hydraulic detention time can mask its effects. In fact, Arceivala (1983) noted that some waste stabilization ponds located in hot climates had measured dispersion numbers greater than 4 when the bulk liquid was thermally stratified.

Considering the importance of the thermal stratification phenomenon, we propose in this paper a mathematical model to determine the temperature profile and the hydraulic correction factor for waste stabilization ponds. The results from the mathematical model were compared with experimental data from two waste stabilization ponds located in different climatic zones.

**Determination of the vertical temperature profile**

The mathematical model presented here is based on Norton and King (1974) and Fritz et al. (1980). It is a one-dimensional model that allows the determination of the temperature profile in a waste stabilization pond, as well as its effective volume and a hydraulic correction factor that can be used to improve the estimation of treatment efficiencies. Figure 1 illustrates the physical model used to assemble the mathematical formulation.

The physical model was assembled as a superposition of layers of the same thickness, except for the surface layer whose thickness varies depending on existing weather conditions, since it is influenced directly by precipitation and evaporation. Each element of the control volume is able to receive or to lose advective flows (influent and effluent), so preserving the mass balance. The heat flows through the horizontal boundary surfaces of each control volume element by advection or by diffusion. The introduction of thermal energy by insulation depends on the depth of the control element, as the water and its suspended solids dampen the solar energy. Due to the flow imposed by the influent and convective currents, thermal energy is transferred from one element to another almost exclusively by advection and only a small fraction is transferred by diffusion.

**Figure 1** Conceptual representation of a stratified pond
Regardless of the inflow pipe position, the influent will find its equilibrium layer depending on its initial density; that is, the influent moves in the vertical direction until a balance among the densities of the influent and the liquid contained by a certain control volume of the pond is reached.

The effluent, and consequently part of the pond’s thermal energy is removed from the element of the control volume which is at the same depth as the effluent outlet.

**Thermal energy balance**

The balance of thermal energy in a volume element can be expressed as:

\[
\frac{\partial H_j}{\partial t} = (h_j - h_o + h_{zz}) - \left( h_{w_j} - h_{w_{ji+1}} \right) - \left( h_{d_j} - h_{d_{ji+1}} \right)
\]

where \( H_j = c \cdot r \cdot V_j \cdot T_j \) is the thermal energy contained in the \( j \)th element (J); \( c \) is the specific heat of water (J kg\(^{-1}\)ºC\(^{-1}\)); \( r \) is the specific mass of water (kg m\(^{-3}\)); \( T_j \) is the temperature in element \( j \) (ºC); \( h_i = c \cdot r \cdot Q_i \cdot T_i \) is the thermal energy introduced by the influent flow (J s\(^{-1}\)); \( h_o = c \cdot r \cdot Q_o \). \( T_o \) is the thermal energy removed by the effluent flow (J s\(^{-1}\)); \( h_{zz} = F_z \cdot A_z \) is the direct insulation (J s\(^{-1}\)); \( F_z = (1 - b) \cdot F_0 \cdot e^{-k \cdot z} \) is the flow of solar radiation at depth \( z \) (J m\(^{-2}\) s\(^{-1}\)); \( F_0 \) is the net solar radiation flux that penetrates the surface (J m\(^{-2}\) s\(^{-1}\)); \( b \) is the radiation rate absorbed in the liquid surface; \( k \) is the coefficient of light attenuation (m\(^{-1}\)); \( h_{w_j} = c \cdot r \cdot Q_{z_j} \cdot T_j \) is the heat advected along the vertical axis; and \( E_z \) is the coefficient of vertical dispersion (m\(^2\) s\(^{-1}\)) that comprises molecular and turbulent diffusions.

The determination of the thermal flux \( F_0 \) provided by solar radiation and the air is primarily a function of the latitude of the pond site, the distance between the Earth and the Sun (varying along the year), the temperature of the air and the fraction of cloud cover. The calculation of the thermal flux is beyond the scope of this paper; it can be found in full detail in Fritz et al. (1980) and Pires and Kellner (1999).

**Thermal energy stored in a volume element**

The amount of thermal energy stored in a volume element,

\[
\frac{\partial (V_j \cdot H_j)}{\partial t}
\]

is determined from the balance of thermal energy which, after substitutions and simplification, results in the equation:

\[
\frac{\partial (V_j \cdot \delta H_j)}{\partial t} = \frac{(Q_{z_j} \cdot \delta T_j - Q_{z_{ji+1}} \cdot \delta T_{ji+1})}{\text{local advection}} + \frac{1}{c \cdot \rho} \cdot \frac{\partial}{\partial z} \cdot A_z \cdot \delta T_j - \left( Q_{z_j} \cdot \delta T_j - Q_{z_{ji+1}} \cdot \delta T_{ji+1} \right)
\]

\[
- E_j \cdot \delta A_{z_j} \cdot \frac{\partial T_j}{\partial z} \bigg|_{ji} \quad - E_{j+1} \cdot \delta A_{j+1} \cdot \frac{\partial T_j}{\partial z} \bigg|_{ji+1}
\]

\[
\cdot \frac{1}{c \cdot \rho} \cdot \frac{\partial}{\partial z} \cdot E_z \cdot \delta A_z
\]

After discretization Equation (2) becomes:

\[
\frac{\delta T_{ji}}{\delta t} = \frac{1}{V_j} \cdot \frac{E_j \cdot \delta A_{z_j}}{z} \cdot \delta T_{ji-1} - \frac{1}{V_j} \cdot \left( V_j \cdot \delta Q_{z_{ji+1}} - Q_{z_{ji+1}} \right) + \frac{1}{V_j} \cdot \frac{E_j \cdot \delta A_{z_{ji+1}}}{z} + \frac{1}{V_j} \cdot \frac{E_{j+1} \cdot \delta A_{z_{j+1}}}{z} \cdot \delta T_j
\]

\[
+ \frac{1}{V_j} \cdot \delta Q_{z_{ji+1}} + \frac{1}{V_j} \cdot \frac{E_{j+1} \cdot \delta A_{z_{j+1}}}{z} \cdot \delta T_{ji+1} + \frac{1}{V_j} \cdot \delta Q_{z_{ji+1}} \cdot \frac{E_j}{c \cdot \rho} \cdot \frac{\partial A_{z_{ji+1}}}{\partial z}
\]

(3)
For the temperature increment a fourth order Runge-Kutta method was applied, as represented by the equation:

\[ T_{j+1} = T_j + \frac{1}{2} \Delta t \left( \frac{K_{1,j}}{6} \Delta t K_{2,j} + 2 K_{3,j} + K_{4,j} \right) \]  

(4)

where \( \Delta t \) is the adopted time interval and

\[ K_{1,j} = f\left(T_j\right), \quad K_{2,j} = f\left(T_j + \frac{1}{2} \Delta t K_{1,j}\right), \quad K_{3,j} = f\left(T_j + \frac{1}{2} \Delta t K_{2,j}\right), \quad K_{4,j} = f\left(T_j + \Delta t K_{3,j}\right) \]

and \( K_{4,j} = f\left(T_j + \Delta t K_{3,j}\right) \).

**Determination of the effective pond volume and correction of the theoretical hydraulic detention time**

When a liquid body is thermally stratified two very different zones are found: the epilimnion, a layer close to the surface, with higher temperatures and, therefore, with smaller density; and the hypolimnion, a layer close to the bottom, with a lower temperature, thus denser (Dor et al., 1993).

A mass flow between these two liquid layers is impaired by the density differences. As a result the volume occupied by the hypolimnion becomes a dead zone, decreasing the volume actually used for wastewater treatment. Thus, the effective volume of the pond is defined as the volume of the epilimnion itself. Therefore the corrected hydraulic detention time (\( t^* \)) can be estimated by the equation:

\[ t^* = \frac{V_u}{Q} \]  

(5)

where \( t^* \) is the corrected mean hydraulic detention time (h), \( V_u \) is the useful volume of the pond (m\(^3\)) and \( Q \) is the influent flow rate (m\(^3\)h\(^{-1}\)).

At this point it is important to observe that thermal stratification could be prevented if the pond outlet were located at the bottom of the pond. Standard construction practice, however, is to locate the outlet near the surface to avoid any settled solids leaving the pond.

Prior to determining the effective pond volume it is necessary to verify whether stratification is taking place. A clear value for the thermal gradient that characterizes the occurrence of the stratification phenomenon is not found in the literature. Some investigations have used values that vary from 0.6ºC/m to 1.0ºC/m (Pires and Kellner, 1999). In this study a value of 0.6ºC/m was assumed to characterize the occurrence of thermal stratification.

At the point of maximum temperature gradient an imaginary plane exists which is called a thermocline. Thus, for the calculation of the effective pond volume it is first necessary to determine the position of this plane, which also defines the useful depth (\( h_u \)):

\[ h_u = z \text{ at } \frac{\partial T}{\partial Z} = \text{maximum} \]  

(6)

where \( z \) is the depth at which the greatest value for \( \partial T/\partial Z \) occurs.

Given the useful depth of the pond, the useful volume is determined from:

\[ V_u = \frac{A_s + A_z}{2} \delta h_u \]  

(7)

where \( A_s \) is the surface area of the pond and \( A_z \) is the area of the liquid layer at depth \( z \).

The hydraulic correction factor (HCF) that can be used to correct the hydraulic detention time is defined by the ratio:

\[ HCF = \frac{V}{V_u} \]  

(8)
where $V_u$ is the effective volume (m$^3$) and $V$ is the physical volume of the pond (m$^3$).

**Methodology**

In order to verify the quality of the model, its results were compared with experimental data from two earlier studies, (Silva, 1982; Vidal, 1983). The pond studied by Silva is located in Campina Grande, Paraíba, northeast Brazil (latitude 7°13′11″S), which has a hot, dry climate, with small daily temperature variations; and the pond studied by Vidal is located in Santa Fé do Sul, São Paulo, southeast Brazil (latitude 20°46′03″S), an area with a higher daily temperature variation (Figure 2).

The variation of the useful volume of each pond was simulated for a one-year period. The hydraulic detention time obtained from tests with tracer at Campina Grande pond and the ones obtained from the simulations were compared.

Silva (1982) measured the temperature variation with depth, on 6–7 October 1987, in a facultative pond of length 25.70 m, width 7.40 m and depth 1.25 m, located in Campina Grande. Vidal (1983) performed his measurements on a facultative pond in Santa Fé do Sul, with a length of 80 m, a width of 66 m and a depth of 1.5 m.

**Results and discussion**

Figure 3 shows the temperature profiles calculated using the proposed model and the results from Silva (1982) for measurements made at 6:00, 10:00, 12:00, 14:00, 16:00 and 22:00 hours. At 10:00 hours, probably due to the increase in the air temperature, a small increase in the temperature of the layers close to the surface was observed, although the calculated values remained constant. Between 14:00 and 16:00 hours, the temperature variation with depth of the pond reached its maximum value. At 22:00 hours, most probably due to a decrease in air temperature, a fall was observed in the surface temperature of the pond.

Most of the simulated results differed only from −5% to +5% of the experimental value. The largest relative differences were observed for points close to the surface at 12:00 hours, when the simulated values were from 5% to 10% above the measured values, and at 16:00 hours, when the simulated values were from 5% to 15% below the experimental results. Considering the several factors that occur in the thermal phenomena in waste stabilization ponds, those differences can be considered small. It should be observed that for the calculations several meteorological data were assumed using reported values instead of direct measurement. The fact that the largest relative differences appear close to the surface of the pond can be related to the complex mechanisms of thermal energy transfer between the liquid surface and the air. In this zone wind gusts and surface waves play a significant role.
in the transfer mechanisms, but owing to their random behaviour it is difficult to predict their effects correctly.

Using the results of the temperature distribution the annual variation of the effective volume of the pond was determined. This simulation indicated that, while the sun was above the horizon, the pond had a useful volume of approximately 60% of its physical volume, while in the evening this figure increased to 70 to 80% of its physical size, as can be seen in Figure 4.

Figure 3 Calculated and measured temperature profiles for a facultative pond located in Campina Grande – PB, Brazil. Note: experimental data: Silva (1982); theoretical curves: this paper

Figure 4 Annual variation of the useful volume of the facultative pond in Campina Grande
Figure 5 shows experimental results from Vidal (1983) and the variation of temperature with depth obtained from the mathematical simulation. The experimental data of the pond from Santa Fé do Sul show that thermal stratification prevailed most of the time, with rapid mixing occurring between 6:00 and 10:00 hours. The simulated results indicated a more accentuated stratification during the day, and a decrease in its magnitude during the night.

Comparing the simulated values with the experimental data, it was observed that, in most cases, the relative difference varied from –5% to +5% of the experimental value. As happened with the Campina Grande pond, in the Santa Fé do Sul pond the maximum relative differences occurred for points close to the surface and close to the bottom.

Figure 6 shows that the effective volume of the pond varied from 35% to 85% of the total volume, reaching the maximum during the winter season. With the Sun above the horizon, the pond researched by Vidal had an effective volume of 35 to 55% of its physical volume; in the evening it varied from 35 to 85%.

Of the two experiments used to evaluate the proposed mathematical model, the results reported by Silva (1982) also presented tests with tracer to determine the actual hydraulic retention time. The measured actual dimensionless hydraulic retention time for the pond of Campina Grande (0.70), is in agreement with the researched temperature data, which confirm the occurrence of thermal stratification. The simulated dimensionless hydraulic retention time was 0.58 for the same period. The relative difference between the experimental and simulated values has the same magnitude as that observed for the temperature profiles.
Conclusions

• Thermal stratification has a strong influence on the hydraulic detention time of waste stabilization ponds, decreasing the actual treatment time;
• The knowledge of the local climatic conditions of a waste stabilization pond is very important for its design;
• The evaluation of the annual variation in effective pond volume supplies important information concerning its hydraulic behaviour;
• A thermal gradient of 0.6°C/m proved satisfactory as a limit value for identification of the occurrence of thermal stratification for tropical climatic regions;
• The proposed mathematical model for determination of the temperature profile in waste stabilization ponds provided satisfactory results, with average differences from measured to simulated values in the –5% to +15% range.

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