MODELING THE TEMPERATURE PATTERN OF A COVERED ANAEROBIC POND WITH COMPUTATIONAL FLUID DYNAMICS

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Abstract. This paper presents the development of a 3D computational fluid dynamics (CFD) model of a covered deep anaerobic pond treating raw sewage. The model was based on an unsteady-state laminar flow which was solved in accordance with the finite volume method and simulated the hydrodynamic pattern and thermal energy balance of the anaerobic pond throughout a year of operation. The model input included hourly ambient air temperature, monthly soil temperature profile, daily influent wastewater temperature and velocity, which were incorporated through an external routine in C^{++}. Numerical simulation was validated by temperature measurements from the experimental pond. The mean relative error and correlation factor out of 164 temperature values of the simulated pond, in comparison with the experimental one, was 9.34% and 0.91, respectively. The average temperature of the simulated pond throughout the experimental period was 18.9 °C. The validated 3D thermal model can be used as a tool for assessing and evaluating the impact of various design modifications (changes in construction material, adding insulation, installing a heat exchanger, etc.) on the thermal behaviour of an anaerobic pond, aiming at its average temperature increase which will, in turn, positively affect its organic removal performance. The thermal model presented, is the first stage of a complete anaerobic pond model which will include wastewater quality transport and basic biochemical reaction mechanisms of the anaerobic decomposition process present in an anaerobic pond. The complete anaerobic pond model will be able to predict the effluent COD of the pond.

Keywords: Anaerobic pond, CFD modeling, natural systems, temperature, wastewater

1. Introduction

One of the most important factors affecting anaerobic pond efficiency in waste removal is local climatic conditions, (Mara, 2000). It has been observed that the digestion rates of anaerobic microorganisms are greatly influenced by temperature (Lettinga *et al.*, 2001). It is generally accepted that, at temperatures below 15 °C, bacteria growth and metabolism is reduced and the anaerobic breakdown of organic matter is thus affected (Tebbut, 1992). The types of bacteria involved in the anaerobic processes, (i.e. acidogenic and methanogenic bacteria), prefer warm conditions; 30–35°C being considered the optimum temperature range for mesophilic anaerobic digestion (Tchobanoglous and Schroeder, 1987).

The major issues of the wastewater industry involve meeting effluent quality standards and guaranteeing reliable and efficient processing. Nowadays, the use of powerful predictive modeling and simulation tools, which are able to take into account the interactions between all wastewater quality and process design parameters, are widely used to achieve these ends (Shilton *et al.*, 1999).

Due to the increasing sophistication of computers, Computational Fluid Dynamics, (CFD), has become an efficient tool for behavior analyzing, monitoring and optimizing a wastewater treatment digester. CFD is based on the numerical solution of partial differential equations expressing local balances of mass, momentum and energy, which may eventually couple to transport equations of non-reactive or reactive flows for given operating conditions.

The main advantages of using a CFD model in wastewater pond treatment technology, and which distinguish it from the limitations of the existing models, are:

1. It gives a complete picture of the whole flow field, something that is generally difficult to obtain by experimental means.
2. It examines flow patterns in situations where it is simply not possible to take measurements.
3. It can be used as a predictive tool, examining different design scenarios (inlet, outlet arrangements, digester shape, type of construction etc.).
4. It takes into account spatial variations in fluid velocity, pollutant concentration etc.

Concerning conventional wastewater plant design, CFD modeling has been applied to assess the operation of a full-scale activated sludge digester (Karama *et al.*, 1999), a sedimentation tank (Laine *et al.*, 1999), a chlorination tank (Sanjay, 2000), coagulation, flocculation (Do-Quang *et al.*, 1999), etc.

As regards the use of CFD software in the study of stabilization ponds, little research work has been published, although it is believed that CFD will be the basic tool for pond design during the next decade (Shilton, 2000). The processes which can be simulated by a CFD model, with regard to an anaerobic or aerobic pond ecosystem, are as follows:

i. hydrodynamic pattern
ii. thermal energy balance
iii. water quality biochemical reaction.

One of the first research papers to study the hydrodynamic behavior of a pond was published by Wood *et al.* (1995). It describes the use of a commercial software package for the design of a stabilization pond by developing a 2D geometric model, assuming laminar flow. CFD modeling of aerobic or facultative stabilization ponds focuses on the hydrodynamic flow pattern by examining the residence time distribution (RTD), the determination of which is required in order to design the optimal geometry of the reactor. CFD may reliably predict the hydrodynamic impact of different pond shapes, or of hypothetical ‘inlet’, ‘outlet’ and ‘baffle’ arrangements. Eliminating dead spaces or short circuiting and increasing the hydraulic retention time will improve the pollution degradation process (Wood *et al.*, 1998; Peterson, 1999; Persson, 2000; Peterson *et al.*, 2000; Salter *et al.*, 2000; Shilton *et al.*, 2000; Baleo *et al.*, 2001).

Very little is known of the three processes mentioned above in anaerobic ponds (Pena *et al.*, 2000). A significant limitation of the models predicting BOD_5 and pathogen removal (Saqqar and Pescod, 1995; Silva *et al.*, 1996; Mara *et al.*, 1997), COD removal (Toprak, 1995a) and CH_4 generation (Gupta *et al.*, 1988; Toprak, 1995b), is that isothermal conditions are assumed for the whole anaerobic pond domain (Wood *et al.*, 1995).

Since seasonal temperature fluctuations occurring in the Mediterranean area either accelerate or slow down the anaerobic degradation rate of the wastewater organic matter in an anaerobic pond, accurate temperature prediction during its operation is required as a basis for reaction flow modeling.

The aim of this study is to describe the development of a 3D CFD unsteady model, describing the hydrodynamic pattern and thermal energy balance of a full scale covered anaerobic pond. The temperature behavior of the pond was assessed and the computed temperature results were compared to the recorded data in order to check the validity of the anaerobic pond model. In addition, the thermal behavior of the anaerobic pond modeled was presented.

Thermal numerical modeling of an anaerobic pond may be used as a tool to raise the mean temperature of an anaerobic pond in its design stage and is one of the first steps towards evaluating and improving the organic removal performance of the pond.

The commercial CFD software FLUENT was employed to complete this study, which is based on the finite volume method of discretization, and, apart from simulating the field flow, it was also used for geometric and mesh generation and post-processing (FLUENT Inc., 1999).

2. Material and Methods

2.1. The experimental anaerobic pond

The anaerobic pond studied was constructed at the experimental station of the National Agricultural Research Foundation (NAGREF) in Thessaloniki, Northern Greece, and used as a first stage treatment unit in a pilot scale wastewater treatment plant with stabilization ponds or lagoons. The anaerobic pond was an inverted, truncated pyramid, with surface dimensions 21×21 m, base 3×3 m, embankment slope 2:1 and a free board of 0.5 m. Its water depth was 4 m and treatment volume 570 m^3. It was lined with geomembrane (High Density Poly Ethylene) 1 mm thick and topped by a floating cover (Low Density Poly Ethylene) 1 mm thick.

The structure was covered to eliminate odour release, reduce evaporation and heat losses during the night and provide a safety precaution against accidental drowning. The floating cover consisted of a flexible membrane which floated on the surface of the wastewater stored in the pond. The anaerobic pond was supplied with 150 m^3/d of wastewater, after grit removal, from the adjacent Wastewater Treatment Plant. The inlet pipe was located 1.5 m above the pond bottom, having a diameter of 110 mm, and the outlet weir at the pond side, was 0.5 m wide.

The mean volumetric loading of raw sewage into the pond was 110 g/m^3d and its hydraulic retention time was estimated at $\approx$4d. The reactor operated semi-continuously, i.e. a discrete amount of wastewater was added once a day, requiring approximately 6 h for complete loading.

The overall BOD_5 and COD removal reported by Papadopoulos *et al.* (2003), was satisfactory (50% and 53%, respectively) and within the design limits, whereas the high SS and VSS removal achieved, (64% and 71%, respectively), indicated that the anaerobic system functioned efficiently in removing organic material present in the untreated wastewater.

Field measurements were carried out with a portable instrument (HORIBA) which was used for temperature recording from November 1999 until November 2000. Temperature was recorded simultaneously within the digester profile and at the outlet point of the pond. Temperature profiles in the pond were taken through an opening (gate) in the centre of the floating cover.

The temperature at the centre of the pond was recorded at depths of 0.2 m (surface), 1.0 m and 2.0 m. In all, 41 sets of measurements at four locations, i.e. 164 values of temperature data, were recorded during the experimental period. The Wastewater Treatment Plant Authority kindly provided raw sewage temperature on a daily basis. A meteorological station located at a distance of 500 m from the pond provided air temperature per hour.

3. Model Development

The FLUENT software package was employed on a Pentium PC in the Sector of Hydraulics and Environmental Engineering at the Department of Civil Engineering of the Aristotelian University of Thessaloniki. The geometric structure and grid of the experimental pond was completed on GAMBIT, which is the pre-processor program of FLUENT for geometric modelling and mesh generation.

For all flows, CFD software solves conservation equations for mass and momentum, which describe the basic hydrodynamic flow, whereas, in cases involving heat transfer, an additional equation of energy conservation is solved. Energy equation describes the thermal mixing of the fluid within the geometric volume (Anderson, 1995).

The model was developed to simulate the operation of the anaerobic pond during a calendar year, from November 1999 until November 2000, a total of 396 days

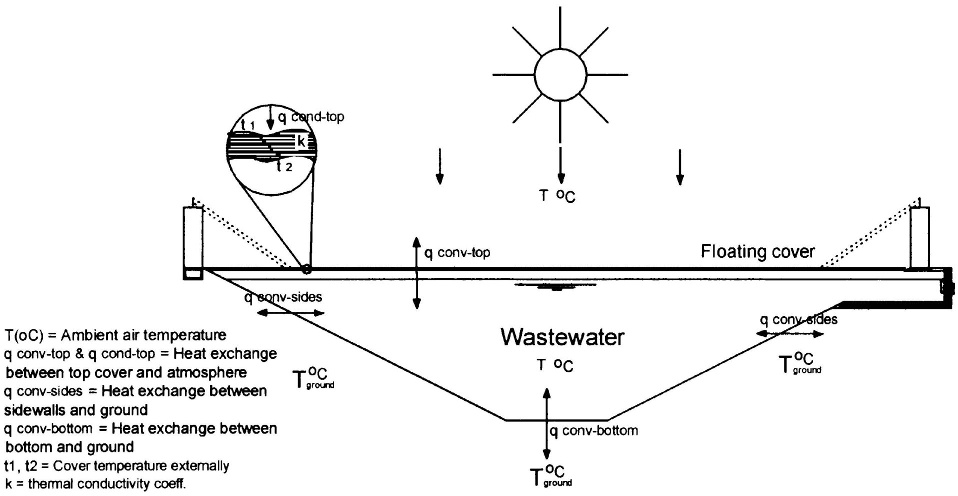


Figure 1. Simplified heat transfer diagram of a section of the experimental anaerobic pond.

or 9504 hours. Equations of mass, momentum and energy were solved in time-dependent form (unsteady-state) in a laminar flow regime. Laminar flow conditions, although assumed in the model for the sake of simplicity, were justified by a number of velocity measurements taken in the profile of the experimental pond. Although the velocities recorded were extremely low in the pond, it is possible, due to the large inlet pipe diameter ($D = 110$ mm) in some areas of the pond, that some turbulent flow did exist.

A precise hydrodynamic modelling of the anaerobic pond was, however, beyond the objectives of this study. Our concern was to make as accurate as possible a prediction of the thermal behaviour of the pond, for the purpose of the successive reaction flow modelling. Furthermore, turbulent flow modelling would require more CPU time in order for the flow field to reach a solution.

The overall heat transfer of the pond wastewater mass is governed by heat exchange across its upper, lower and sidewall boundaries (Figure 1).

Heat transfer at the floating cover boundary consists of i, convection between the cover and the atmospheric air ($q_{\text{conv-top}}$) and ii, conduction expressing the thermal resistance offered by the wall ($q_{\text{cond-top}}$). Heat transfer at the bottom consists of convection between the bottom wall and the ground ($q_{\text{conv-botttom}}$) and, at the sidewalls, heat exchange is due to convection between the walls and the soil profile ($q_{\text{conv-sides}}$).

For a convective heat transfer wall boundary, Heat Transfer Coefficient (h) and External temperature (T_{ext}) inputs (i.e. air or soil temperature) should be defined in order for the heat flux to the walls to be computed using Equation (1).

$$q = h(T_{\text{ext}} - T_{\text{wall}}) \tag{1}$$

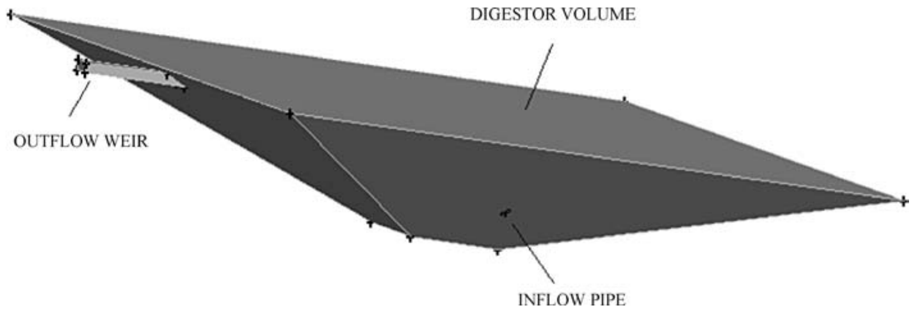


Figure 2. 3D view of the anaerobic pond.

where: q = Heat flux to the wall (W/m^2), h = Heat transfer coefficient (W/m^2-°C), T_{ext} = External temperature (°C), T_{wall} = Wall temperature (°C).

Heat transfer coefficient values across the upper, lower and sidewall boundaries of the anaerobic pond were approximated by model calibration.

Radiation losses are not included, because at the normal digestor operating temperatures, these losses are so low that they can be safely ignored (Stafford *et al.*, 1981). Nevertheless, radiation effect is indirectly included in the pond thermal system through the external air temperature applied at the surface boundary of the simulated pond.

Neither is the vertical temperature gradient effect included in the anaerobic pond model because the buoyancy process cannot be modelled in conjunction with reacting flows. It is generally accepted that thermal stratification influences the operation and performance of aerobic ponds, as opposed to anaerobic ones, thus the absence of the buoyancy process is not crucial.

3.1. Geometric model – mesh generation

The 3D geometric model of the experimental pond was developed in accordance with the dimensions of the full-scale digester (Figure 2). The main volume of the pond comprised of 18 nodes/vertices, 24 edges and 13 faces. From an overall of 4828 mesh elements, 4827 were tetrahedral and one (1) pyramidal.

The boundaries of the geometric model assigned were, the sidewalls of the pond, the inlet structure and the exit point of the wastewater out from the pond. Properties of the internal domain of the pond were specified at the solver stage.

4. Model Input

4.1. Material properties

The physical properties of the fluid material, representing wastewater and a solid material representing the floating cover and geomembrane, were defined at this stage, according to the active physical models (mass, momentum, energy).

Fluid material within the domain was assigned constant physical values. According to Stafford *et al.* (1981), wastewater density (ρ) is equal to 1020 kg/m^3 during primary sedimentation and heat capacity (Cp) is equal to 4094 J/kg°C, assuming that the wastewater in the anaerobic pond had a 3% solid content. Thermal conductivity (λ) and fluid viscosity (μ) were taken as 0.35 W/m°C and 0.0014 kg/m-s (Peterson *et al.*, 2000), respectively.

The top floating cover and geomembrane of the pond were given the following physical-thermal property values:

Density = 920 kg/m^3

$$\text{Thermal Conductivity} = 0.35\text{J/kg}^\circ\text{C}$$
$$\text{Heat Capacity} = 2150\text{W/m}^\circ\text{C}$$

4.2. Boundary conditions

Boundary conditions were specified for wall and inlet boundary zones, as follows:

4.2.1. *Wall Zones*

As regards wall boundaries, the geometric model consisted of a top, a bottom (floor) wall and four (4) sidewalls. The conditions input for all wall boundaries of the model were as follows:

- Heat flux into or out of all wall boundaries.
- Solid material type.
- Wall thickness.

Thermal boundary conditions defined for the top, bottom and sidewall zones are given in Table I and further explained below.

The 1 mm thick floating cover of the experimental anaerobic pond was the medium between the wastewater content of the pond and the air environment. The Heat Transfer Coefficient (‘h’ factor in Equation (1)) was taken as being equal to 2 W/m^2-°C after model calibration.

An external routine, written in C^{++}, which included hourly air temperatures during the experimental period (9504 values), provided the external temperature parameter (‘T_{ext}’ factor in Equation (1)). The average, maximum and minimum hourly air temperature during the experimental period was 14.6 °C, 41 °C and −7.1 °C, respectively. The Heat Transfer Coefficient (h) through the sidewalls was taken as being equal to 3 W/m^2-°C, after being justified by model calibration. Since the whole volume of the anaerobic pond was constructed underground, the external temperature of the sidewalls was taken as being equal to the surrounding ground

TABLE I
Thermal boundary conditions applied on wall zones

Wall zones	Thermal condition	Heat transfer coefficient (‘h’ in Equation 1) (W/m^2-°C)	Free stream temperature (‘T_{ext}’ in Equation 1) (°C)	Thickness (m)
Top	Convection/Wall thickness conduction	2	Unsteady air temp. per hour	0.001
Bottom	Convection	1	Constant ground temp. per month	–
Sidewalls	Convection	3	Constant ground temp. profile per month	–

temperature. Monthly soil temperature profiles were reported by the central meteorological station of Thessaloniki by Flokas (1997), at current depths of 0, 0.02, 0.05, 0.1, 0.25, 0.5, 1, 1.2, 1.5, 1.8 and 3 m together with ambient air temperature. Since air temperature is the most significant factor affecting soil temperature, thus, for the sake of accuracy, soil temperature was re-calculated for the experimental period (November 1999 to November 2000).

The new set of modified soil temperature profiles were approximated by mathematical equations (exponential, polynomial or linear) expressing soil temperature as a function of soil depth (Table II). Each equation expresses the external temperature profile (T_{ext}) of the sidewalls for each simulated month.

External temperature (T_{ext}) at the bottom wall zone (4 m deep) was constant for each simulated month and was derived from the respective temperature profile equation in Table II (calculated by substituting in each equation $x = 4$ m). Maximum and minimum monthly temperatures at 4 m depth were 20.5°C and 3.6°C, respectively. Figure 3 illustrates the soil temperature applied to the simulated pond bottom, in relation to air temperature variation, indicating that during summer (June–September), soil at 4 m depth is cooler than air, becoming warmer in winter.

The Heat Transfer Coefficient (h) through the bottom wall was assumed equal to 1 W/m^2-°C after model calibration.

4.2.2. *Velocity-Inlet Zone*

Velocity inlet boundary conditions were used to define the flow velocity, along with all relevant properties of the flow, at the flow inlet. Conditions applied to the velocity inlet boundary include the following:

- Velocity magnitude and direction
- Influent temperature

TABLE II
Soil temperature profile equations

Month	Soil temperature profile equation (x = depth in m)	R^2
November-99	$-0.8779x^2 + 4.6737x + 9.0665$	0.99
December-00	$-0.6098x^2 + 5.1511x + 4.8249$	0.98
January-00	$-0.1402x^2 + 1.2131x + 0.978$	0.99
February-00	$2.7034x + 6.812$	0.97
March-00	$0.4045x^2 - 0.2951x + 8.3139$	0.71
April-00	$1.314x^2 - 4.9728x + 18.139$	0.73
May-00	$1.7625x^2 - 8.1467x + 24.407$	0.91
June-00	$1.8534x^2 - 9.5097x + 28.89$	0.91
July-00	$30.595e^{-0.1996x}$	0.90
August-00	$30.183e^{-0.1583x}$	0.91
September-00	$23.51e^{-0.0598x}$	0.76
October-00	$-0.7495x^2 + 3.18x + 15.683$	0.88
November-00	$-1.1425x^2 + 6.0822x + 11.799$	0.99

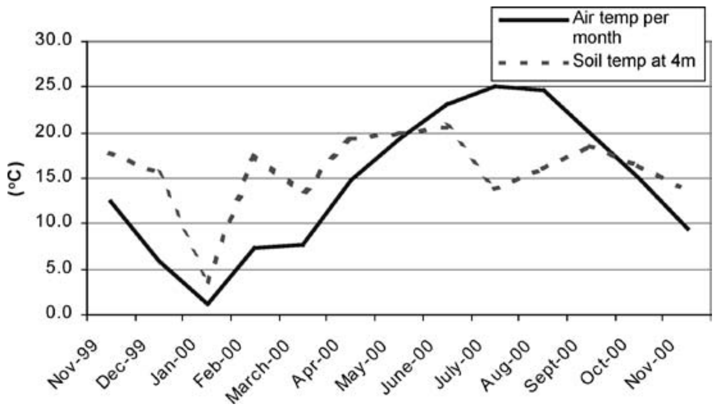


Figure 3. Soil temperature at pond bottom (4 m depth) in relation to ambient air temperature.

With regard to velocity magnitude, an external routine algorithm defining the unsteady influent velocity of the wastewater in the pond was required, since wastewater inflow in the anaerobic pond was an intermittent flow process. Velocity was equal to 0.73 m/s from 9.00 a.m. till 3.00 p.m., and zero (0) for the rest of the day (no wastewater supply). Figure 4 illustrates the pulse inflow velocity of a 7-day simulation period which was assigned to the inlet boundary zone of the anaerobic pond.

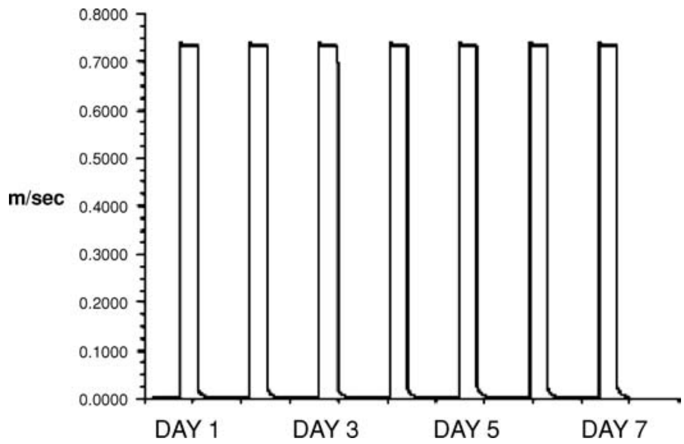


Figure 4. Periodic inlet velocity in a simulation time of 1 week ($q = 0.73$ m/s).

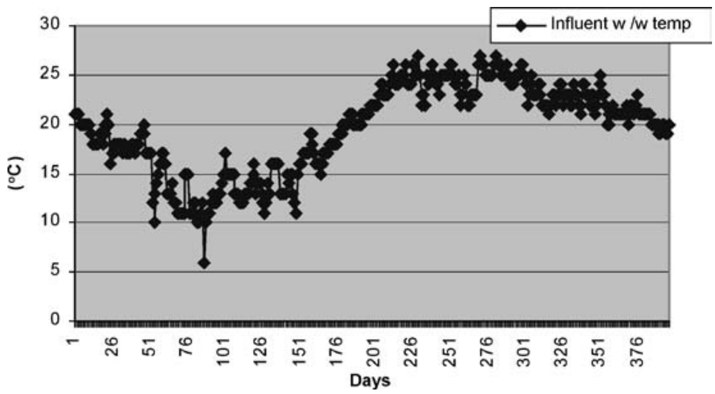


Figure 5. Influent wastewater temperature variation per day (in °C).

Influent wastewater temperature per day varied. Its temperature fluctuation during simulation, which can be observed from a total of 396 temperature values taken, is illustrated in Figure 5. Throughout the experimental year, average, maximum and minimum influent wastewater temperature was 19.6°C, 27°C and 6°C, respectively. These temperature values were automatically read by the CFD solver from an external algorithm.

4.3. Initial conditions

The initial conditions applied to the flow field of the anaerobic pond, which ensured quick initial numerical solution, are presented in Table III. The initial average pond temperature, at the beginning of November, was set to 19°C and the initial flow

TABLE III
Initial conditions used in the model

Parameter	Initial flow field value
x-axis velocity (m/s)	0.73
y-axis velocity m/s)	0
z-axis velocity (m/s)	0
temperature (°C)	19

velocity of the pond was taken to be 0.73 m/s. Velocity magnitude was assigned at the x-component (horizontally) of the flow direction (the y, z components were set to zero (0)), according to the x, y, z coordinate system on which the geometric model was built. The time step (Δt) was set to 120 s (2 min). The residual value, for which the solution of each variable was considered converged was 0.001, for both continuity equation and for x, y, z velocities and 10^{-6} for the energy equation.

5. Model Validation

CFD modeling requires reference to data from actual experimental studies, in order to verify the validity of the simulation results. Thus, experimental and calculated temperature data were compared. For the purpose of comparison, four (4) point surfaces, representing the relative points where temperature was recorded in the full-sized experimental pond, were created in the geometric model as follows (Figure 6):

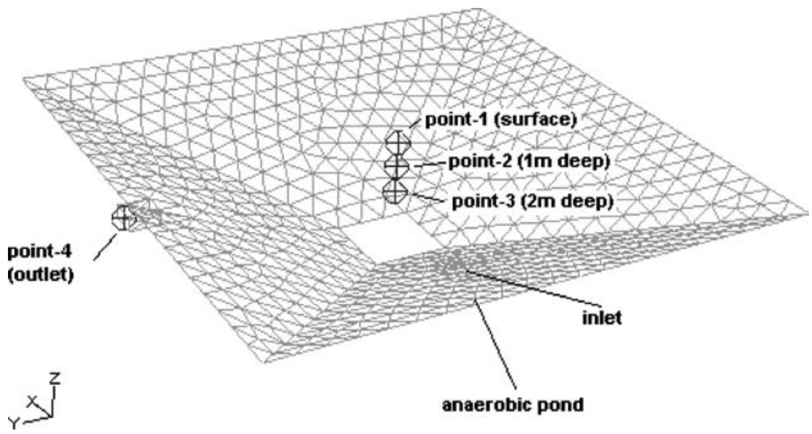


Figure 6. Points of temperature recording within the anaerobic pond model.

– point 1, at the pond surface (0 m depth) in the middle of the pond
– point 2, at a depth of 1 m in the middle of the pond
– point 3, at a depth of 2 m in the middle of the pond
– point 4, at the pond outlet

The accuracy of the 3D thermal model was evaluated by estimating the relative error (%) and the correlation between simulated and recorded temperature values. The relative error (%) calculation was based on Equation (2).

$$\text{Relative error (\%)} = \sum_{j=1}^{n} \frac{a_j - \beta_j}{\beta_j} \times \left(\frac{100}{n}\right) \tag{2}$$

where: α = Simulation value j, β = Measured value j, $j = (1, 2, \ldots, n)$ Number of data set ($n = 41$ temperature values at each measurement point)

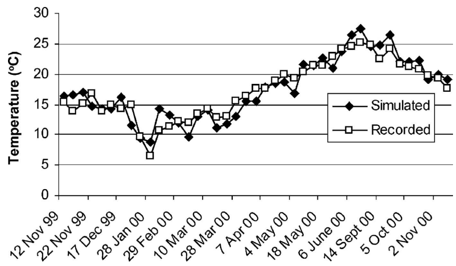
The relative error (%) between simulated and recorded temperature data at the points located on the surface, at a depth of 1 m, 2 m and at the outlet, was 8.74%, 10.62%, 9.12% and 8.88%, respectively. The overall mean relative error of all temperature data recordings (a total of 164 temperature values) of the simulated anaerobic pond was 9.34% (Table IV). About 34.7% of the temperature recordings attained a relative error of less than 5%.

Figure 7(a, b, c and d) represents the simulated and recorded temperature variations in the experimental period for each recording point of the anaerobic pond. It should be noted at this point, that the comparison procedure was based on instant temperature values recorded in the experimental and simulated anaerobic pond during the experimental period. It appears that the simulated and recorded temperature values follow a similar trend throughout the experimental period, although it was notified especially in Figure 7(b and c), that simulated values were systematically higher than recorded during autumn–winter period and lower during

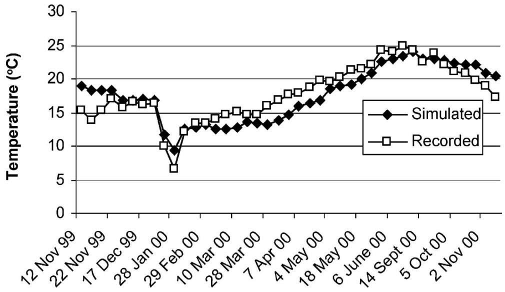
TABLE IV

Relative error (%) between simulated and recorded temperatures of the experimental anaerobic pond during the experimental period

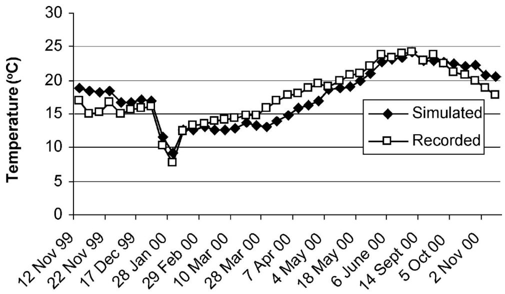
Point of measurement	Number of measurements	Mean relative error (%)	No. of measurements with relative error (<5%) (in percentage)	No. of measurements with relative error (>5%) (in percentage)
Surface	41	8.74	16 (47%)	25 (53)
1 m deep	41	10.62	10 (24.4%)	31 (75.6)
2 m deep	41	8.88	15 (36.5%)	26 (63.5)
Outlet	41	9.12	16 (39%)	25 (61%)
Overall	164	9.34	57 (34.7%)	107 (65.3%)



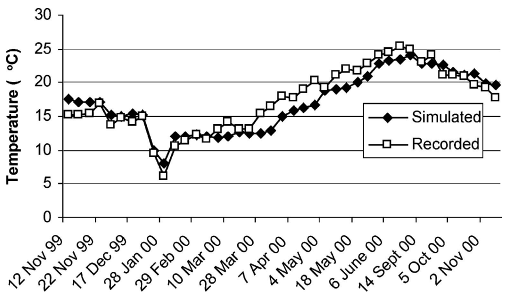
(a)



(b)



(c)



(d)

Figure 7. (a) Simulated vs. recorded temperature data at the surface (Point 1; Figure 6) of the anaerobic pond; (b) Simulated vs. recorded temperature data at 1 m depth (Point 2; Figure 6) in the anaerobic pond; (c) Simulated vs. recorded temperature data at 2 m depth (Point 3; Figure 6) in the anaerobic pond; (d) Simulated vs. recorded temperature data at the outlet (Point 4; Figure 6) of the anaerobic pond.

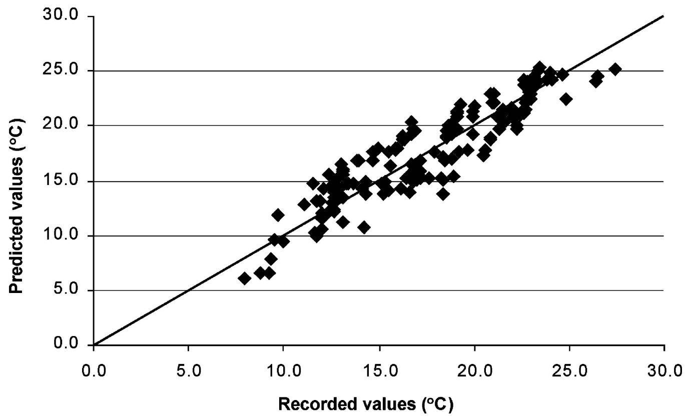


Figure 8. Correlation between predicted and recorded temperature values ($n = 164$).

spring–summer time. Incorporating a seasonal coefficient in the model, in a future re-calibration process, may possibly eliminate this element.

The mean temperature difference between simulation and experiment, at the points located on the surface, at a depth of 1 m, 2 m and at the outlet, was 1.3 °C, 1.7 °C, 1.5 °C and 1.5 °C, respectively, all of which may be deemed insignificant.

Figure 8 illustrates the correlation between temperature data pairs of observed and simulated values. The correlation coefficient between simulated and recorded temperature data at the points located on the surface, at a depth of 1 m, 2 m and at the outlet was, 0.94, 0.88, 0.90 and 0.92, respectively. The overall correlation coefficient of all temperature data sets was 0.91.

Comparison results indicate that the temperature prediction of the covered anaerobic pond was realistic, proving satisfactory model accuracy and quality.

6. Model Results

After successfully completing the anaerobic pond model validation stage, the hydraulic flow and temperature pattern of the simulating model flow field, is presented.

6.1. Hydrodynamic pattern

The hydrodynamic field, during wastewater inflow, of the simulation performed on the anaerobic pond is shown in Figure 9, which represents an instant velocity vector plot. The velocity flow field ranged from 0.001 m/s to 0.73 m/s, with prevalent velocities (98% of the total number of geometric cells) between 0.001 m/s and 0.06 m/s. The average velocity of the pond volume and the outlet structure was equal to 0.02 m/s and 0.038 m/s, respectively.

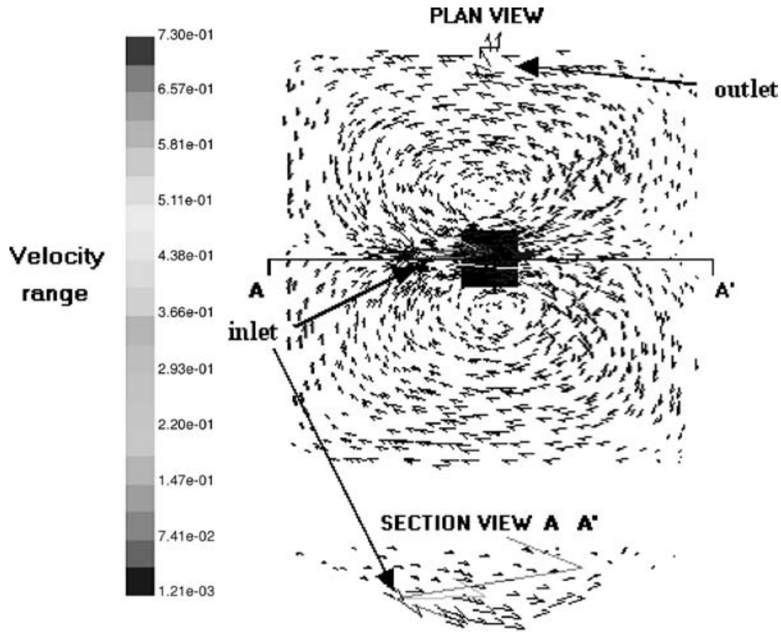


Figure 9. Speed vector plan and section view of the interior of the anaerobic pond during sewage inflow.

The plan and section velocity vector interior view reveal that the wastewater, after entering the pond with a relatively high velocity, moves along the floor structure until it reaches the opposite wall, from where it moves up to the surface. A twin recirculation flow pattern appears in the bulk of the pond. Stagnant regions are positioned mainly at the corners and surface of the pond. Higher velocity magnitude is located at the base, at the surface sides of the pond and at the centre of the surface.

6.2. Temperature pattern

The instant temperature of the whole volume of the simulated pond was obtained every 12 h out of the 9504 h of pond simulation. Thus a total of 792 temperature values for the whole simulating period were recorded. Temperature recording was not done more frequently due to the fact that the pond temperature variations throughout the day were insignificant. It should also be stated that the post-processing utility of the CFD software is capable of reporting temperature (as well as other flow field variables) averaged on the whole fluid domain of the model at a particular moment in the simulation period. The volume-average temperature of the anaerobic pond was used in this study rather than the temperature report of the pond outlet point, since the former represents more accurately the temperature status of the pond.

Figure 10 illustrates the instant temperature variation of the whole volume of the simulated anaerobic pond throughout the simulating year, clearly indicating the

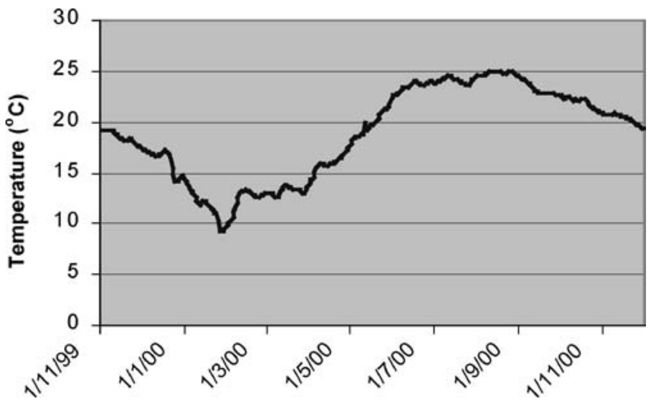


Figure 10. Simulated anaerobic pond temperature fluctuation during the experimental period (n = 792).

temperature decline until January 2000 and temperature rise until August 2000. The minimum and maximum instant temperature was 9.2 °C (during January 2000) and 25.1 °C (during August 2000), respectively.

Table V presents the pond volume temperature per month, together with the monthly average influent wastewater temperature. The average temperature of the simulated pond was 18.9 °C and that of the influent wastewater was 19.6 °C, having a temperature difference of 0.7 °C.

Although annual average temperature difference between the influent wastewater and that of the pond does not seem significant (i.e. 0.7 °C), on a monthly basis these temperature differences broaden up to 2.2 °C (during May 2000). Apart from January 2000 and September 2000, when the simulated pond achieved a temperature gain of 0.2 °C and 0.4 °C, respectively, during the rest of the experimental period, the pond temperature was less than that of the incoming wastewater, indicating heat losses. According to Table V, higher differences between the pond wastewater mass and influent wastewater temperature were recorded in spring and early summer, than in winter.

In addition, 74% of the instant volume-average pond temperatures obtained by simulation were above 15 °C, suggesting that for most of the time during the simulating period (approximately 290 days), adequate temperature conditions for anaerobic decomposition existed in the pond.

Heat flux through the wall zones of the simulated anaerobic pond, i.e. top cover, sidewalls and floor, was evaluated during its operation. In 65% of the heat flux recordings, 48% of pond heat loss was through the top cover, 50% through the sidewalls and the remainder through the floor. In 16% of the recordings, the pond system lost heat only through the sidewalls and in the remaining 16% of the heat flux recordings, the sidewalls and the pond floor were responsible for 81% and 19%, respectively, of the total heat loss of the pond. All in all, the simulated anaerobic

TABLE V

Simulating influent and pond wastewater temperature and respective temperature differences per month

Month	Pond volume temperature (°C) (T_{pond})	Influent temperature (°C) (T_{infl})	Temperature difference (°C) ($T_{pond} - T_{infl}$)
November-99	18.5	19	−0.5
December-00	16.2	16.7	−0.5
January-00	11.7	11.5	0.2
February-00	12.3	13.7	−1.4
March-00	13.2	14.1	−0.9
April-00	15.9	17.8	−1.9
May-00	19.8	22	−2.2
June-00	23.5	24.4	−0.9
July-00	24.1	24.4	−0.3
August-00	24.8	25	−0.2
September-00	23.2	22.8	0.4
October-00	21.9	22	−0.1
November-00	20.3	20.6	−0.3
Average	18.9	19.6	−0.7

pond lost heat mainly through the sidewalls, since, for most of the time, the soil temperature was lower than that of the pond wastewater.

The validated 3D thermal model developed, can be used as a simulating tool to investigate the temperature influence of a number of design modifications applied to the covered anaerobic pond model under similar boundary conditions – in preparation period. Average pond temperature may increase either by reducing the heat losses of the pond, through walls, roof and floor, or raising the temperature of the feed wastewater entering the digester. The temperature of each modified anaerobic pond, should be compared to the simulated floating covered anaerobic pond (‘control’ pond), the results of which are presented above. Any significant increase in the mean temperature of the modified anaerobic ponds will positively affect the organic removal performance of the pond.

In addition, by incorporating into the thermal model wastewater quality transport and basic biochemical reaction mechanisms of the anaerobic decomposition process, the COD of the pond content can be predicted. Such a complete anaerobic pond model—in the preparation period—can be used, to predict the impact of various design modifications (change in geometry and/or inlet-outlet arrangements, raising the mean pond temperature, etc.) on the effluent COD of the anaerobic pond.

7. Conclusions

The FLUENT CFD software package was used to develop an unsteady state laminar flow model of a full-scale covered anaerobic pond treating raw sewage. The temperature pattern of the anaerobic pond was successfully modeled. The relative error (%) and correlation coefficient between simulated and recorded temperature data at the points located on the surface, at a depth 1 m, 2 m and at the outlet, was 8.74%, 10.62%, 9.12% and 8.88%, and 0.94, 0.88, 0.90 and 0.92, respectively. Overall, numerical modelling achieved a reliable prediction of the thermal pattern of the pond.

The validated CFD model developed can be used, either in the design or operational phase, to assess the impact of different pond design scenarios (different type of constructive material, cover insulation, introducing heat-exchanger supplied by solar panels, etc.) on the average pond temperature. The average temperature of each modified anaerobic pond, should be compared to that of the simulated floating covered anaerobic pond during the experimental period examined, in order to find the optimum scenario. The average temperature of the simulated anaerobic pond was 18.9 °C, meaning that for 290 days of the experimental year, adequate temperature conditions for anaerobic decomposition existed in the anaerobic pond. Pond wastewater temperature increase will positively affect the organic removal performance of the pond.

A complete anaerobic pond model may also include the wastewater quality transport and biochemical reaction mechanism of the anaerobic decomposition process. Commercial CFD software, can model such processes using reacting flow models which can be developed to suit biologically reacting systems. The thermal model presented predicts, sufficiently accurately, the temperature of the anaerobic pond, for the purpose of reaction flow modeling. A CFD model predicting the COD of the wastewater content of the pond is being developed at present, extending the possibilities of the thermal model presented in this paper. Such a validated anaerobic bioprocess (COD) model will allow to reliably examine the impact of temperature variation, different pond geometry and other design arrangements, on the anaerobic pond treatment efficiency, aiming at its performance improvement.

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