Computational Fluid Dynamics Modelling of Baffled Waste Stabilization Ponds

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

Current design procedures for waste stabilization ponds do not take into account (i) hydraulic short-circuiting and stagnation that reduce their treatment efficiency; (ii) the improved treatment efficiency and the hydraulic performance that is initiated when baffles of various configurations are fitted in the pond; and (iii) the effects of wind velocity and thermo-stratification.

Computational fluid dynamics (CFD) is an innovative design approach that overcomes the limitations of classic and modern pond design methods. CFD is used as a reactor model to assess realistically the treatment efficiency and the hydraulic performance of waste stabilization ponds under the effects of short-circuiting and stagnations, baffles, wind velocity and thermo-stratification. Validation of the CFD model was based on experimental data of *E. coli* numbers, BOD_5 concentration and tracer experiments that were obtained from the unbaffled and baffled pilot-scale primary facultative ponds at Esholt, Bradford.

The results of *E. coli* numbers and the hydraulic performance of the CFD model of the standard facultative pond showed that the 70% pond-width baffles do not *always* improve the pond performance to the extent previously reported. *E. coli* removal and the hydraulic performance in waste stabilization ponds with the 70% pond-width baffles diminished in situations where the width of flow channel in baffle compartments was less than that at the baffle-opening (i.e., less than 30% pond-width) due to the initiation of the significant hydraulic short-circuiting. However, the most effective baffle length that gave the maximum pond performance was the one (i.e., 82% pond-width in the standard pond tested) that formed uniform flow channel width in baffle compartments and at baffle openings as this created a ‘very strong’ plug flow pattern. The CFD model showed that wind effects can affect significantly the pond performance depending on the prevailing wind direction with respect to the wastewater flow in the pond. The wind speed that blows in the same direction as the wastewater flow reduced the pond performance while that in the opposite direction of the wastewater flow improved the pond performance.

The experimental data and numerical results from the CFD analysis showed that there was insignificant difference in the treatment performance of the pilot-scale primary facultative pond when isothermal and thermo-stratification conditions developed in the pond. The experimental data showed that the treatment performance of waste stabilization ponds could be improved significantly by installing the 70% width-baffles across the longitudinal axis of the pond at a uniform separation.

The 3D-CFD model satisfactorily predicted the treatment performance of the three pilot-scale primary facultative ponds that were operated with and without baffles. The significance of these CFD model results is that regulators and designers can use CFD confidently both as a reactor model and as a hydraulic tool to assess realistically the treatment efficiency of waste stabilization ponds under the effects of baffles, thermo-stratification, wind and the hydraulic short-circuiting. The results of the baffled pilot-scale primary facultative ponds show that baffles can reduce significantly *E. coli* concentrations and other wastewater pollutants to achieve the required level of pathogen reduction for either restricted or unrestricted crop irrigation, thus obviating the need for maturation ponds and so minimizing the land area requirements of waste stabilization pond systems.

In memory of my father and my sister, Joseph Banda and Dorrah Banda. I know that they would have been truly pleased with this achievement. This work is dedicated to my wife, Hilda, and my daughter, Annabelle.

Table of contents

List of Tables

List of Figures

Abbreviations and Symbols

APHA	American Public Health Association
A_f	area of facultative pond
BOD	biochemical oxygen demand for 5 days
c	tracer concentration
CFD	computational fluid dynamics
COD	chemical oxygen demand
C_D	drag coefficient
Cv	specific heat capacity
cv	volume of a cell
d	dispersion number
D_f	depth of facultative pond
D	coefficient of longitudinal dispersion
e	net evaporation
E. coli	*Escherichia coli*
H_2S	hydrogen sulphide gas
i	internal energy
k	thermal conductivity
k-e	kinetic and dissipation energy model
$K_{1(T)}$	first-order rate constant removal of the pollutant at temperature T
$K_{1(20)}$	first-order rate constant removal of the pollutant at temperature 20^{o}C
$K_{BOD\,P}$	BOD removal constant rate in the plug flow pond model
$K_{BOD\,D}$	BOD removal constant rate in the dispersed flow pond model
L_e	effluent BOD_5 concentration
L_i	influent BOD_5 concentration
l	length of the flow path
L	pond length
L_o	baffle opening
n	number of maturation ponds
N_i	influent *E. coli* count per 100 ml
N_e	effluent *E. coli* count per 100 ml

N_{faces}	number of faces in a cell
p	pressure
pH	activity of hydrogen ions = $\log_{10}$(hydrogen ion concentrations)
Q,	mean design wastewater flow
s^2	variance of the residence time distribution
QUICK	quadratic upstream interpolation for convective kinetics
R^2	coefficient of correlation
S_m	momentum source term
S_i	energy source term
$S\phi$	source term of scalar variable ϕ
SO_4	sulphate
SS	suspended solids
T	temperature
t	time taken by tracer from the inlet to outlet
$\bar{t}$	mean hydraulic retention time obtained from tracer experiments
TKN	total Kjeldahl nitrogen
USA	United States of America
USD	United States Dollar
UDF	user defined function
U	velocity vector
u, v, w	velocity in x, y and z directions respectively
U_{10}	wind velocity at 10 m elevation above the pond surface
W	length of the pond, baffle spacing, pond width
WHO	World Health Organization
WSP	waste stabilization ponds
θ	theoretical hydraulic retention time
λ_s	surface BOD loading
λ_v	volumetric organic BOD loading rate
t	Shear stress due to wind velocity
ρ_a	density of air
°C	degree Celsius
∞	infinity
ρ	density of wastewater

$\partial x, \partial y, \partial z$	differential change in distance
∂t	differential change in time
μ	dynamic viscosity
Φ	energy dissipation
ϕ	scalar variable
2D	two dimensions
3D	three dimensions