

# **Computational Fluid Dynamics Modelling of Baffled Waste Stabilization Ponds**

**Chimwemwe Gawasiri Banda**

Submitted in accordance with the requirements for the degree of  
**Doctor of Philosophy**

School of Civil Engineering  
University of Leeds

May 2007

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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## **Acknowledgments**

Over the three years that I have worked on this thesis, I have received help, assistance and guidance from a number of people. Of these, I will only be able to mention a few. My supervisors, Professor Duncan Mara and Dr. Andrew Sleigh must be first in these acknowledgments. Professor Duncan Mara provided excellent guidance and advice on the performance of waste stabilization ponds, while Dr. Andrew Sleigh was very supportive on the CFD models of waste stabilization ponds that were undertaken. Thank you, Duncan and Andrew, for the high standard you set for the thesis. Without your support and advice, this thesis could not have been produced the way it is. Professor Duncan Mara and Dr. Andrew Sleigh deserve special thanks for believing in my potential that I could do the research work successfully. This has been a source of strength and encouragement in carrying out this thesis.

Dr. Catherine Noakes should also be given credit for the help and guidance she provided in running FLUENT software.

I also wish to express my appreciation to the structural engineering technicians of the School of Civil Engineering for the support they provided during the construction of baffles in the pilot-scale primary facultative ponds. In addition, I am thankful to the public health engineering technicians for their guidance of carrying out various experiments in the laboratory. I am also thankful to the postgraduate research staff of the School of Civil Engineering for their administration work towards the research work. Let me also thank my fellow PhD students, especially Michelle Johnson, Eleanor van der Linde and Miller Carmargo Valero for their encouragement during times when the research work was difficult and demanding.

I am very grateful to my sponsors, the Overseas Research Scheme Scholarship and the University of Leeds for their financial support that enabled my study and stay in England. Finally, let me thank my family in Leeds who have been the source of comfort whenever I felt weak and discouraged due to pressure of the research work. I am grateful to my wife, Hilda, who gave me encouragement and support during the three-year period of the PhD programme.

## 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<sub>5</sub> 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.*

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## 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
$C_v$	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
<i>E. coli</i>	<i>Escherichia coli</i>
H <sub>2</sub> S	hydrogen sulphide gas
$i$	internal energy
$k$	thermal conductivity
k-e	kinetic and dissipation energy model
$K_{I(T)}$	first-order rate constant removal of the pollutant at temperature T
$K_{I(20)}$	first-order rate constant removal of the pollutant at temperature 20°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 <sub>5</sub> concentration
$L_i$	influent BOD <sub>5</sub> concentration
$l$	length of the flow path
$L$	pond length
$L_o$	baffle opening
$n$	number of maturation ponds
$N_i$	influent <i>E. coli</i> count per 100 ml
$N_e$	effluent <i>E. coli</i> count per 100 ml



$N_{\text{faces}}$	number of faces in a cell
$p$	pressure
$\text{pH}$	activity of hydrogen ions = $\log_{10}(\text{hydrogen ion concentrations})$
$Q$ ,	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 $\phi$
$\text{SO}_4$	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
$\theta$	theoretical hydraulic retention time
$\lambda_s$	surface BOD loading
$\lambda_v$	volumetric organic BOD loading rate
$\tau$	Shear stress due to wind velocity
$\rho_a$	density of air
$^\circ\text{C}$	degree Celsius
$\infty$	infinity
$\rho$	density of wastewater

$\partial x, \partial y, \partial z$	differential change in distance
$\partial t$	differential change in time
$\mu$	dynamic viscosity
$\Phi$	energy dissipation
$\phi$	scalar variable
2D	two dimensions
3D	three dimensions