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Estimation of Residence Time Distribution and Solid Wastes Transportation of an Orbal Biological System using Computational Fluid Dynamics (CFD)

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ABSTRACT

There is a current emphasis on minimising energy consumption in the global wastewater industry which requires the development of more efficient ways of operating treatment processes. Treatment processes must achieve high effluent quality to satisfy discharge requirements while also taking into account factors such as minimising cost, space, as well as the energy which is used. This research focuses on modelling the relationship between biochemical oxygen demand (BOD) reduction and the power consumption of a common energy-intensive biological treatment process, the oxidation ditch. Specifically, the research considers the Orbal Biological System (OBS) oxidation ditch process that is commonly used in Malaysia, with the Bayan Baru Sewage Treatment Plant used as a case study. The first step of the research plan was to develop a preliminary process model based on established fundamental principles of biochemical reactions in wastewater, to represent the relationship between BOD, oxygen utilization rate (OUR), and power consumption. This model makes simplifying assumptions such as constant hydraulic residence time (HRT) and oxygen (O_2) concentration throughout each of the three channels of the OBS. A more complex model of the OBS using computational fluid dynamics (CFD) modelling was then developed to take this investigation further. CFD analysis was chosen because it can take into account the distribution of HRT throughout the channels. The modelling was calibrated and validated against experimental data gathered onsite. The major outcome of the research will be an improved understanding of the energy consumption (directly related to oxygen transfer rate) required for BOD reduction in the oxidation ditch process and the development of a tool which will aid in enhancing the operation of this oxidation ditch process to achieve acceptable effluent water quality with minimised power consumption.

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INTRODUCTION

Over the last fifty years, a variety of methods of wastewater treatment systems have been developed in order to improve effluent quality. Lately, the aims of wastewater treatment have been expanded to become more comprehensive in terms of environmental, social and economical aspects (Gray, N.F., 2004). Computational Fluid Dynamics (CFD) has recently been recognized as an efficient and useful means to optimize the design and the operation of processes in wastewater treatment plants (Oda, T., 2006). CFD is a computer-based mathematical modelling tool that incorporates the solution of the fundamental equations of fluid flow, the Navier-Stokes equations, and other allied equations (Reddy, S., 2003). Based on the literature reviewed, several scholars have found out that CFD provides many advantages compared with experimental fluid dynamics (Brouckaert, C.J. and C.A. Buckley, 1999). Most methods used to design and operate water and wastewater treatment plants employ heuristic and empirical techniques (Brannock *et al*. 2002). CFD makes it possible to model processes that involve fluid flow from a fundamental level. Flow modelling provides insights into the fluid flow problems that would be too expensive or costly by experimental techniques alone. CFD has proven to complement physical modelling and other experimental techniques by providing a detailed look into the fluid flow problems, including complex physical processes such as turbulence, chemical reactions, heat and mass transfer, and multiphase flows (Fluent, 2007).

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Australian Journal of Basic and Applied Sciences, 9(3) Special 2015, Pages: 19-24

Biological treatment aims to coagulate and remove nonsettleable colloidal solids and to stabilize the organic content of wastewater (Tchobanoglous, G. and F.L. Burton, 1991). In biological treatment processes, wastewater is brought into contact with microorganisms which degrade carbon-based and nitrogen-based pollutants (Sardeing, R., 2005). Traditional biological treatment processes have undergone significant changes and improvements since their introduction in the late nineteenth century and this has led to greater treatment efficiency. Various research activities have been conducted in order to enhance processes and there has also been a growth of new biological wastewater treatment technologies (Qasim, S.R., 1999). There are several wastewater treatment processes that may be chosen to meet requirements of effluent quality, land availability, construction and running costs, mechanization level and operational simplicity (Sperling, M.V. and C.A.D. Chernicharo, 2005) including the activated sludge process, aerated lagoons, trickling filters, rotating biological contactors, stabilization ponds and oxidation ditches.

The activated sludge has been widely used and recognized as an efficient biological treatment process for carbonaceous and nitrogenous oxygen demand removal. The oxidation ditch, a modification of the activated sludge process, is normally operated as an extended aeration process and often referred to by the manufacturer's trade name such as Pasveer, Orbal or Carrousel. Even though they have different names, they have the same underlying principles. The two main variations are the ditch configuration and the type of aeration device. Sewage is treated in large round or oval channels with aeration and mixing provided by devices such as disc aerators, jet aerators, and brush rotor mechanical surface aerator (Barnes 1983).

2. Objectives:

The Orbal Biological System (OBS) was originally designed to provide a better approach of the biological treatment process with more process flexibility, efficiency, reliability and simplicity (Technologies, S.W., 2007). However, sewage treatment plants which have used the OBS face operational challenges associated with high energy consumption and occasionally also low treatment efficiency. The energy consumption of OBS operation is mainly from the power requirements for the aeration and mixing processes. Power consumption is associated with the amount of oxygen transferred into the channels by the aeration devices. Therefore, it is this energy utilisation of the OBS through its aeration and mixing processes that must be targeted for minimisation. The most important goal of wastewater treatment is to comply with effluent water quality regulations and discharge permits, but it does not mean that energy has to be over-supplied just to achieve that goal. There must be a balance between complying with effluent quality regulations and minimising energy consumption (and therefore carbon footprint) by optimising process operation wherever possible.

MATERIALS AND METHODS

CFD simulation involves at least five major stages. The CFD software used in this research is FLUENT (Fluent, Inc., Lebanon, USA). The model development is initialised with the application of GAMBIT (a sub-component of FLUENT software) for the purpose of building the geometry model (similar to CAD). The geometry model of the OBS has been created based on the design layout and dimensions provided by IWK. Two dimensional (2D) CFD modelling has been chosen due to the small depth dimension relative to length and width, and the desire to reduce computational time (3D models are computationally intensive). After the development of 2D geometrical model was completed, the meshing or grid generation procedure was started. Meshing or grid generation is an important step of CFD modelling. The accuracy of the outputs given by CFD modelling is mostly dependent on the meshing sizes. Finer meshing produces the most accurate results. However, in order to run a model with fine grids, a very high computer capacity is needed, so the desired accuracy level and the available computer capacity have to be balanced. The meshing procedure is somewhat trial and error and continues until the produced grids achieve the acceptable accuracy level and satisfy the available computer capacity.

3.1 Experimental Works:

Sampling and experimental works was conducted in order to calibrate and validate the CFD model. Model validation was conducted to assess if the calibrated model correctly describes the real system. Principally, the performance of the models was assessed based on the difference between CFD simulated values and observed system variables. Standard laboratory methods was conducted to determine the BOD and various forms of nitrogen (including TKN, ammonia and nitrate) in wastewater samples, which are the variables included in the mathematical models selected. Samples were collected at certain points which have already been identified within the channels to give an indication of the incoming and outgoing water quality parameters for each channel.

Australian Journal of Basic and Applied Sciences, 9(3) Special 2015, Pages: 19-24

RESULTS AND DISCUSSION

CFD model was developed to understand the flow of wastewater in each channel. CFD models were set up for two different cases as shown in Figure 1. One of the cases involved the development of basic CFD model of OBS without incorporating the aeration discs. The velocity values given by the model were compared to the sampling data obtained from the experimental observation onsite. The result showed that the velocity values given by the models were much lower than the real values observed onsite. The basic CFD model gave a justification of the need of an improved model which can increase the velocity values to closely match the observation values. With the intention of providing a better model, CFD simulation was set with some improvement feature.

Another CFD model was set up by incorporating the number of shafts operated in the OBS. The main purpose of setting up the second case was to provide a clearer picture of the impact of using and not using the mixers. Identifying the significance of the mixers will give a better understanding on how to optimize the OBS. The aeration discs were defined as fans without any pressure drop value in two dimension model. The results of the simulation demonstrate an increment in the velocity values of outer channel, but still in the middle and especially inner channel, the velocity values are very low. Even after changing the fan direction, the model still did not describe the real flow patterns as observed onsite. The results have guide to development of the next model with some improvements in term of the pressure drop values.

Some hypothetical values of pressure drop were defined and tested. The best combination of pressure values was selected for further analysis. The combination of 30 Pa pressure drop value for outer and middle channel and 150 Pa for inner channel gave the velocity values that well matched the observed values. This combination also produced the right flow direction in every channel, even in the critical part of the inner channel, where the flow almost loses its momentum. This ensures flow continuity inside the OBS system.

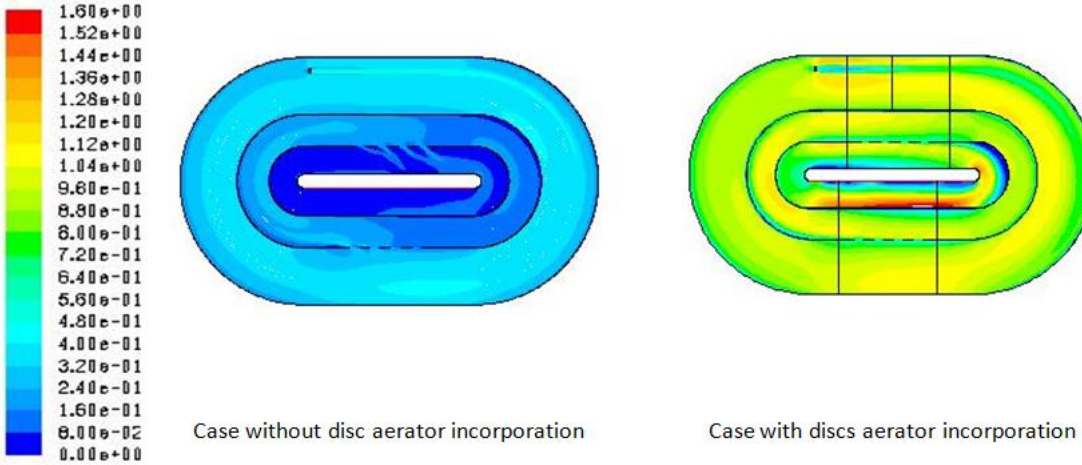

Fig. 1: Comparison of velocity magnitudes obtained from different cases of CFD model.

4.1 Hydraulic Residence Times Given by CFD Model:

HRT values were estimated from the developed CFD model. This was made possible by injecting particles which had similar properties as that of water into the OBS simulation system. Around 5000 particles were tracked to determine the HRT values for each channel. According to previous researchers, a significant residence time distribution can be achieved on condition that enough particles trajectories are calculated. (Le Moullec, Potier *et al*. 2008). Le Moullec and his colleagues had performed 4000 particles tracking. Number of particles being tracked is subjected to computer memory limitations and time required to track those particles is not prohibitively longer. The maximum value of HRT for the case without mixer was 378 minutes and the average value of HRT for the same case was 110 minutes. The HRT values were estimated for case without mixers to find the time required for water to exit OBS under natural flow condition (without any influence from the mixers). By doing so, we can evaluate the influence of the mixers having in each channel. The maximum value of HRT for the case with the incorporation of the mixers was 210 minutes and the average HRT value for this case was 53 minutes. Table 1 shows the values of maximum and average HRT obtained for the individual channel when the mixers are incorporated.

Table 1: Summary of HRT values based on CFD model.

Channel	Maximum HRT value (minutes)	Average HRT value (minutes)
Outer	146	11
Middle	44	25
Inner	19	16

The maximum and average values as shown in Table 1 are not really practical considering the high possibility of recirculation of the wastewater in all the channels. That is why another case study involving the unsteady state of particles was injected into the system. It is first necessary to estimate the distribution of particle concentration that exits from the system. This would provide a fair idea, about the time range, during which maximum particles exit via the effluent. Therefore, in order to estimate the distribution of particles that exit the system, an unsteady cluster of particles was injected near the influent region. Around 5000 particles were injected into the outer channel which is under steady supply of water. It is necessary to define unsteady nature of the particles, in order to find the time required by the particles to trace the water channel length. Thus, every time step corresponded to 0.01 second, which means that in order for the particles to trace 1 sec, it must be subjected to at least 100 time steps. This is necessary to maintain requisite accuracy of the iteration and to avoid, subsequent iterative errors which would magnify disproportionately under higher time steps. Nevertheless, the water flow inside the channel was maintained under steady mass flow rate of 0.5 m^3/s. The case was set to auto save mode at the rate of 100 sec per case. The simulation would save the case files for every 100 seconds. Initial few cases were manually saved at the rate of 10 sec per case to keep track of the particles. Simulation was continued till the particle exit concentration did not vary on any further iteration. The whole process took about 16 days to complete, with more than 120 cases written. Each of these cases represent different time intervals and it would provide the concentration of particle that exit the system for that given time interval.

The figure 2 gives the overall estimate of RTD throughout all the channels. It shows the variation of particle concentration at the outlet with respect to time for the discrete phase model. (DPM). From the plot it is clear that, most of the particles (about 2/3rd) would exit the OBS in time interval ranging between 100 seconds to 500 seconds. On subsequent time intervals, very few particles tend to exit. Beyond 30 minutess, the amount of particles that exit the OBS has decreased substantially and only a very few particles exit the system. This can be attributed to the recirculatory motion of these particles, which tend to be trapped in an infinite loop of motion around different channels. As a consequence, the overall residence time of given mass of water entering the OBS will be much larger.

It can be inferred from this figure in the context of this OBS, the retention ability of this system is very small. About 2/3rd of the volume of water that enters the OBS would have exited the system well below 10 minutes. That means, the OBS facilitates the effective and efficient mixing of oxygen only for a short duration. Probably, it is for this reason that the water is circulated over and over again, back to the same channel having once passed through the same process. In general, for a given volume of water entering the OBS, its effectiveness is limited to less than 10 minutes. It is in this duration of 10 minutes the mixers supply the requisite amount of oxygen for which it is designed for.

As a corollary, one can determine the importance of OBS design and postulate that any design of the OBS should facilitate increased retention time inside the system. One way of doing this is to decrease the influent flow rate which in turn would decrease the velocity of flow.

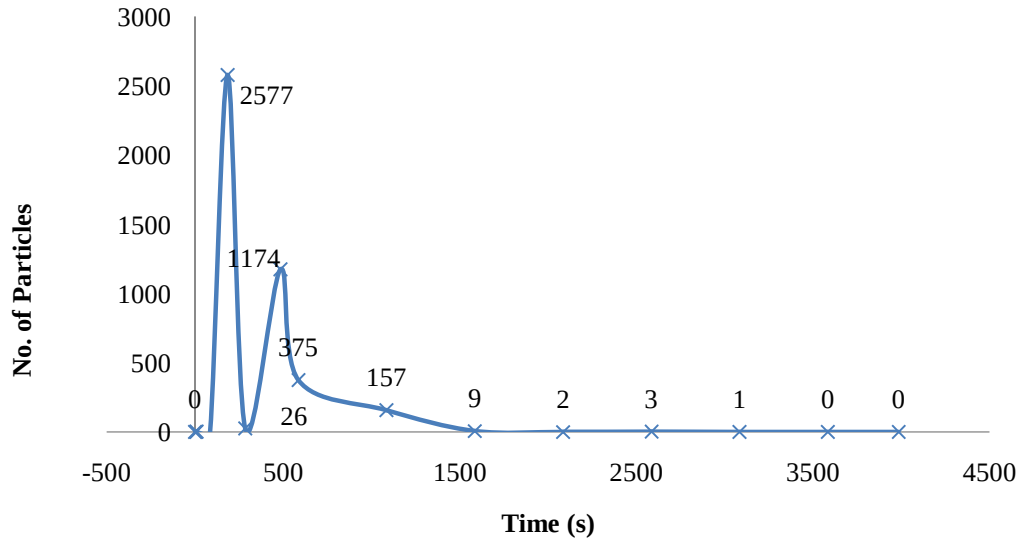

Fig. 2: Variation of particle concentration at the outlet with respect to time.

5.0 Conclusion:

The developed CFD model has been verified to represent hydraulic condition of the OBS. One of the advantages of CFD application compared to the conventional process model is its ability to provide distributions of hydraulic residence times across the channels. These values can lead to a better understanding of oxygen consumption in every channel. The distribution of residence time (RTD) can be estimated from the CFD simulation. In future, the developed CFD model will be used for further investigation of the solid wastes transportation, oxygen profiles throughout the ditch and other useful parameters such as turbulence intensity.

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Abbreviations and Nomenclatures:

BOD	biochemical oxygen demand
OBS	orbal biological system (OBS)
OUR	oxygen utilization rate
HRT	hydraulic residence time
CFD	computational fluid dynamics
S	effluent BOD5 concentration (soluble BOD) (g/ m3)
Xv	mixed liquor volatile suspended solids, MLVSS (g/ m3)
V	tank volume (m3)
Q	influent flow (m3/d)
ΔTKN	TKNinfluent- TKNeffluent (g/m3)
TKN	total kjeldahl nitrogen, equal to organic nitrogen and the ammonia nitrogen
ΔTN	TNinfluent-TNeffluent (g/m3)
TN	total nitrogen
OUR	oxygen utilization rate or also referred as oxygen requirement (kg/d)
So	influent BOD5 concentration (total BOD) (g/m3)
a	1.46-1.42Y
b	1.42fbKd
1.46	conversion factor (BODu/BOD5)
Y	yield coefficient (gVSS produced per gBOD removed) (gXv /gBOD5)
fb	fb'/ [1+(1- fb')Kd θc]
fb	biodegradable fraction of MLVSS generated in a system subjected to a sludge age θc (Xb/Xv)
fb'	biodegradable fraction of the VSS immediately after its generation in the system, that is, with θc =0.
θc	sludge age (d)
Kd	endogenous respiration coefficient (d-1)
P	power consumption in kW

OUR oxygen requirement in kg/hr
ηp in-process energy efficiency for mechanical aeration system in kg O2/ kW.hr