NUMERICAL SIMULATIONS OF AIR-WATER FLOW IN AERATION PROCESSES

By Martin Skote

Abstract: The two phase flow set up by air bubbles rising through water in a tank was investigated numerically in order to examine the effect of horizontal flow of the water on the aeration process. Separate 2D equations of mass and momentum balance for each phase of the mixture were used as they describe the physics better than a simpler single phase model.

When a horizontal flow of the water was introduced the simulations predicted that the retention time for the air bubbles in the water increased due to a decrease of the bubble induced vertical flow of the water. Above a critical horizontal velocity the induced flow was completely broken and no further increase of the retention time was possible. The critical velocity was found to be a function of the air flow injected into the water.

The results agreed with data obtained from full scale tests with measurements of the oxygenation in aeration tanks.

1. INTRODUCTION

The economy for a waste water treatment plant is greatly affected by the air flow and the number of aerators used during the aeration process. In the aerobic zone, air is injected from aerators at the bottom of the tank and while the bubbles rise through the water to the surface, oxygen is transferred from the air bubbles to the water. Experiments have shown that introducing a horizontal flow of the liquid phase in the tank can increase the oxygen transfer rate and thus reduce the need for aerators and air supply. There are difficulties in producing general rules for the dimensioning of the aeration system through measurements of the oxygenation level. It is also very expensive to set up test plants capable of obtaining sufficient data to produce dimensioning rules. A numerical simulation of the two phase flow in the aeration tanks can make this task simpler and less expensive.

The numerical simulations were made in a general purpose Navier-Stokes solver, PHOENICS, from CHAM Ltd.

2. OBJECTIVES

The aim if this work was:

- To set up a model for the two phase flow. The model should describe the physics correctly and be suited for numerical simulations.

- To explain, from the results of the simulations, the experimentally observed improvement of oxygen transfer rate when a horizontal flow of the water is introduced.

3. NUMERICAL SIMULATIONS

Numerical simulations require formulation of the governing equations together with physical assumptions and simplifications. There are two possibilities to model a two phase flow. Either the air-water mixture is treated as a single fluid, i.e. water with dispersed air, having properties depending on the concentration of air, or water and air are treated as separate fluids, i.e. a real two phase model. In the latter case, the mutual force between the phases has to be modelled from experimental data. The real two phase model was chosen because it describes the physics more accurately, and the model is based on well verified experimental data.

In the present work the two phases, water and air, are treated as inviscid and incompressible. The effects of these physical assumptions have been investigated and found to be negligible, which is explained in sec. 3.4. The flow is mainly two dimensional and one possible simplification is to neglect the movement in the third dimension and make the simulations in only two dimensions.

The equations to be solved are the conservation laws for momentum and mass for each phase (water and air). The momentum equations are coupled through a term describing the mutual force acting on each phase. Since the equations cannot be solved analytically, numerical simulations have to be conducted by performing a discretisation of space and time and treating the derivatives as differences. Space is divided into cells and time is divided into time steps. Because of limited computer capacity, the number of cells and time steps must be kept moderate. The size of the cells is much larger than the size of the bubbles and the mutual force acting between the phases is the drag on each bubble multiplied by the number of bubbles in each cell.

The numerical software program used in these simulations is PHOENICS, a general-purpose Navier-Stokes solver. It uses the method of finite volumes to solve the equations. The differential equation system is discretised as above and the algebraic equation system thus obtained is solved with an iterative method.

3.1 Conservation Equations

The conservation equations to be solved for steady state flow of the two phases water (i=1) and air (i=2) are written as:

$$\nabla\left(\rho_i \alpha_i \vec{u}_i \varphi_i\right) = S_{\varphi_i}, \qquad (1)$$

where

∇ is the Nabla-operator, in 2D: $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right)$

ρ_i is the density of phase i

α_i is the volume fraction of phase i

$\vec{u}_i$ is the velocity vector for phase i, in 2D: $\vec{u}_i = \left(u_i, v_i\right)$

φ_i determines which variable of phase i is conserved in the equation.
φ_i = velocity (u_i or v_i)$\Rightarrow$ momentum equations,
φ_i = 1 $\Rightarrow$ continuity equations (mass conservation)

S_{φ_i} is the source term for variable φ_i

If both phases are treated as inviscid (see sec. 3.4), the sources are

$$S_1 = 0$$

$$S_{u_i} = -\alpha_i \frac{\partial p}{\partial x} + F_{x_{ij}} \qquad (2)$$

$$S_{v_i} = -\alpha_i \frac{\partial p}{\partial y} - \alpha_i \rho_i g + F_{y_{ij}}$$

Where $F_{x_{ij}}$ and $F_{y_{ij}}$ are the components of the force acting on phase i from phase j, i.e. the inter phase force. p is the pressure and g is the gravity.

The conservation equations for each phase written out with these sources become:

$$\varphi_i = u_i$$

$$\frac{\partial}{\partial x}\left(\rho_i \alpha_i u_i^2\right)+\frac{\partial}{\partial y}\left(\rho_i \alpha_i u_i v_i\right)=-\alpha_i \frac{\partial p}{\partial x}+F_{x_{ij}} \tag{3}$$

$$\varphi_i = v_i$$

$$\frac{\partial}{\partial x}\left(\rho_i \alpha_i u_i v_i\right)+\frac{\partial}{\partial y}\left(\rho_i \alpha_i v_i^2\right)=-\alpha_i \frac{\partial p}{\partial y}-\alpha_i \rho_i g+F_{y_{ij}} \tag{4}$$

$$\varphi_i = 1$$

$$\frac{\partial}{\partial x}\left(\rho_i \alpha_i u_i\right)+\frac{\partial}{\partial y}\left(\rho_i \alpha_i v_i\right)=0 \tag{5}$$

and

$$\alpha_1 + \alpha_2 = 1, \tag{6}$$

The variables to be solved for are u_i ,v_i ,α_i and p .

For the two phases i =1 and i =2 there are seven equations and seven variables.

3.2 Model

The inter phase force for each cell expressed as force per cell volume is written

$$F_{x_{ij}} = C_d \frac{1}{2}\rho_1 v_{rel}\left(u_j - u_i\right)A$$

$$F_{y_{ij}} = C_d \frac{1}{2}\rho_1 v_{rel}\left(v_j - v_i\right)A \tag{7}$$

Where C_d is the drag coefficient,
v_{rel} is the relative velocity, defined as

$$v_{rel} = \left[\left(u_2 - u_1\right)^2 + \left(v_2 - v_1\right)^2\right]^{1/2} \tag{8}$$

A is the sum of the projected bubble areas per cell volume,

$$A = \frac{3}{2}\alpha_2 \frac{1}{D_p} \tag{9}$$

D_p is the particle diameter.

C_d can be written [1] as $C_d = f(\mathrm{Re}_p)$ where Re_p, the particle Reynolds number, is expressed as $\mathrm{Re}_p = \dfrac{v_{rel} D_p}{\nu}$

ν is the kinematic viscosity of water.

The function $f(\mathrm{Re}_p)$ must be produced from experimental data. Possible functions are shown in Figure 1, where C_d for bubbles in clean water, bubbles in contaminated water and solid spheres as a function of Re_p are shown.

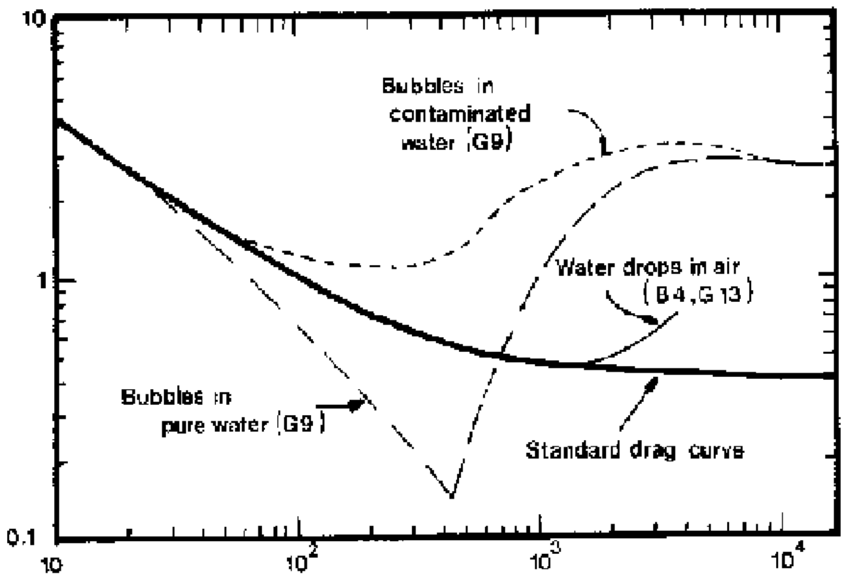

Figure 1. *Drag coefficient versus Reynolds number. From ref. [2].*

The Reynolds number for the bubbles, which have a diameter of 2 mm when they enter the water, lies in the region 400-600 depending on the degree of contamination. In this region the function $f(\mathrm{Re}_p)$ for bubbles is greatly affected by the degree of contamination. The standard drag curve for spheres is chosen as a compromise.

3.3 Boundary Conditions

The boundary conditions are specified as sources in the equations activated only at the boundaries. The equations solved in PHOENICS will therefore be, cf. (1) :

$$\nabla(\rho_i \alpha_i \vec{u}_i \varphi_i) = S_{\varphi_i} + S_{BC\varphi_i}, \tag{10}$$

where

$$S_{BC\varphi_i} = C(V - \varphi_i) \tag{11}$$

C is a coefficient and
V is the value of the variable φ_i to be specified at the boundary.

When a fixed flux boundary condition is prescribed, the coefficient is small and the value is the flux divided by the coefficient. This is done to make the source independent of φ_i .

If a fixed value is to be prescribed (e.g. the pressure at the surface), the coefficient is given a large value to make this term the dominant in the equation. A too large coefficient when giving pressure a value at the surface can make the outlet boundary (for the air) an inlet boundary. This is due to inevitable truncation errors in computers. The consequence is that air flows into the water from above the surface. This is of course not a physical process and is easily detected if the flow field is investigated, which should be done every time a new test case is run. For more information see ref. [3].

3.4 Cases Simulated

In the simulations the length of the tank was varied from 3 m to 9 m. The depth was varied from 1 m to 6 m, and the number of aerators from one to thirty. The length of the aerators was set to 0.2 m, the diameter of the circular aerators used in the experiments. The number of cells was varied from 450 to 6000, and was varied for the same case to check the convergence.

When there was no horizontal flow of the water some instability problems were detected. Instead of using the whole basin in the calculations the tank was split in the symmetry line and only one half was used. All simulations were made in two dimensions.

Simulations with viscous liquid phase showed little difference from those with viscosity set to zero. The $k-\varepsilon$ turbulence model was incorporated, but again, the differences were negligible.

The bubbles expand due to decrease in hydrostatic pressure during their rise through the water. The effect of this expansion on the terminal velocity of the bubbles is small, see ref. [2], and consequently compressibility of the air can be neglected.

4. Results

The results from the simulations indicate three distinct flow regimes.

- No horizontal flow applied, the flow field is dominated by the induced swirl flow (Figure 2).
- Horizontal flow with low velocity applied, horizontal and swirl flow are of the same order of magnitude (Figure 3).
- Horizontal flow with high velocity applied, the flow field is dominated entirely by the horizontal flow (Figure 4).

Figures 2, 3 and 4 combine the concentration of air, shown as contour lines, and the velocity of the water, shown as arrows. The view is from the side and air is injected at the bottom of the tank where the contour lines start.

Figure 2 shows the flow field in the water as air is injected. The flow of air induces a swirl flow in the water. The induced flow increases the upward velocity of the bubbles and hence decreases the time of contact between the air bubbles and water, i.e. the retention time. In Figure 3 a horizontal velocity, V_{hor}, of the water is introduced. The swirl flow is depressed and the vertical velocity of the bubbles is reduced, hence retention time is increased.

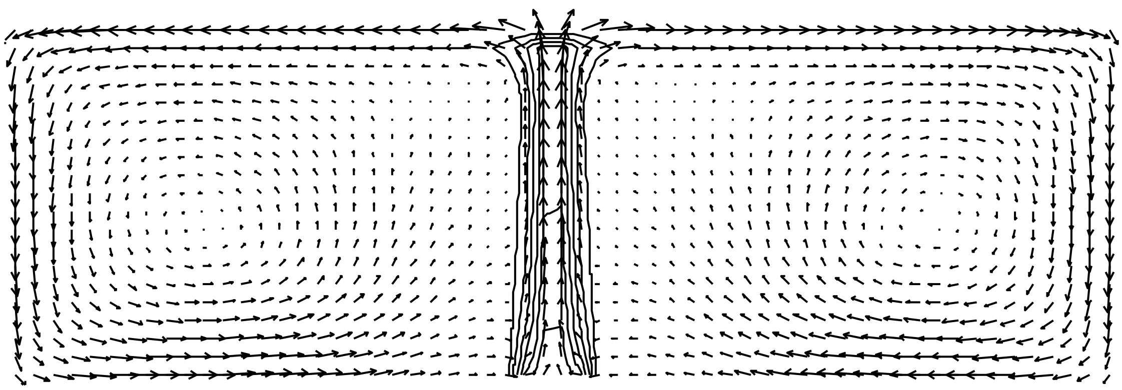

Figure 2. *Concentration contours for air and velocity vectors for water.*

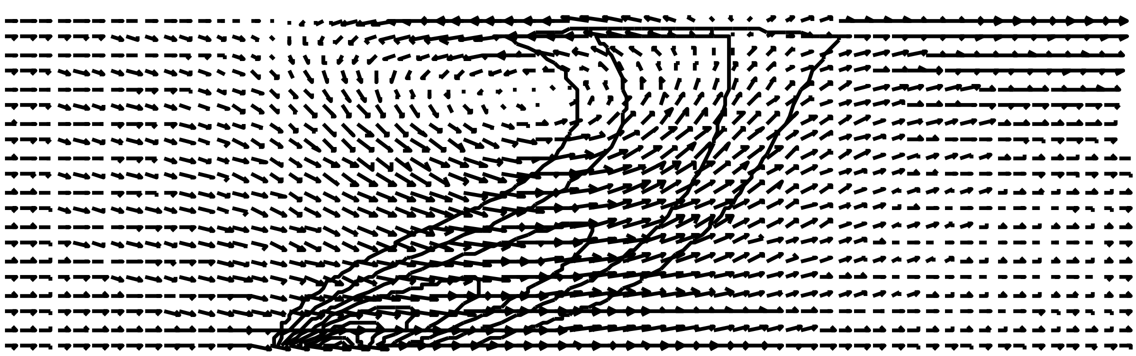

Figure 3. *Horizontal flow of the water decreases the upward velocity.* $V_{hor} = 0.1\ m/s$

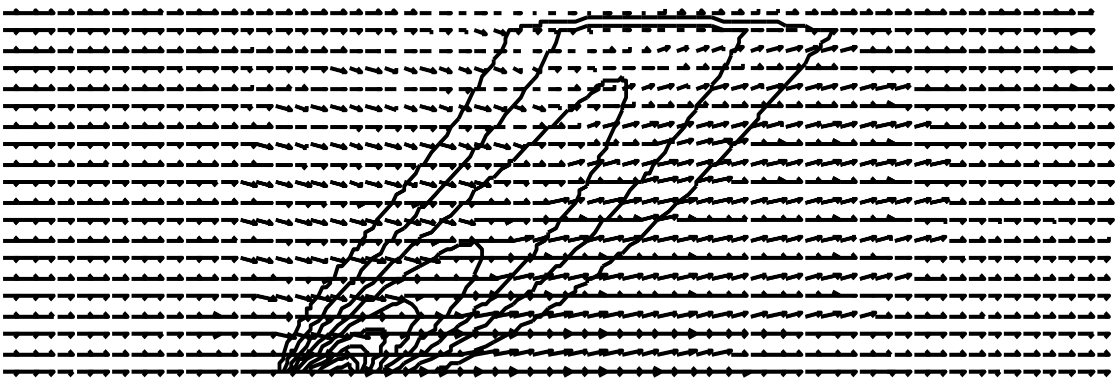

Figure 4. *At high enough horizontal velocity of the water, the induced swirl flow is broken.* V_{hor} *=0.2.*

Above a certain value of the horizontal velocity there is no further increase of the retention time. The reason for this is that the reduction of the induced swirl flow is completed. This is shown in Figure 4, where the swirl flow showed in Figures 2 and 3 has vanished. Consequently the vertical velocity of the bubbles approaches the terminal rising velocity in still water.

To quantitatively evaluate the results the retention time is used as it is directly related to the oxygenation rate, see ref. [4]. To allow comparison of different simulations, the retention time is normalised with the retention time for a single bubble rising with its terminal velocity through still water. The curve in Figure 5 shows the relative retention time versus horizontal velocity of water for the same case shown in Figures 2-4. The curve flattens out above a horizontal velocity of 0.2 m/s, i.e. when the induced swirl flow is broken as previously described and shown in Figure 4.

When simulating the flow in the tank without horizontal flow, the solution is not steady. The air plume is oscillating in the horizontal direction but this does not affect the retention time.

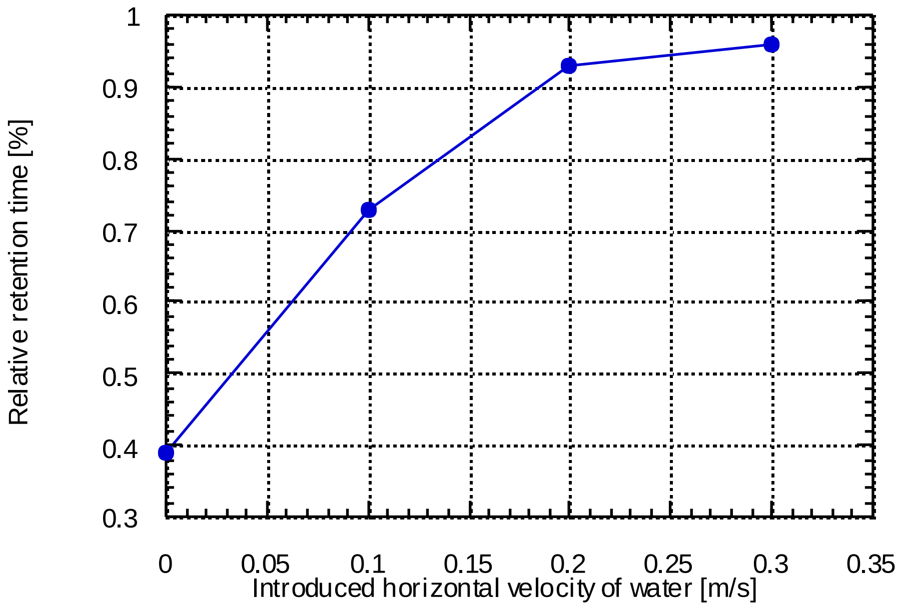

Figure 5. *Air content at four different velocities.*

In Figure 6 the results from various cases with different numbers of aerators seated in a row, with the same distance (one diameter, 0.2 m) between each other, are shown. The figures in the legend are the numbers of aerators @ air flow per aerator area [$ls^{-1}m^{-2}$]. When no horizontal flow is present, there is a larger relative retention time with many aerators with small air flow than a few with a larger air flow. As the horizontal flow increases these differences diminish. The short distance between the aerators explains why the influence of the horizontal flow on the retention time is independent of the number of aerators. The induced water flow between the aerators is weak and easily broken by the horizontal flow. It is only the swirl flow at both ends of the aerator row that affect the bubbles rising velocity.

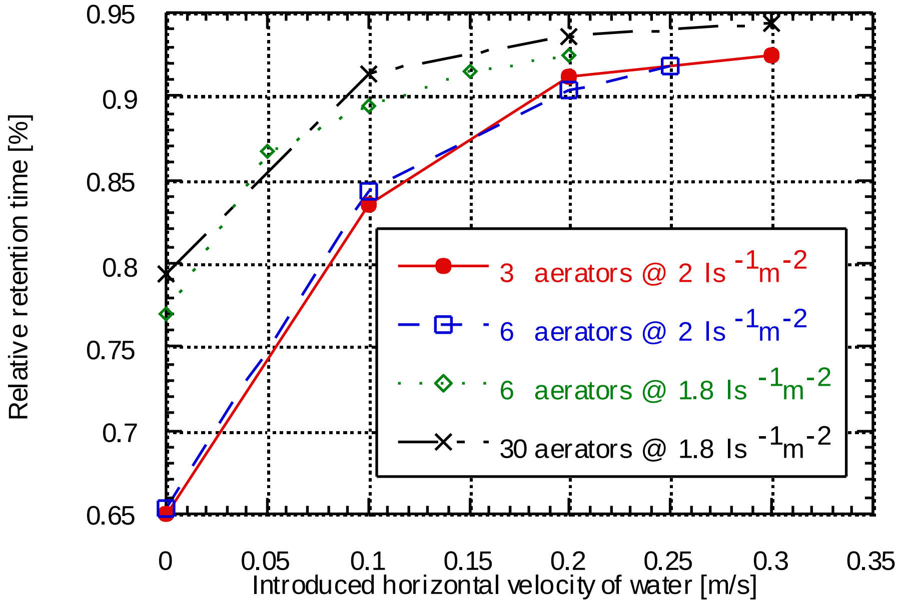

Figure 6. *Curves for different numbers of aerators and air flow.*

Figure 7 shows results for different depths of the tank. The deeper the tank, the lower the relative retention time, when no horizontal flow is present. But as above the discrepancies diminish with increased horizontal velocity. In a deeper tank, more vertical flow of the water is induced, but also more horizontal momentum is introduced, and the same value of the horizontal velocity is required to break the induced flow.

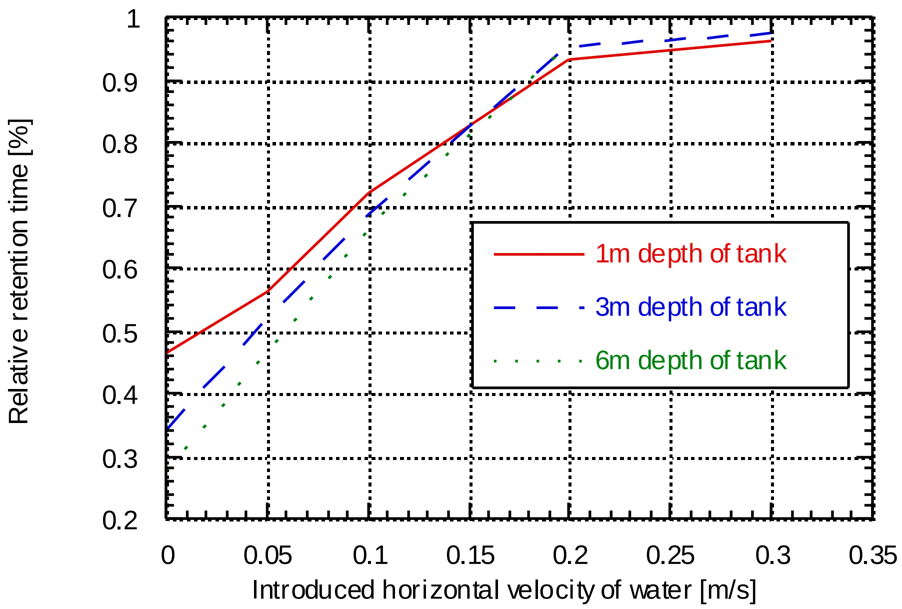

Figure 7. *Curves for different depths of tank. All curves are for 1 aerator @ 6 ls^{-1}m^{-2}.*

Note that the curves in Figures 6 and 7 have a distinct ‘knee’ at a horizontal velocity between 0.1 m/s and 0.2 m/s that seems to depend on the air flow per diffuser.

When varying the air flow for the aerators the discrepancies also vanish as above but now at different values of the horizontal velocity, see Figure 8. The higher the air flow per aerator the stronger the horizontal flow that must be introduced. The ‘knee’ in the curves moves to higher velocities. This increase in the required horizontal flow is explained by that the higher air flow creates a stronger induced flow of the water, and therefore a higher horizontal velocity is required to break it up.

Figure 9 shows the same curves as in Figure 8, except that the horizontal velocity is scaled with the buoyancy flux, see ref. [7]. In the scaled variable, Q is the air flow per aerator per meter [ls^{-1}m^{-1}] and g is gravity [ms^{-2}].

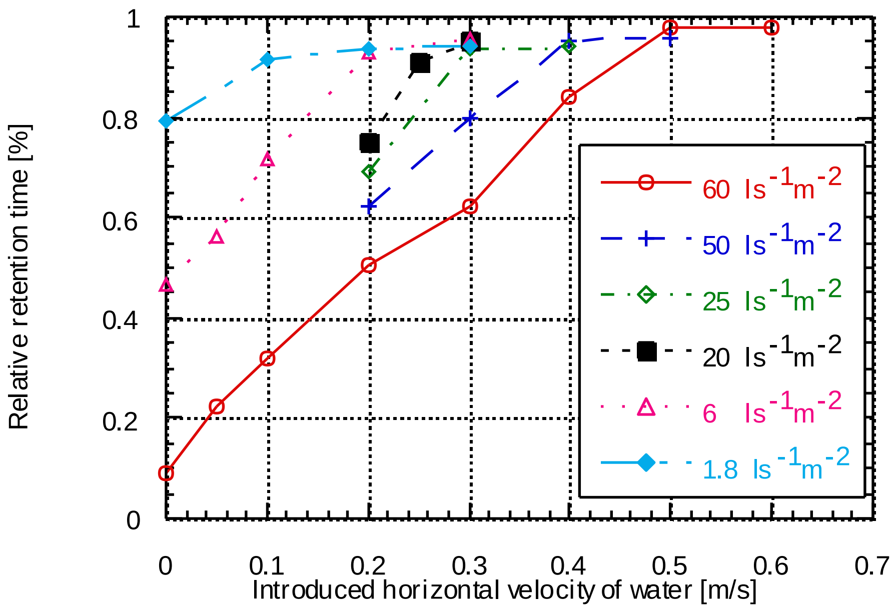

Figure 8. *The curves for higher air flow flatten out at higher horizontal flow.*

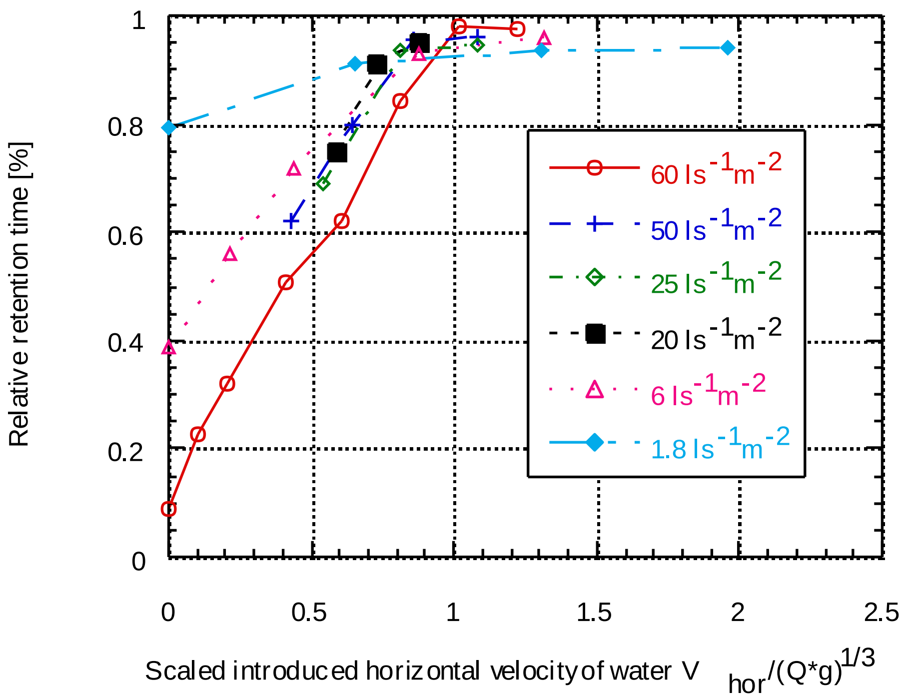

Figure 9. *The relative retention time versus the scaled introduced velocity.*

5. Comparison with experiments

Figure 10 shows oxygen transfer rate (OTR) measurements. The OTR is plotted as a function of the horizontal flow. The measurements have been made by Cemagref in France, see ref. [6]. They used 720 aerators in an annular 'race-track' tank. The values on the y-axis are not directly comparable with those from the simulations since the simulations show the retention time for the air in the tank and not the amount of oxygen transferred. The trends in the curves are however the same, and the conclusion is that the increase in oxygen transfer rate is due to the increase of the retention time for the air bubbles in the water.

Comparing experiments and simulations shows that the 'knee' in the curves occurs at higher velocities in the experiments . This may be explained by the fact that the simulations are made in 2D. The induced swirl flow in the water is in three dimensions and thus 'more difficult' for the horizontal flow to break.

It may be argued that it is not only the retention time that determines the oxygenation effectiveness, but also the mixing of water and air. However, the amount of dissolved oxygen in the water is so low that the mixing has no influence on the rate of oxygenation, see ref. [5].

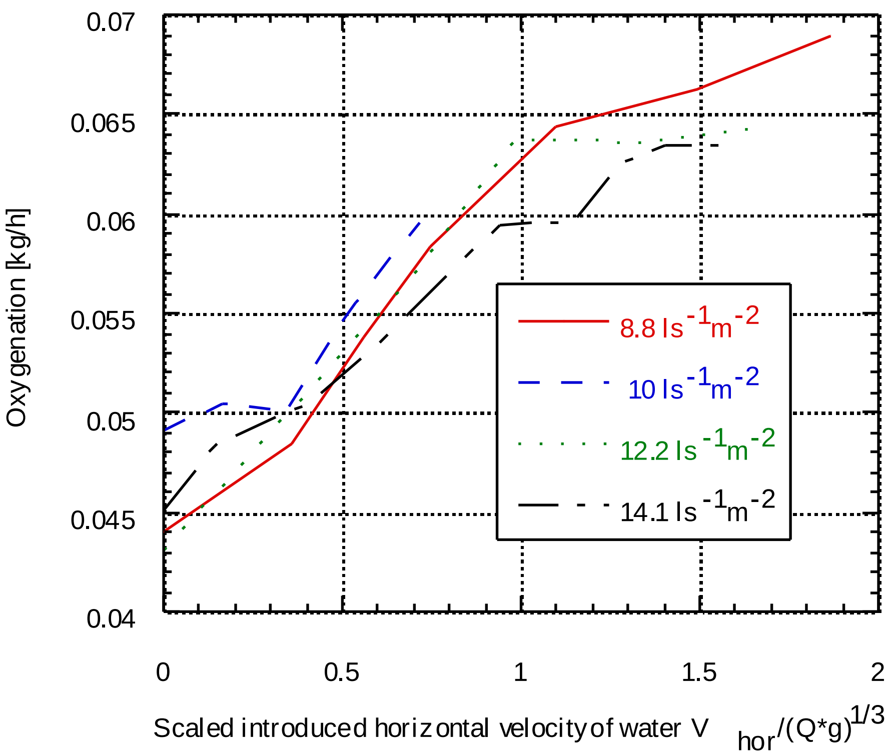

Figure 10. *Data from measurements of the oxygen transfer rate.*

6. Conclusions

When simulating the two phase flow set up by air bubbles rising through water, separate mass and momentum equations for each phase should be used.

The increase in oxygen transfer rate observed in aeration systems with horizontal flow is due to increase of retention time of the air injected. The induced swirl flow of the water is broken by the introduced horizontal flow. The velocity of the required horizontal flow is determined by the injected air flow and is not affected by the depth of the tank. The higher the air flow, the higher the required horizontal flow.

7. Further Investigations

Simulations in three dimensions may give results in better quantitative agreement with the experiments. An appropriate choice of the function describing the drag coefficient dependence on the Reynolds number is essential to achieve accurate quantitative results. This function is greatly affected by contamination of the water. There are possibilities to incorporate a chemical model for the transfer of oxygen between air and water that would make the comparison with experiments more direct.

Acknowledgements

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