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Flow structures in MBR-tanks

J. Saalbach and M. Hunze

ABSTRACT

In this paper a CFD model is presented that allows for an approximation of the flow field within MBR-tanks. The technique is demonstrated by means of two examples considering both hollow-fibre and sheet-membrane modules. The flow field is computed and a comparison between measured and computed flow velocities shows the good quality of the numerical model.

Key words | CFD-modelling, flow structures, MBR-tank

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INTRODUCTION

Membrane technologies are used in a variety of applications today in both industrial and municipal wastewater treatment. Through the operation of membrane bioreactors already in use in several existing plants, knowledge has been gained for the planning process of new MBR-tanks.

The design of membrane filtration tanks in submerged membrane bioreactors (sMBRs) is significantly influencing the rate of mixing, the residence time distribution (RTD), the mass transfer coefficient (Joshi 2001), the cross-flow velocity, and by that the required transmembrane pressure (TMP) within the membrane stage of the wastewater treatment plant (Ueda *et al.* 1997; Liu *et al.* 2000). In this context, it has been shown that the sludge settleability, the bacteriological properties, the pollutant removal, and in turn the nitrification of the MBR process are strongly affected by the mixing characteristics within the system (Chambers 1982; Jones & Franklin 1985; Chudoba *et al.* 1985*a*, *b*; Horan 1991). Therefore, coarse bubble aeration is used to induce flow, to generate shear at the membrane surface (Cui *et al.* 2003), and to improve the overall hydraulic conditions within the filtration unit. However, approximately 70% of the total energy input is originating from the aeration sequence (Kraume & Bracklow 2003). Moreover, the foot print of the wastewater treatment plant is an important issue with respect to investment costs of full-scale MBR plants (Melin *et al.* 2006). Thus, efforts have been made to further investigate the hydrodynamics within the membrane vessel in order to (i) reduce the size of the treatment plant and (ii) to reduce aeration requirements.

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To meet this challenge, the impact of design parameters on the filtration performance has been analysed by means of energy balancing (Chisti & Moo-Young 1993) and comparative experimental test series (Shim *et al.* 2002). Nevertheless, the complex multiphase flow pattern is inhibiting the development of the tank design (Joshi 2001). Although a variety of monitoring techniques have been identified (Chaouki *et al.* 1997) and applied to membrane processes (Chen *et al.* 2004), most of these analytical tools are not applicable to opaque fluids, strongly transient flow patterns, and to large-scale test facilities. In addition, these experiments are restricted to very few locations in the membrane vessel due to shortage of space (Tacke *et al.* 2007).

Since CFD simulations are already used to analyse and optimize processes in traditional water treatment plants simulations have been conducted to show the potential of CFD in combination with MBR technologies in respect to both planning and operation (Hunze & Schumacher 2005; Ghidossi *et al.* 2006).

Investigations on the hydraulic conditions in a filtration tank can be used to optimize:

- the position of membrane modules and module design,
- the position and type of aeration elements as well as the air-loading,
- the geometry and design of the filtration tank itself.

Besides micro- and meso-scale investigations of the bubble-entrained liquid flow (Taha & Cui 2002; Buetehorn *et al.* 2007), the macro-scale flow behaviour in MBR processes has been analysed by a number of research groups (Brannock 2003; Prieske *et al.* 2007).

When using CFD to model a whole MBR-plant a variety of obstacles have to be tackled. Phenomena surrounding membranes take place on a micro-scale requiring high mesh resolutions which result in a large element number even for the investigation of very small areas. For modelling a whole MBR-plant a macro-scale approximation has to be used in order to keep the element number and computation effort within certain limits. Therefore, an appropriate modelling technique has to be applied to transfer phenomena from one scale to the other.

In this study the possibility of modelling membrane modules as zones of porous media is investigated. The idea is to regard a whole membrane module as one zone with macroscopically identical characteristics. This way, single membranes - hollow-fibres or sheets - do not have to be modelled individually. Effects on the flow field caused by the area normally occupied by a membrane module are transferred to a zone of porous media. The flow resistance values have to be calibrated according to the type of membranes used in the membrane module in order to produce a corresponding flow field. In this study two types of membrane modules are modelled. Hollow-fibre membranes are flexible whereas sheet-membranes remain at a fixed position within a module. The latter pose a challenge because the flow field inside a sheet membrane should be unaffected by the flow field around it. At the same time, it has to be permeable to allow a flux across the membrane, resulting in a significant modelling challenge.

Additionally the influence of aeration which is linked to the use of membrane technology is considered. As a result the flow field largely depends on the amount and position of the aeration elements. The effects of aeration on the flow field will be taken into account in the model. In this article the modelling procedure will be demonstrated on the basis of two systems.

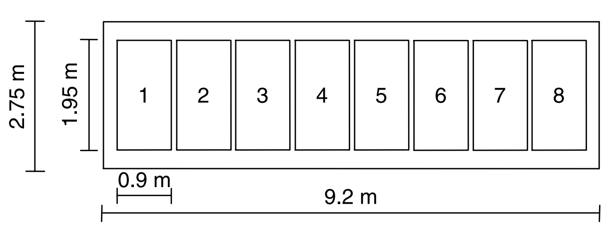

Figure 1 | Top view sketch of the MBR-tank of WWTP Sobelgra (Belgium).

METHODS

An MBR-tank can be considered as a multiphase system consisting of the interacting phases water, air, and activated sludge. For modelling work the software package Fluent (Fluent Inc. 2006) is used. It is extended by self-developed approaches. The Algebraic-Slip-Mixture-model (Manninen *et al.* 1996) is used for the description of the movement of water and air resulting in a two-phase-fluid with volume fractions for the corresponding phases. On the basis of this, a 3-dimensional flow field is computed.

Processes involving aeration tend to be highly turbulent thus requiring a suitable turbulence model. In this study a modification of the k-ϵ model, the *rng*-k-ϵ model (Orszag *et al.* 1996) is used. The turbulent kinetic energy k and the turbulent dissipation rate ϵ are used to calculate the turbulent viscosity η_t.

The activated sludge is modelled as a substance concentration in the water phase which accounts for density and viscosity impacts on the fluid as well as the settling process of the sludge. Activated sludge transport is carried out by the advection-diffusion-equation.

The membrane modules are modelled as zones of porous media. This assumption is suitable for considering

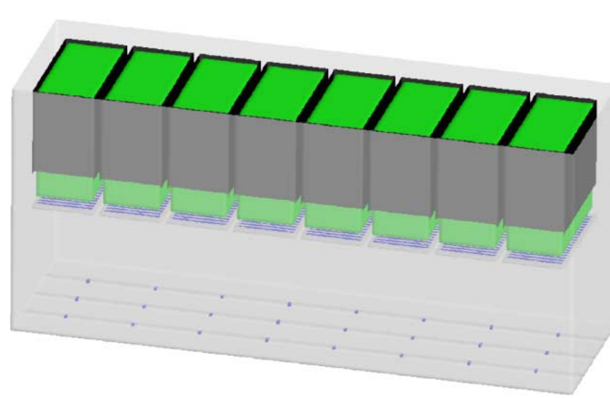

Figure 2 | Computer model of the MBR-tank of WWTP Sobelgra (Belgium). Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

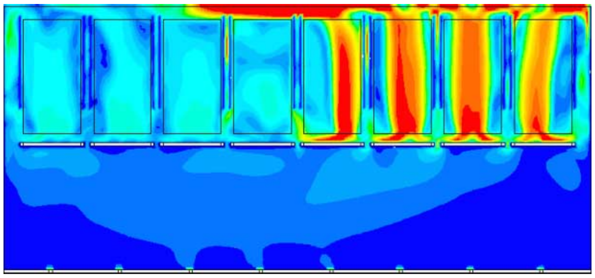

Figure 3 | Velocity magnitude [m/s]; scaled from 0.0 [blue] – 0.5 [red], WWTP Sobelgra. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

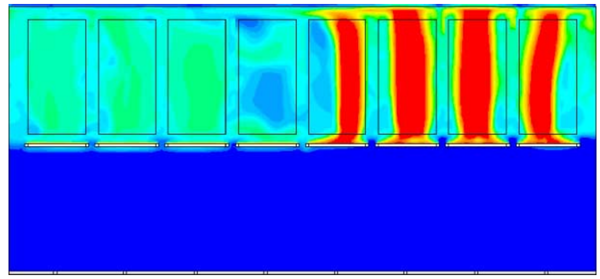

Figure 5 | Air-phase distribution by volume fraction; scaled from 0.0 [blue] – 0.3 [red], WWTP Sobelgra. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

the influence the modules have on the flow field, i.e. the flow resistance. Resistance values for all three spatial directions are associated with the porous zones and can be altered to match the values of the modules under investigation. Resistance values have to be determined on the basis of velocity measurements within real MBR-tanks under realistic system conditions.

RESULTS AND DISCUSSION

The MBR-tank of WWTP Sobelgra

The first system under investigation is an MBR-tank of WWTP Sobelgra (Belgium). A top view sketch is provided in Figure 1. The tank has eight membrane modules (KOCH Membrane Systems) installed 2.2 m above the bottom. Around each module walls are installed thus water will mainly have a vertical flow direction. Height of the modules is 1.8 m and the water level is at 4.2 m.

The 3-dimensional computer model is provided in Figure 2. The green boxes indicate zones of porous media modelling the eight hollow-fibre membrane modules. Walls surrounding the modules are depicted in black. Below the modules aeration elements are installed which are depicted in blue. At the bottom of the tank, pipes with drill holes serve as inlets. The modelled inlets can be seen depicted as little blue squares at the bottom of the tank in Figure 2.

In the state which is simulated, only four of the membrane modules are operational thus a permeate flux only occurs in modules 5–8, the four modules to the right in Figure 2. A permeate flux of 26 m^3/h is considered for the four modules combined. Accordingly 10% of the total air-load is used for aeration below modules 1 to 4 and 90% is used for aeration below modules 5–8. A total air-load of 29 m^3/min is considered.

Simulation results after t = 700 s are presented in Figures 3 to 5 which give a detailed insight of the system conditions. Clearly aeration has a significant influence on the flow field. The velocities below the aerators are generally lower than in the upper zone. This can be seen in the contour plot of velocity magnitude (Figure 3) and the

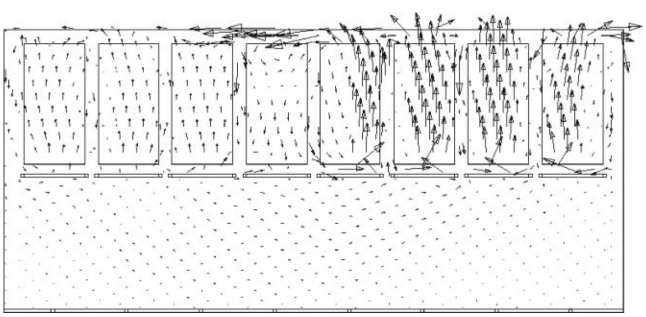

Figure 4 | Velocity magnitude vectors, WWTP Sobelgra.

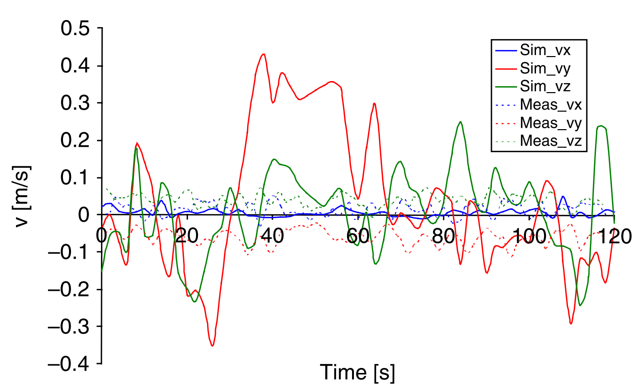

Figure 6 | Comparison of measured and computed velocity values, WWTP Sobelgra.

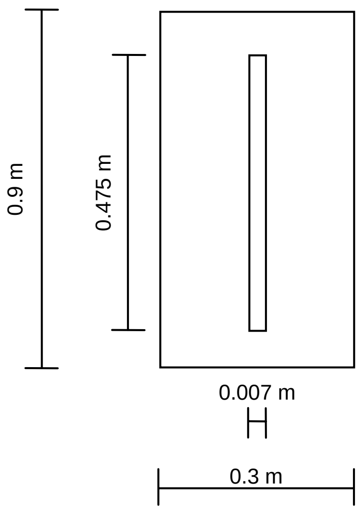

Figure 7 | Top view sketch of a sheet membrane model.

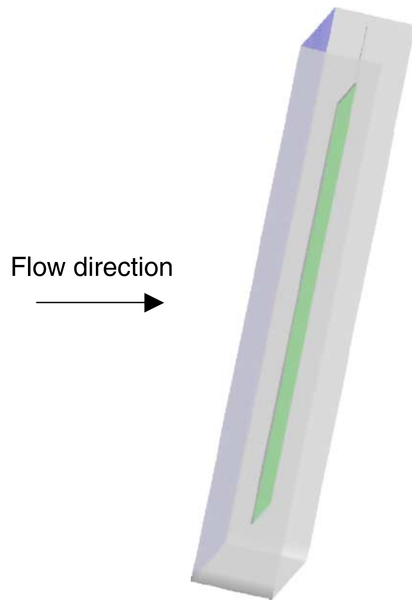

Figure 9 | Computer model of a sheet membrane; side view.

vector plot (Figure 4) where the arrow length denotes velocity magnitude. The presented cross sections are located in the middle of the tank.

Comparing the velocities to the air-phase distribution (Figure 5) the influence of aeration on the flow field becomes obvious. A general upward movement above the aerators can be seen in the vector plot. The associated downward movement takes place at the very left and right side of the tank, but also in the area of module 4. The buoyancy due to aeration is less than the suction applied by module 5. Therefore in the area of module 4, although aerated from below, a downward movement occurs.

Validation of the model assumptions is done by comparing velocity measurements to computed values. Figure 6 presents time series of measured and computed velocities over a period of 120 s. Due to the highly unsteady

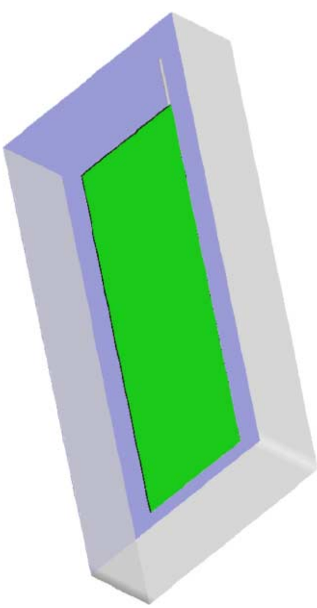

Figure 8 | Computer model of a sheet membrane.

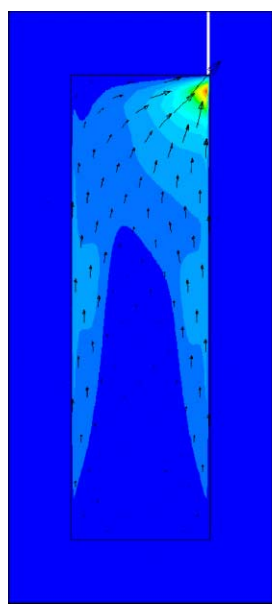

Figure 10 | Velocity magnitude [m/s]; scaled from 0.0 [blue] – 1.0 [red]. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

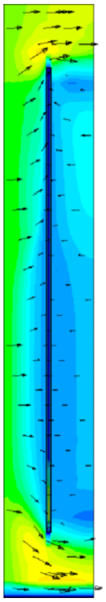

Figure 11 | Velocity magnitude [m/s]; scaled from 0.0 [blue] – 0.002 [red]. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

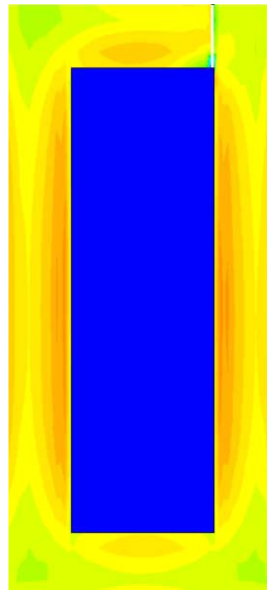

Figure 13 | Pressure distribution [N/m^2]; scaled from −0.01 [blue] – 0.01 [red]. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

nature of aerated systems a complete matching of the curves is not expected. However, the overall range and fluctuation of the x- and z-velocities show good accordance. The computed y-velocities, vertical velocities, differ significantly from the measured ones. Overall the simulated values are slightly larger than those measured. This may be due to a difference in the air-load between measured and simulated state because a direct determination of the air-load during

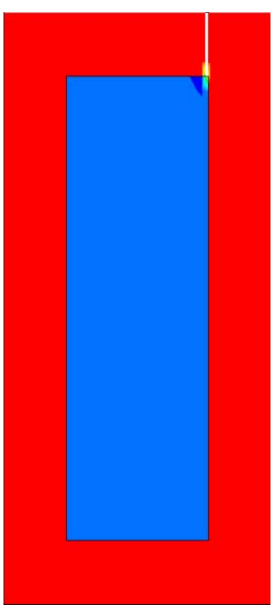

Figure 12 | Pressure distribution [N/m^2]; scaled from −80000.0 [blue] – 0.0 [red]. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

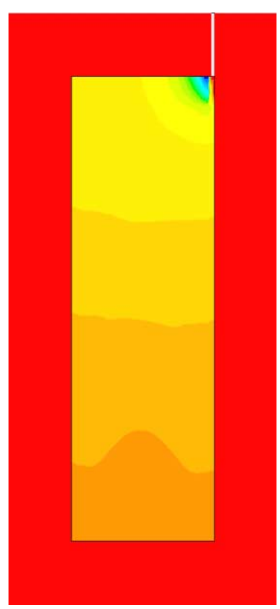

Figure 14 | Pressure distribution [N/m^2]; scaled from −77000.0 [blue] – −74000.0 [red]. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

the measured state was not possible. Additionally the period of 120 s considered for comparison is chosen arbitrarily from the simulation results. For a different period of time vertical velocities may differ from those shown in Figure 6 significantly. The impact of aeration is the dominant factor on the vertical velocities causing it to be highly unsteady.

The MBR-tank of WWTP Heenvliet

The second system under investigation is an MBR-tank of WWTP Heenvliet (The Netherlands). Modules consisting of sheet-membranes (Toray Membrane) are installed in this tank. In order to develop an approach for modelling sheet-membrane modules for use within a CFD-model, first a single sheet-membrane model is investigated.

Figure 7 shows a top view sketch of the model setup and Figures 8 and 9 show the computer model. A modelled sheet membrane comprises of two porous zones acting as cover sheets with a fluid zone in between. The simulation setup can be seen in Figure 9 with the flow direction as depicted. Porous zones, modelling the membrane are depicted in green. A negative pressure of 1 bar is applied in order to obtain a permeate flux. The height of the membrane is 1.57 m and the water level is at 2.0 m. In order to calibrate the model resistance values for the porous zones were chosen to match a permeate flux of 1000 l /(m^2 h bar) (Judd 2006).

Results on the basis of the calibrated model are presented in Figures 10 to 14. The flow field, Figures 10 and 11, is influenced by the resistance posed by the sheet. The water is mainly directed around the sheet (Figure 11) and only to a small extend sucked through the membrane.

Calculated pressure distributions can be seen in Figures 12 to 14. Clearly a large pressure difference between inside the sheet membrane and the outside water is calculated (Figure 12). Outside the membrane, the pressure distribution builds up according to the flow field. The water has to move around the membrane (Figure 11) with the highest velocities right next to the sheet. Accordingly the pressure distribution is characterized by the dynamic pressure with the highest values next to the membrane (Figure 13). Inside the membrane a pressure gradient builds up from top to bottom (Figure 14). The lowest pressure can be seen where the permeate withdrawal takes place, i.e. in the top right corner of the sheet-membrane (Figure 14). Further down the membrane higher pressure values can be observed. All pressure values are relative values.

CONCLUSIONS

This paper presents a 3-dimensional numerical simulation model which allows a realistic description of the flow structure in MBR-tanks. Computation of the flow field is carried out by the Algebraic-Slip-Mixture-model. Transport of activated sludge is taken into account the model. In order to be able to investigate an entire MBR-tank, membrane modules are modelled as a whole, combining single membranes. These modules are taken as zones of porous media with resistance values according to the type of membrane module installed. Resistance values are determined on the basis of velocity measurements. Two examples demonstrating the modelling process are presented. The results obtained, show that the modelling technique used is suitable for investigations on flow structures in MBR-tanks.

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