final report

Project Code: A.ENV.0149
Prepared by: Damien Batstone / Paul Jesen
Date published: June 2013
PUBLISHED BY
Meat and Livestock Australia Limited
Locked Bag 991
NORTH SYDNEY NSW 2059

Integrated agri - industrial wastewater treatment and nutrient recovery, Year 2

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government and contributions from the Australian Meat Processor Corporation to support the research and development detailed in this publication.

Abstract

Membrane bioreactor performance is highly dependent on reactor hydrodynamics, i.e. fluid mixing and shear imparted on the membrane. Computational fluid dynamics (CFD) has been successfully utilised as a tool for the prediction of wastewater reactor hydrodynamics (mixing) by a number of researchers, and is hence adopted in this study for the characterisation of fluid flow and membrane shear in the existing pilot scale anaerobic membrane bioreactor.

This report outlines the development of two and three phase CFD models which comprise Milestone 4. Two phase (liquid and gas) models are able to provide an estimate of membrane shear and fluid velocity profiles by approximating the solid-liquid phase as a single non-Newtonian fluid. A three phase approach was however required in the cases studied in this report due to solids separation from the liquid phase (settling), which made the assumption of a single non-Newtonian fluid invalid. It was also found that two phase models underestimate fluid velocities and membrane shear intensities compared with three phase models. Therefore, while a two phase approach is computationally inexpensive and simpler to develop than a three phase model, it is also more conservative approach to reactor hydrodynamic modelling.

Milestone 4 also required successful confirmation of PhD candidature, which was achieved on 22nd March 2013. Therefore, Milestone 4 has been completed successfully.

The PhD future work programme will comprise the development and integration of a membrane fouling model (non-reactive and reactive) with the CFD models developed in Milestone 4.

General project objectives

1. Implement and long-term trial anaerobic membrane bioreactor systems in slaughterhouse applications;

2. Provide demonstrable improvements to performance through research and development activities;
3. Provide and demonstrate nutrient recovery and removal options, with an emphasis on recovery;
4. Develop complete options to capture and utilise produced biogas.

Success in achieving milestone

Development of two and three phase CFD models describing reactor hydrodynamics

***Background*:**

Reactor hydrodynamics, or mixing, is a key parameter that is often overlooked in membrane fouling studies as it is difficult to determine experimentally (Brannock, Wang et al. 2010). Membrane fouling is closely related to reactor mixing and it has been found that lab scale studies of membrane fouling are of limited value in full-scale applications due to the unrepresentative hydrodynamics of the lab-scale reactor (Drews 2010). Reactor hydrodynamics is affected by the position of the membrane modules (internal vs. external), reactor design and position, type and extent of gas sparging, which can differ in full-scale applications from the lab-scale approximations. Monitoring techniques that exist for hydrodynamic determination are difficult to implement in large scale wastewater treatment systems that comprise transient flows and opaque fluids. Empirical techniques are also restricted by the lack of space in reactor systems (Saalbach and Hunze 2008). To address this, a number of researchers have successfully utilised and implemented computational fluid dynamics (CFD) as a tool for predicting the effect of wastewater treatment process design features on the hydrodynamics of full scale installations (as reported by Brannock, Wang et al. 2010).

The pilot scale anaerobic membrane reactor installed at Teys Aust, Beenleigh (presented in Milestone 2,3 report) is designed with a flat sheet membrane module configuration (FS AnMBR). The FS AnMBR designed has been adopted during the development of the CFD models presented in this report. The layout of the FS AnMBR is outlined in Figure 1.

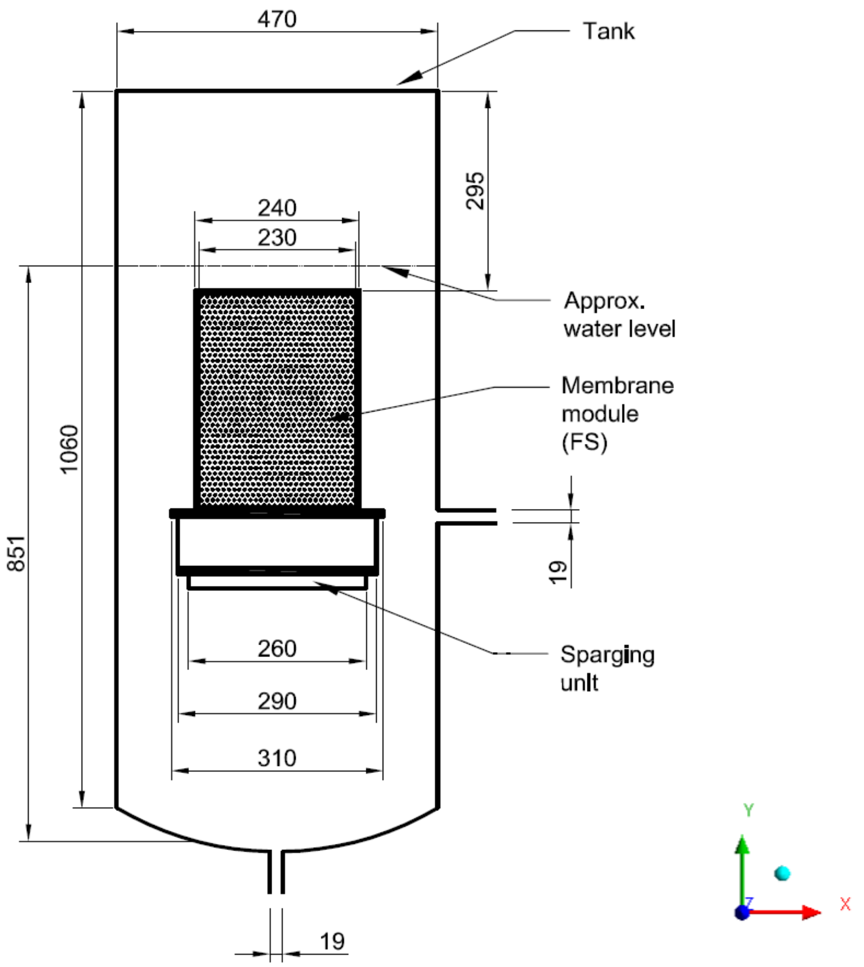


Figure 1: Layout of the pilot scale flat sheet anaerobic membrane reactor (FS AnMBR)

The first step in the development of the CFD model is the ‘spatial discretisation’ of the tank geometry into a three-dimensional meshed computational domain, as illustrated in Figure 2. This meshing process divides the entire reactor geometry into smaller grid-like ‘control volumes’. Fluid mechanics equations such as the Navier-Stokes equations are then used to solve each control volume in a iterative process. Details of fluid flow and constitutive equations are described in Section 3 of the attached confirmation document.

The commercially available ANSYS CFX software is used in this study for the numerical simulation of fluid flow. The CFX solver requires detailed inputs relevant to a fluid flow situation, including initial and boundary conditions, rheological models, drag and lift models, physical properties of the fluids involved, mass transfer behaviour etc. A transient (time-dependent) problem for the geometry and cases studied in this report typically takes between 8 and 48 hours to solve. The solution is then graphically displayed manipulated in the CFX post-processor, key outcomes of which are displayed in the following section.

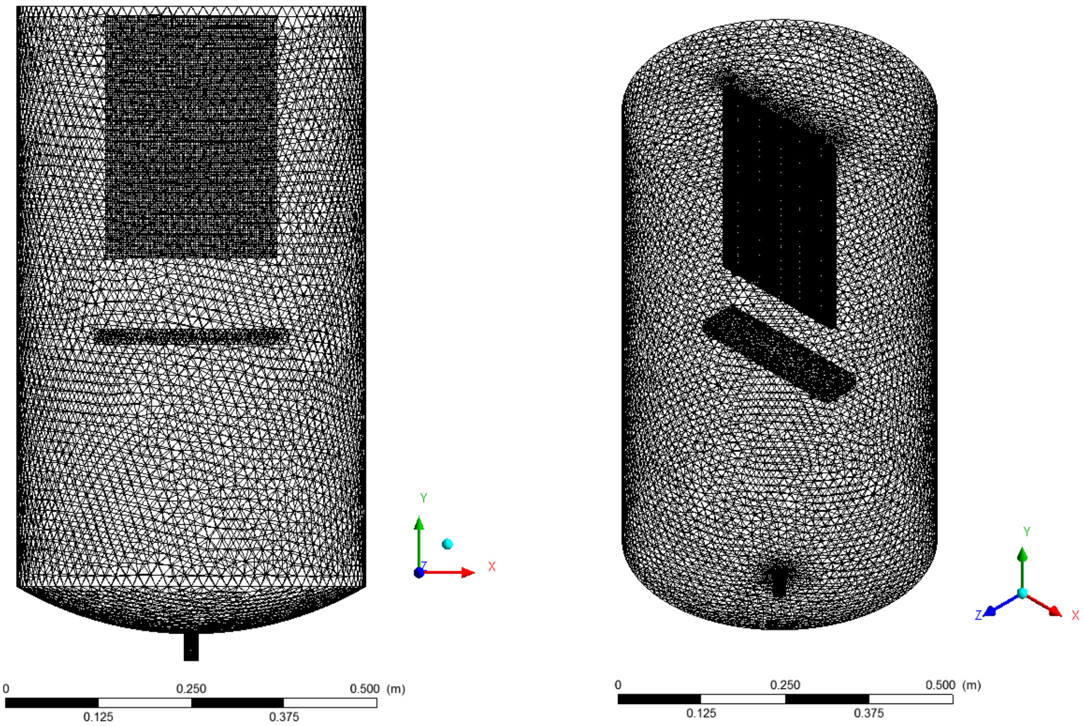


Figure 2: 3D computational fluid domain of the FS AnMBR viewed from the front and in isometric view.

Two Phase Model Development, Results and Discussion

A two phase CFD model comprises liquid and gas phases. The viscosity of wastewater is typically higher water and is estimated using a rheological model specific to the wastewater. Wastewater sludge is typically non-Newtonian, where the viscosity changes as shear is increased, an important consideration in a CFD model as reactor mixing creates shear stress.. The rheological model is related to total solids concentration of the wastewater via a correlation equation. The various rheological models applied to wastewater sludge are described in Section 3.3.5 of the attached confirmation report.

The approximation of wastewater as a uniform non-Newtonian fluid is justified by Brannock, Wang, (2010) who simulated the hydrodynamics in an aerobic MBR using a two phase approach and showed that the effect of buoyancy on solid particles is greater than the settling velocity of solids; and that the activated sludge can therefore be well represented by a uniform non-Newtonian fluid. This is significant, as the computational efforts required for hydrodynamic simulation are greatly reduced.

In this report, AnMBR sludge rheology is approximated by a Bingham model for a continuous flow stirred tank reactor (CSTR) using correlation Equations 1 and 2, developed by Pevere, Guibaud et al (2007).

Equation 1

Equation 2

Where;

μ =viscosity (Pa.s)
= yield stress (Pa)
x= Total suspended solids concentration (mg/L)

A two phase model was developed for the following case scenarios:

a) Effect of viscosity (solids concentration) on reactor hydrodynamics (mixing, membrane shear)
b) Effect of viscosity (solids concentration) on filtration
c) Effect of gas sparging rate on reactor hydrodynamics

The effect of viscosity on reactor hydrodynamics in the two phase model was assessed by comparing solids concentrations of 5g/L and 10g/L, these solids concentrations are typical of concentrations expected in the pilot AnMBR. The rheological parameters at these solids concentrations are calculated using Equations 1 and 2 and are displayed in Table 1.

Table 1: Viscosity and yield stress parameters for 5 and 10g/L solids concentration

TS g/L	TSS g/L	μ_B (Pa.s)	τ_B (Pa)
5	3.75	0.00125	0.089
10	7.5	0.00157	0.203

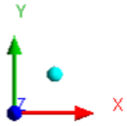
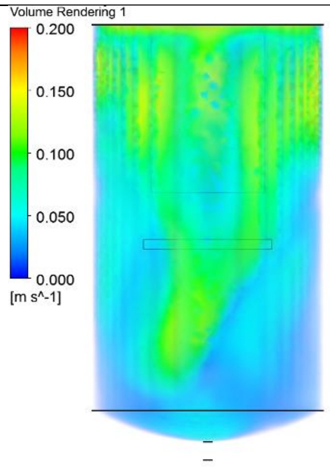
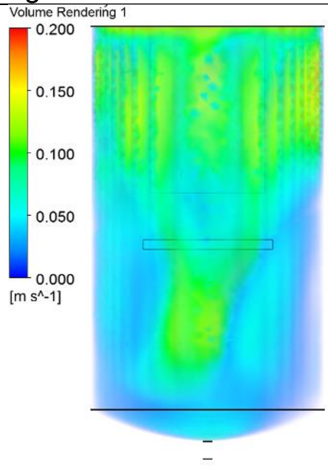
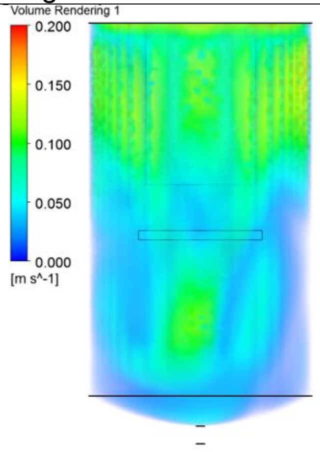
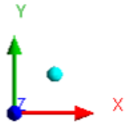
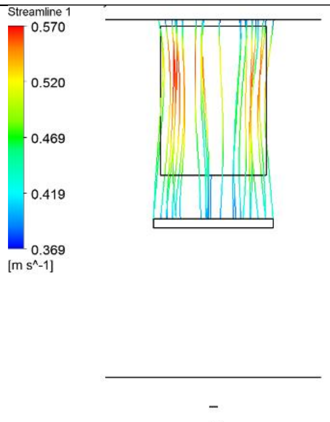
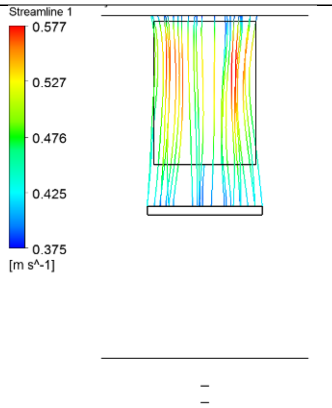
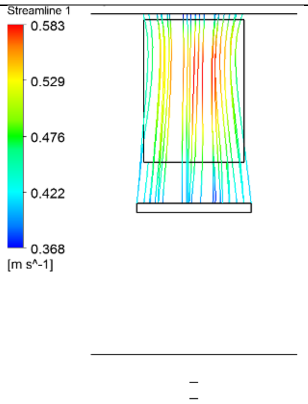
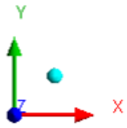
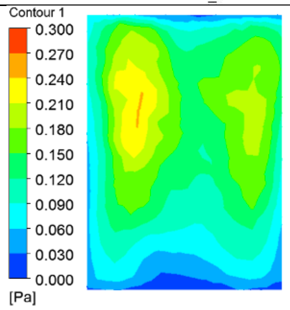
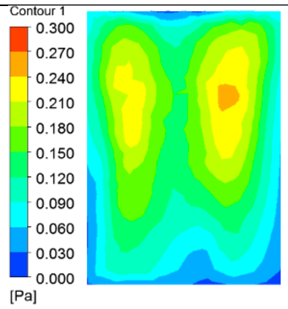
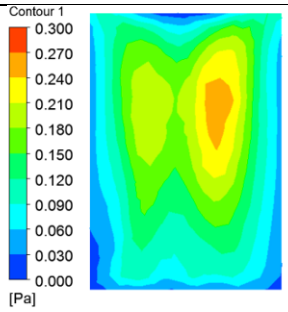
Results from the two phase simulations of the pilot scale FS AnMBR are shown in Table 2. The extent of membrane cleaning via gas bubble shearing and fluid mixing provided by the sparged gas (methane) can be visualised; and the effect of solids concentration (viscosity) on mixing efficiency can be simulated by incorporating a non-Newtonian rheological model into the simulation.

Fluid velocity profiles in Table 2a indicate that the reactor contents are less well mixed at 5 and 10 g/L solids than in a reactor with clean water. This is an indication of an increasing resistance of the more viscous fluid to shear mixing. The maximum velocity in the reactor is decreased from 0.22 m/s in water; to 0.21 m/s in 10 g/L solids. The presence of ‘dead zones’ at the bottom of the reactor in all scenarios also highlights the unsuitable position of the sparger for complete mixing.

Methane velocity increases with viscosity (Table 2b), from a maximum of 0.57 m/s in clean water to 0.58 m/s in 10 g/L reactor solids. This increase in methane velocity is attributed to the higher density of the reactor contents at higher viscosities, resulting in a greater density difference between the gas and liquid phases, and hence a faster gas bubble rise. The maximum shear experienced by the membrane therefore also increases with viscosity, from 0.24 Pa in water to 0.26 Pa in 10 g/L.

The overall membrane shear profile (Table 2c) however; becomes narrower with increasing viscosity; therefore the area of the membrane experiencing shear (cleaning efficiency) is reduced as viscosity is increased.

Table 2: Reactor hydrodynamics in clean water and wastewater with 5 and 10g/L solids concentration

	Clean water	5g/L	10g/L
a. Fluid velocity 			
b. Methane velocity near membrane 			
c. Membrane shear 			

The effect of viscosity on filtration resistance was assessed using a porous media model, combining viscous (Darcy's Law) and inertial resistance. The porous media model is utilised for the simulation of membrane filtration (refer to section 3.2.1.3 of the attached confirmation document for details of the porous media model). The effect of increasing permeate viscosity is simulated using rheological data of sucrose at concentration of 10-60% and is presented in Figure 3. The results show that an increase in viscosity will also increase the resistance across the membrane and therefore the energy required to pump fluid through the membrane, in accordance with Darcy's Law.

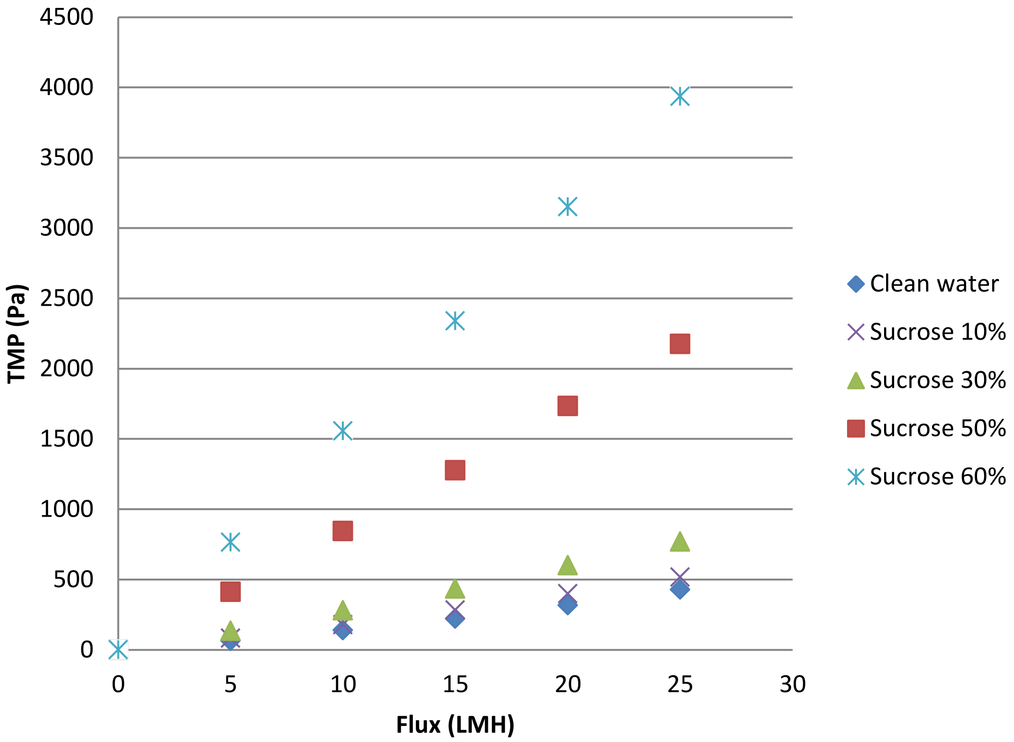
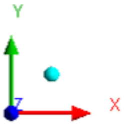
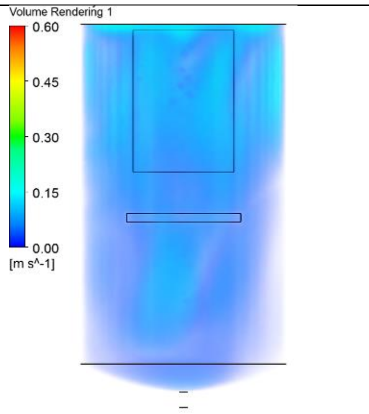
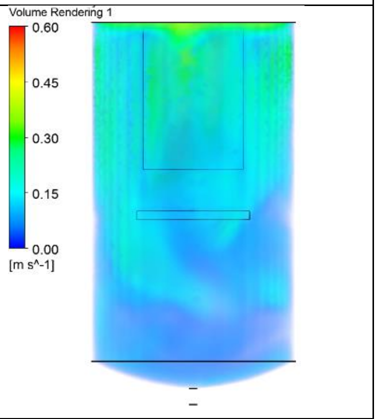
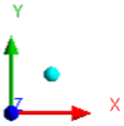
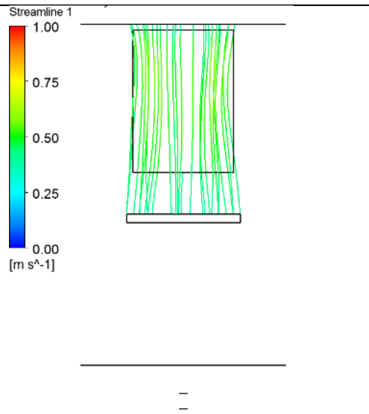
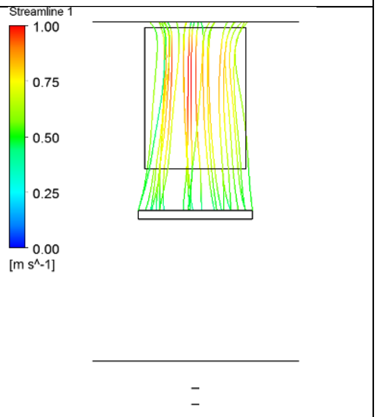
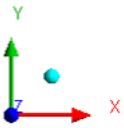
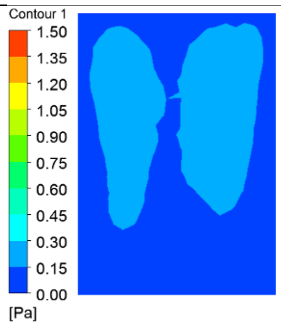
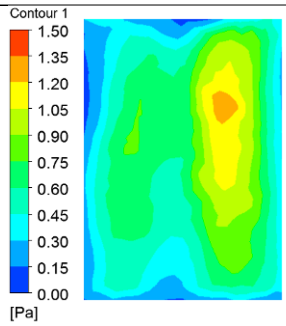


Figure 3: Transmembrane pressure (TMP) vs. filtration flux relationships of clean water and 10 to 60% sucrose solutions

The effect of increasing sparger gas flow rate on reactor hydrodynamics is presented in Table 3. Fluid velocity profiles indicate a reduction in the 'dead zone' at the bottom of the reactor when gas flow rate is increased from 3.5L/min to 30L/min. The increase in sparger flow rate also enhances maximum reactor fluid velocity (0.207m/s to 0.615m/s), methane velocity (0.577m/s to 0.992m/s) and membrane shear (0.254Pa to 1.484Pa).

Table 3: Effect of sparger gas flow rate on reactor hydrodynamics

	3.5L/min	30L/min
a. Fluid velocity 		
b. Methane velocity 		
c. Membrane shear 		

<u>Three Phase Model Development, Results and Discussion</u>

While two phase model approximations provide a reasonable indication of mixing and membrane cleaning via velocity and membrane shear profiles, the modelling of solids behaviour, especially solids settling, requires a more complex three phase approach (refer to section 3.2.1.2 in attached confirmation report for details of multiphase fluid flow).

Solids settling profile:

Actual total solids (TS) measurements at the hollow fibre (HF) pilot scale AnMBR (Teys, Beenleigh) suggest that reactor contents do not undergo complete mixing when operating a at gas sparging rate of 30L/min, with solids concentration varying from 0.4% at mid-height to 1.33% at the bottom of the reactor, therefore suggesting that the assumption of a uniform viscosity may be invalid.

The solids concentration profile obtained from a CFD simulation of this scenario is presented in Figure 4, and illustrates the stratification in solids concentration ranging from a solids concentration of 0.5% at mid-height to 1.0% at the bottom of the reactor. The simulated values are in reasonable agreement with measured values as summarised in Table 4.

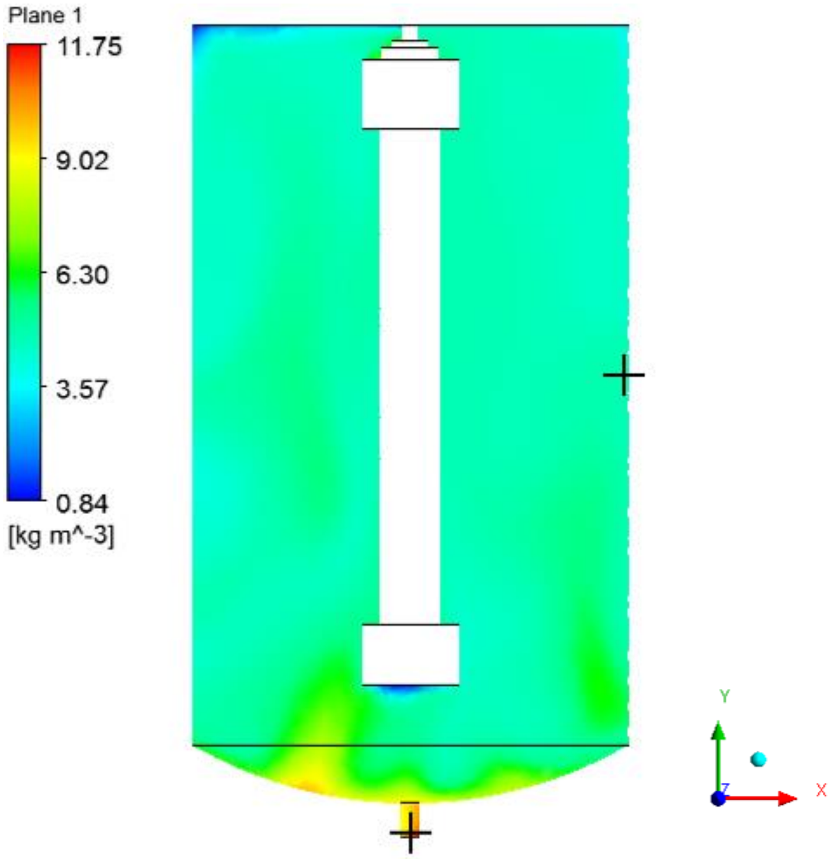


Figure 4: Simulated solids concentration profile in the HF AnMBR at Teys, Beenleigh (sampling points indicated at crosshairs).

Table 4: Measured and simulated solids concentration at the middle and bottom sampling points of the HF AnMBR

	Measured solids concentration (%) (19th February 2013)	Simulated solids concentration (%)
0.4m from bottom of reactor	0.40	0.49
Bottom of reactor	1.33	1.02

<u>Comparison of Two Phase and Three Phase Models</u>

Results of the two phase model simulation highlighted incomplete mixing due to the position of the sparger unit, and this was further confirmed by three phase model results. The vertical straification in solids concentration is illustrated in Figure 5 and summarised in Table 5, showing solids concentration varying from 1.1% at the bottom to 0.46% near the top of the reactor.

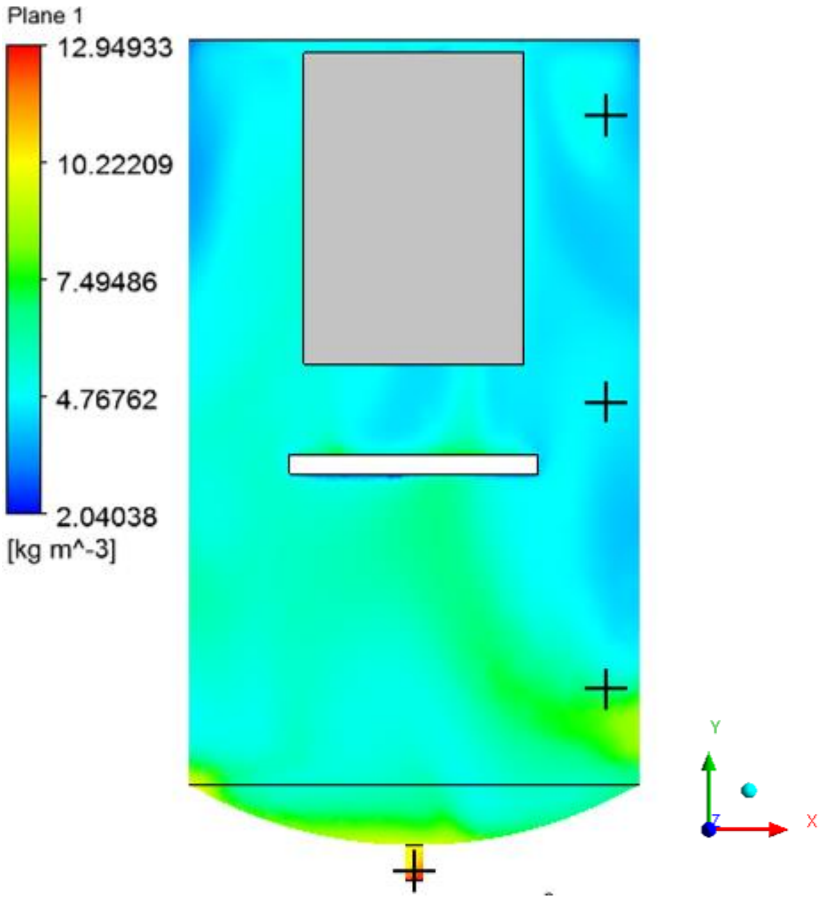


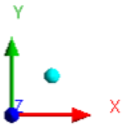
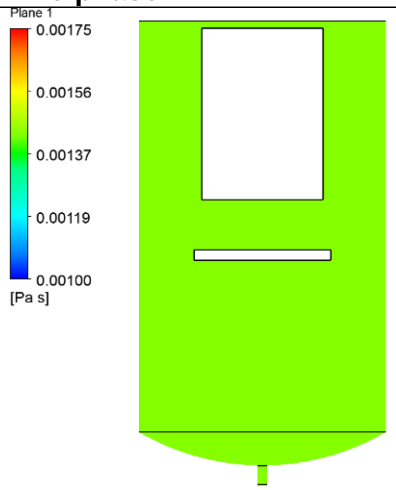
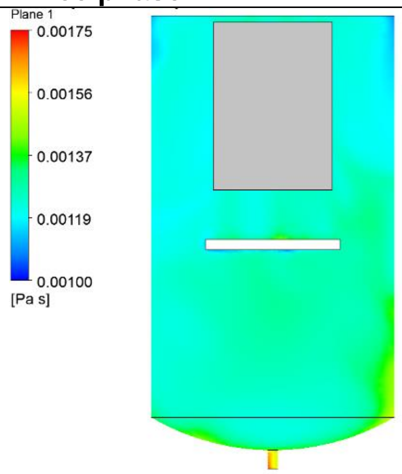
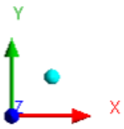
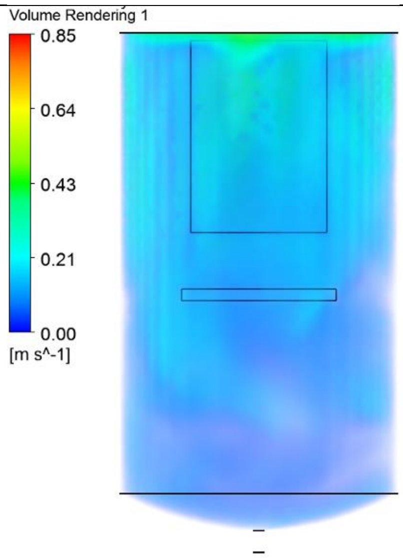
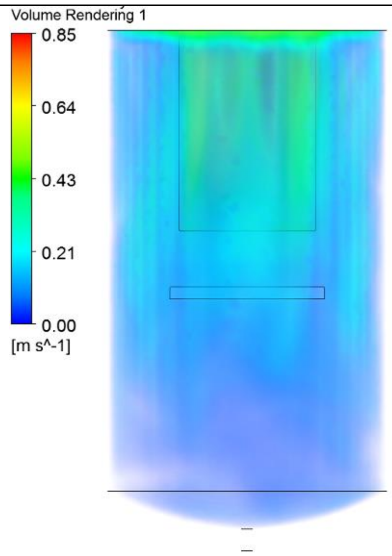
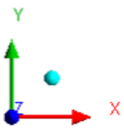
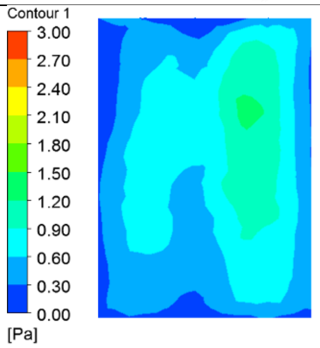
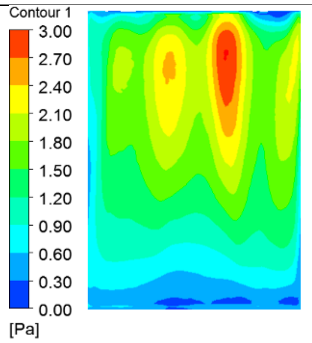
Figure 5: Simulated solids concentration profile in the FS AnMBR (sampling heights marked as crosshairs

Table 5: Simulated solids concentrations at the various sampling heights marked in Figure 5

Location from bottom of reactor, Y (m)	**Solids concentration %**
Bottom	1.14
0.1	0.64
0.4	0.46
0.7	0.46

Additional two and three phase model results are compared in Table 6. The three phase model illustrates the variation in fluid viscosity due to the stratification of solids; in contrast with the uniform viscosity assumption made in the two phase model (Table 6a). The settling of solids in a three phase system would lead to a lower viscosity near the membrane than in a two phase assumption, therefore enabling a higher fluid and methane velocity near the membrane (Table 6b) and resulting in higher membrane shear (Table 6c). The higher membrane shear in the three phase model is also attributed to the additional shear imparted by the dispersed solid particles. It is interesting to note that a two phase approximation underestimates mixing and shearing efficiency and is therefore a more conservative approach to modelling reactor hydrodynamics.

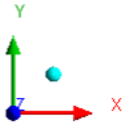
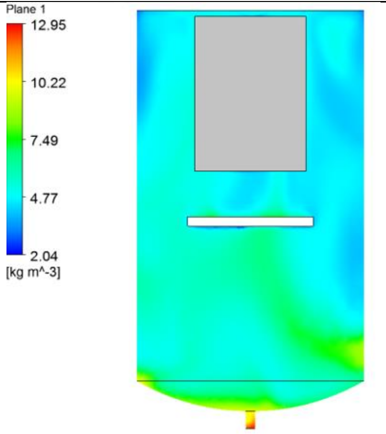
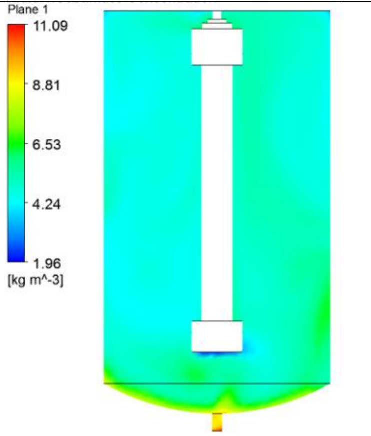
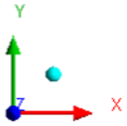
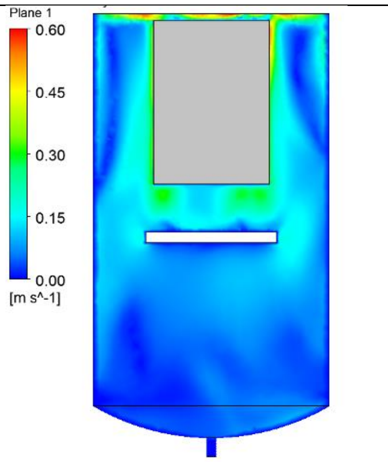
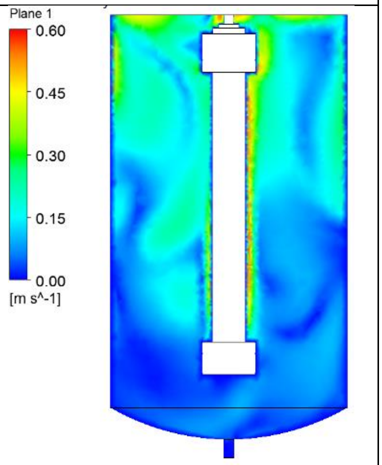
Table 6: Comparison of two and three phase model results

	Two phase	Three phase
a. Dynamic viscosity 		
b. Fluid velocity 		
c. Membrane shear profile 		

<u>Comparison of Flat Sheet and Hollow Fibre Membrane Configurations</u>

Table 7 shows a comparison of the hydrodynamics and mixing between the Flat Sheet (FS) and Hollow Fibre (HF) module configurations. The lower position of the gas sparger in the HF AnMBR enables slightly better mixing than the FS AnMBR suggested by the more uniform solids concentration and fluid velocity profiles. This information will contribute to design and modifications of the pilot scale AnMBR currently operating at Teys Aust. (Beenleigh).

Table 7: Comparison of three phase hydrodynamics in the FS and HF AnMBR configurations

	Flat Sheet	**Hollow Fiber**
a. Solids concentration profile 		
b. Fluid velocity 		

Overall/Other progress

Confirmation of PhD candidate Apra Boyle-Gotla was successfully achieved on 22nd March 2013. The full confirmation report is attached.

The following research objectives have been developed as part of the PhD project plan:

1. Development of CFD, fouling and biokinetic model based on existing reactor configuration. Integration of these models into overall model framework.
2. Experimental validation of individual and integrated models.
3. Model based optimisation of reactor configuration and operation.
4. Successful completion of PhD milestones (first year confirmation, second year review and third year thesis review).

The current work plan will involve the development of a membrane fouling model that can visualise cake thickness, produce flux vs. TMP profiles and predict the value of critical flux. This fouling model will be integrated with the three phase CFD model already developed. Model inputs and model validation will be provided by laboratory scale critical flux experiments (reactor layout shown in Figure 6). Initial laboratory scale experiments will be conducted using ideal foulants such as casein (protein), cellulose (carbohydrate) and palmitic acid (fats), outcomes of which will later be compared with critical flux results of actual slaughterhouse wastewater constituents.

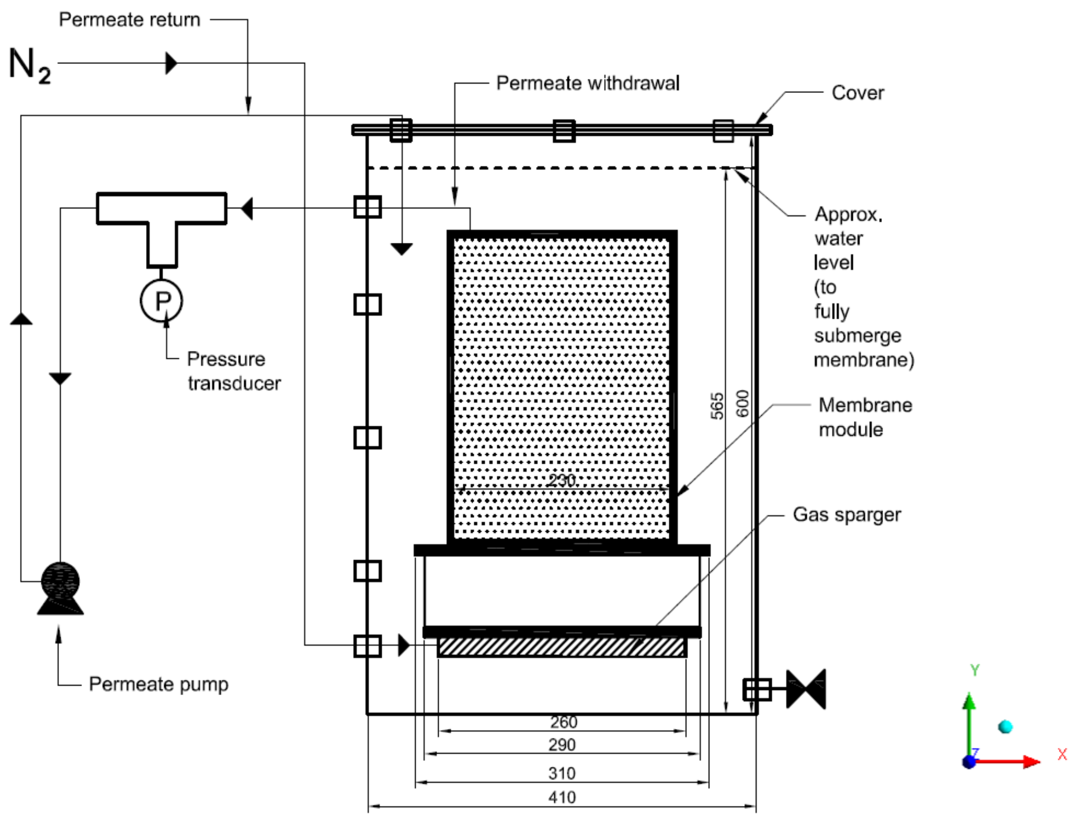


Figure 6: Laboratory scale reactor for critical flux experiments

References

Brannock, M., Y. Wang, et al. (2010). "Mixing characterisation of full-scale membrane bioreactors: CFD modelling with experimental validation." Water Research **44**(10): 3181-3191.

Drews, A. (2010). "Membrane fouling in membrane bioreactors-Characterisation, contradictions, cause and cures." Journal of Membrane Science **363**(1-2): 1-28.

Pevere, A., G. Guibaud, et al. (2007). "Identification of rheological parameters describing the physico-chemical properties of anaerobic sulphidogenic sludge suspensions." Enzyme and Microbial Technology **40**(4): 547-554.

Saalbach, J. and M. Hunze (2008). "Flow structures in MBR-tanks." Water Science and Technology **57**(5): 699-705.