MBR-Network

WORKSHOP

CFD Modeling for MBR Applications

“From the fibre to the plant”

Presentation handouts

Berlin, 3 June 2007

Hosted by KOMPETENZZENTRUM Wasser Berlin

Preface

The MBR-Network, the coalition of European projects dedicated to MBR development, has decided to organise a one-day workshop fully dedicated to the use of CFD modelling for MBR applications.

The objectives of the workshop are:

- to have an overview of the opportunities provided by the CFD tool for quicker development of the MBR technology “from the fibre to the plant”;
- to provide a unique platform of technical exchange to all experts active in this field;
- to foster the exchanges between CFD users and module or plant constructors in order to identify the needs of the industry and encourage useful CFD developments.

This meeting has provided a unique overview of the capacities of CFD technologies for development and optimisation of MBR technology. The event was thought to bridge the gap between modelists and systems producers and operators in order to identify the useful application fields.

The presentations given during this workshop, as well as the minutes of the following discussion, are gathered in this Book of Handouts.

Boris Lesjean and Evelyne Nguyen Cond Duc

Berlin Centre of Competence for Water

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Modelling of the interaction of bubbles on membrane

Modelling of the membrane modules and aeration system

Modelling of the entire MBR station

1. WELCOME AND MEETING INTRODUCTION,

B. Lesjean, E. Nguyen Cong Duc

Workshop CFD modeling for MBR applications
“From the fibre to the plant”
Berlin, 3 June 2007

Welcome & meeting introduction

Boris Lesjean
Evelyne Nguyen Cong Duc
Berlin Centre of Competence for Water

KOMPETENZZENTRUM Wasser Berlin

Welcome and meeting introduction

- A word on MBR-Network
- Liaison Groups in MBR-Network
- Objectives of meeting “CFD modelling for MBR”
- Meeting agenda
- Overview

MBR-Network: a coalition of EU projects

AMEDEUS	Accelerate membrane development for urban sewage purification (STREP, M€ 6.1)
EUROMBRA	Membrane bioreactor technology for advanced municipal wastewater treatment strategies (STREP, M€ 6.2)
MBR-TRAIN	Process optimisation and fouling control in membrane bioreactors (Marie-Curie EST, M€ 2.4)
PURATREAT	Energy efficient approach to MBR operation for decentralised wastewater treatment (INCO, M€ 1.2)

MBR-Network

www.mbr-network.eu

the website dedicated to MBR community

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4 EU FP6 Projects dedicated to MBR

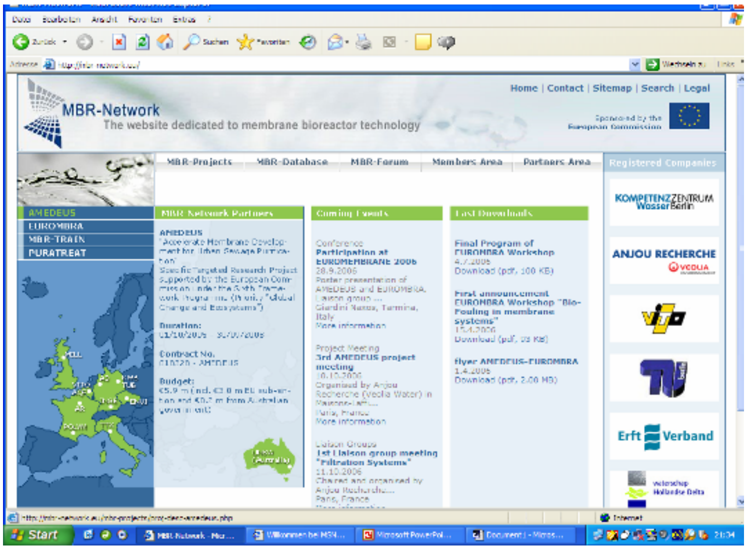
- 4 R&D projects within Oct. 2005 – Dec. 2009
- Total budget: € 16 million, incl. € 9 million EU
- About 50 European and international partners
- About 1.800 person months = 150 person years !
  (~ 40 full-time p.a.)

- Focus on municipal applications
- Build-up on current European expertise and know-how
- Foster MBR technology advances, competitiveness, acceptance and application in EU

www.mbr-network.eu

- 1 year of existence
- Close to 500 international members (100 companies)
- 600 references in data-base
- Monthly Literature Scan
- Discussion forum
- Project reports
- Articles
- Events
- Etc

- Book of handouts of this meeting online ???



AMEDEUS

Duration:

Contract No.

Budget:

Conference
Participation at EUROMEMBRANE 2006
28.9.2006
Poster presentation of AMEDEUS and EUROMBRA Liaison group ...
Giardini Naxos, Taormina, Italy
More information

Project Meeting
3rd AMEDEUS project meeting
10.10.2006
Organised by Anjou Recherche (Veolia Water) in Maisons-Laffi...
Paris, France
More information

Liaison Groups
1st Liaison group meeting "Filtration Systems"
11.10.2006
Chaired and organised by Anjou Recherche...
Paris, France

Final Program of EUROMBRA Workshop
4.7.2006
Download (pdf, 100 KB)

First announcement EUROMBRA Workshop "Bio-Fouling in membrane systems"
15.4.2006

flyer AMEDEUS-EUROMBRA
1.4.2006
Download (pdf, 2.00 MB)

Liaison Groups

- A request from EC to improve interactions between projects AMEDEUS and EUROMBRA
  - Goal: **integration** of the two projects
  - Facilitate exchange on program and results
  - Facilitate ‘critical review’ on respective undertakings
  - Facilitate contacts of partners working on similar issues
  - Format, topic and dates of events according to needs
  - Closed or open meetings

MBR-Network

6 LG-groups + leaders

- LG1 ‘Fouling’ (C. Cabassud, INSA)
- LG2 ‘Cleaning’ (T. Wintgens, RWTH)
- LG3 ‘Filtrations systems’ (C. Brepols, ERFT)
- LG4 ‘Process configuration’ (G. Guglielmi, UNITN)
- LG5 ‘Modelling’ (S. Judd, CRAN)
- LG6 ‘Retrofitting’ (A. van Nieuwenhuijzen, TUD)

- Goal: 1-2 meetings per group and per year

- This meeting: LG3 ‘Filtration systems’ + LG5 ‘Modelling’

MBR-Network

Meeting objectives

- Review and exchange international experience
  - on CFD modelling
  - on hydrodynamic measurement methods
  - for MBR applications
- Discussions with system suppliers and plants constructors and operators to identify the needs of the MBR industry

MBR-Network

CFD and membrane process / MBR systems

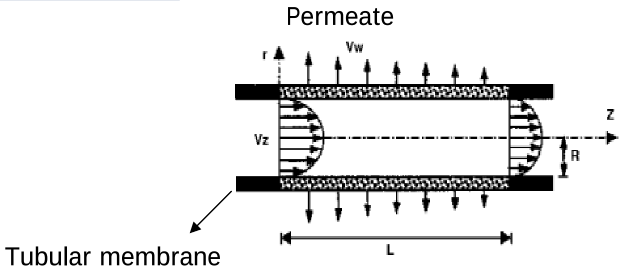
CFD and membrane models

CFD and hydrodynamics

Fundamental

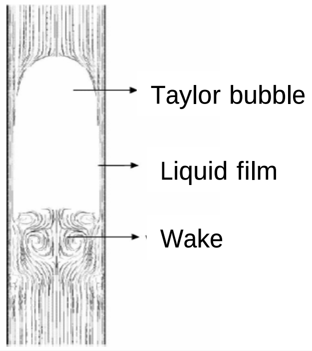
Flow through porous wall

Concentration polarization



Slug flow

Fibre movement



Applied

MBR systems
Module and aerator design
Bassin design

MBR-Network

Meeting agenda

- Modelling of the interaction of bubbles on membrane
    - Effect of the bubble size
    - Effect of the bubble frequency
    - Effect of fibre movement
    - Hollow Fiber / Tubular membrane
- Modelling of the membrane modules and aeration system
    - Module design
    - Aerator positioning
    - Air loading
    - Aerator operation
- Modelling of the entire MBR station
    - Basin design (inlet, outlets, mixing, dead zone, short cut)
- Discussion

University of Oxford

UNSW

UBC

INSA TOULOUSE

UNIVERSITEIT GENT

VEOLIA ENVIRONNEMENT
Recherche & Développement
Centre de Recherche sur l'Eau ANJOU RECHERCHE

TU berlin

RWTHAACHEN

FlowConcept

Acknowledgement

AMEDEUS and EUROMBRA are research projects supported by the European Commission under the Sixth Framework Programme (Priority “Global Change and Ecosystems”)

Contract No. 018328 – AMEDEUS
Contract No. 018480 – EUROMBRA
Duration: 01/10/05 - 30/09/08

They constitute the MBR-NETWORK Cluster
More info: www.mbr-network.eu

2. SURFACE SHEAR FORCES IN AIR SPARGED SUBMERGED HOLLOW FIBER MEMBRANES

C. C. V. Chan, P. R. Bérubé, E. R. Hall

Surface Shear Forces in Air Sparged Submerged Hollow Fiber Membranes

C.C.V. Chan, P.R. Bérubé, E.R. Hall
Department of Civil Engineering
The University of British Columbia, Canada

CFD Modeling Workshop

Berlin, June 3rd, 2007

Overview

- Research objective
- Experimental set-up
- Results to date
- Ongoing research
  - Relating shear force to fouling
  - Validation and optimization at full-scale
- Summary of results to date

Research Objective

- Fouling control mechanisms are a function of the shear forces imparted onto membrane surfaces
- Limited knowledge exists of surface shear forces in air sparged submerged hollow fiber membranes
- The objective of the present research is to characterize ***surface shear forces*** and fouling control mechanisms in air sparged submerged hollow fiber membrane systems

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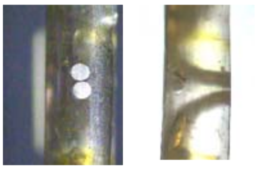
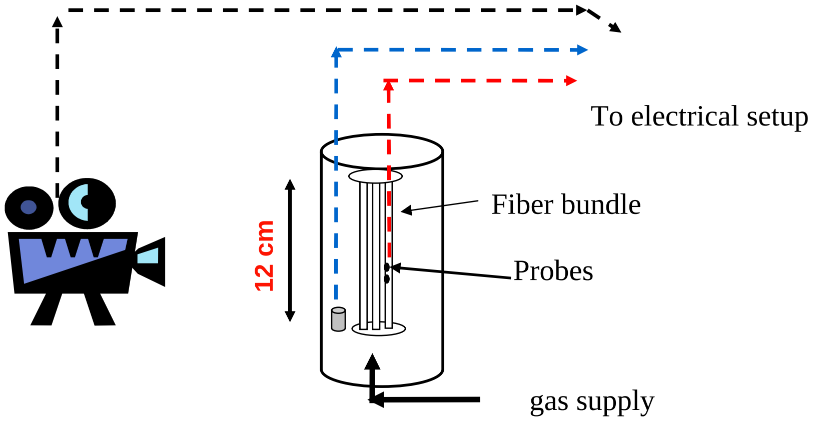
Experimental Set-up

- Electrochemical shear method
  - Magnitude and direction of shear forces
- Fabricated flush to fiber surface



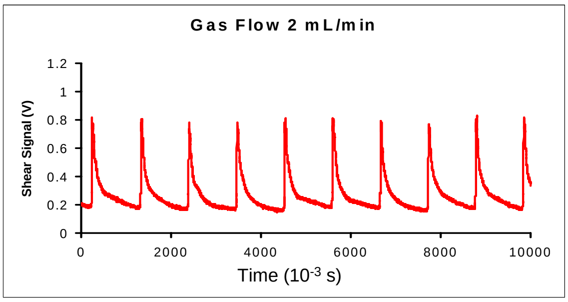
<u>Considered:</u>

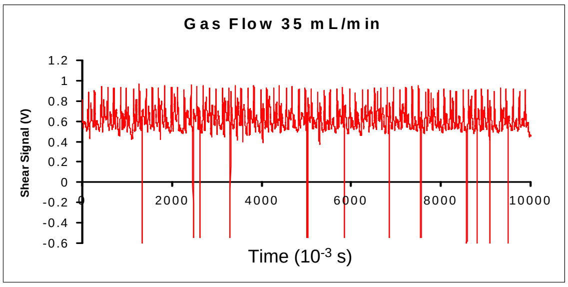
- Diffuser location
  Central and peripheral
- Fiber tightness
  Loose and tight
- Fiber packing density
- Probe location



Results
(Central Bubble Diffuser)

- Bubbles introduced center of the fiber bundle
- Tightly held fibers
  - Imaging indicated that highest forces induced by wake of rising bubble
  - Typically no flow reversal
    - Some at high flow rate and packing density

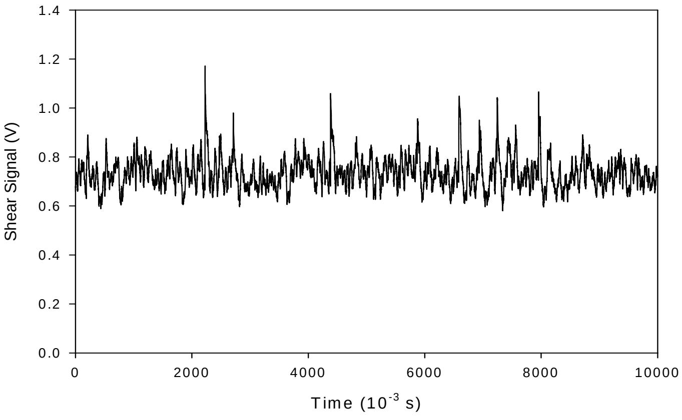




(Adapted from Chan *et al.*, 2007)

Results
(Central Bubble Diffuser)

- Loosely held fibers
  - Again
    - Highest forces in wake
    - No flow reversal
  - Overall lower shear
  - No repeating profiles
    - Bubbles ‘escaped’ from bundle
  - Shear function of:
    - Air flow rate
    - Packing density
    - Bubble size and position

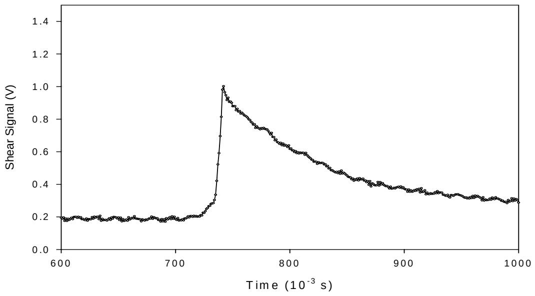


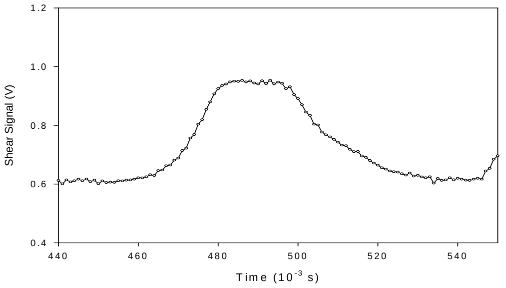
(Adapted from Chan *et al.*, 2007)

Results

Closer look at Shear Profiles

- Different shear profiles observed depending on bubble characteristics
  - Bubble size
  - Bubble shape
  - Bubble flow path
  - Distance from membrane



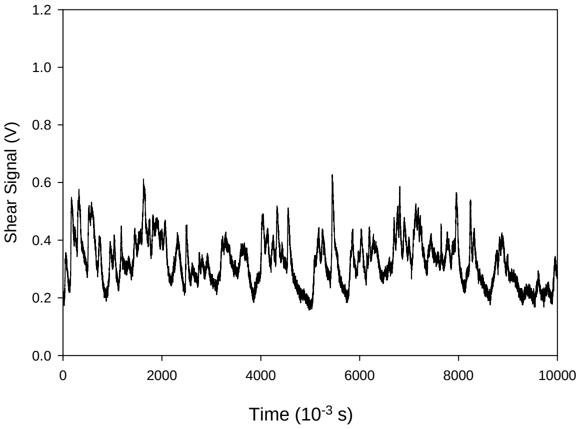


(Adapted from Chan *et al.*, 2007)

Results

(Peripheral Bubble Diffuser)

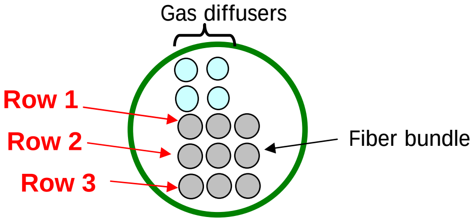
- Bubbles introduced outside of the fiber bundle
  - Again
    - highest forces in wake
    - No flow reversal
    - No repeating profiles
  - Shear lower than with central aerator
  - Shear function of:
    - Air flow rate
    - Packing density
    - Bubble size and position
    - Fiber location

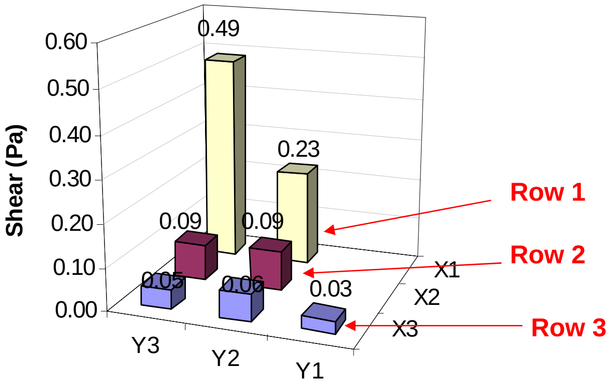


Results

(Peripheral Bubble Diffuser)

- Shielding Effect
  - Shielding of fibers not directly adjacent to bubble
  - Shear on shielded fibers not highly variable





Results

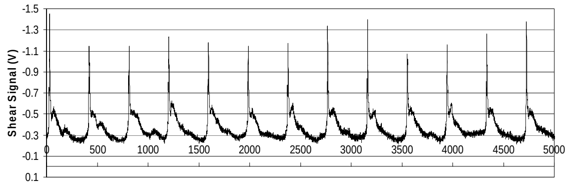
(Fiber Movement and Contact)

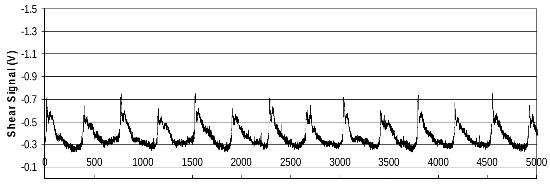
- Fiber movement
  - generates more homogeneous shear distribution

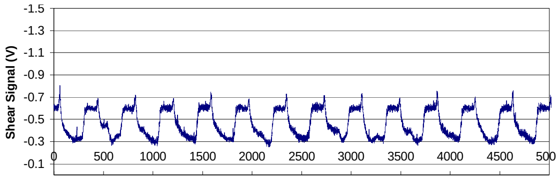
- Physical contact
  - can potentially generate shear that is substantially higher than that from sparging
    - 15 to 30 Pa vs. 2 to 4 Pa

Ongoing Research
(Relating Shear Force to Fouling)

- Shear forces are highly variable
  - Frequency, magnitude, duration, location
- Which is most important with respect to fouling control?
- Relate shear to fouling
  - Create controllable surface shear conditions
  - Conduct fouling experiments under these conditions







Ongoing Research
(Validation and Optimization at Full-Scale)

- Mapping of full-scale modules (GE-Zenon ZW500x3)
- Map shear at 260 ‘locations’ with 65 shear probes
- Consider
  - Fiber spacing
  - Fiber tightness
  - Sparging intensity
  - Location of diffusers
  - ***Fiber contact***

Summary of Results to Date

- Shear forces in air sparged submerged hollow fiber membrane systems are NOT similar to those in confined systems
- Surface shear forces are highly variable in terms of frequency, magnitude, duration, location
- Fiber movement, with or without air sparging, generates relatively homogeneous and high surface shear
- Fiber contact is potentially an important shear inducing mechanism
- Ongoing studies to investigate mechanisms of fouling control and measure shear at full-scale

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Acknowledgements

- Natural Science and Engineering Research Council of Canada (NSERC)
- Canadian Water Network (CWN)
- GE-Zenon

List of Relevant Publications

- Chan C.C.V., P.R. and Hall E.R. (2007) Shear profiles inside gas sparged submerged hollow fiber membrane modules. Journal of Membrane Science, 297(1-2) 104-120.

- Bérubé, P.R., Afonso, G., Taghipour, F. and Chan, C.C.V..(2006), Quantifying the shear at the surface of submerged hollow fiber membranes. Journal of Membrane Science, 279 (1-2) 495.

- Chan C.C.V. , Bérubé P.R. and Hall E.R. Shear stress at radial sections of submerged hollow fiber under gas sparging and the effects of physical contact between fibers on shear profiles., Proceedings of AWWA Membrane Technology Conference, Tampa FL, March 2007

3. EFFECT OF AERATION ON FOULING OF TIGHT HF-MEMBRANE

L. Martinelli, C. Guigui, A. Liné

EFFECT OF AERATION ON FOULING OF TIGHT HF-MEMBRANE

Dr. Laure Martinelli

Pr. Assistant Christelle Guigui Pr. Alain Liné

Workshop CFD Modelling for MBR applications

"From the fibre to the plant"

3 June 2007- Berlin

Hydrodynamics induced by aeration - Outside / In HF

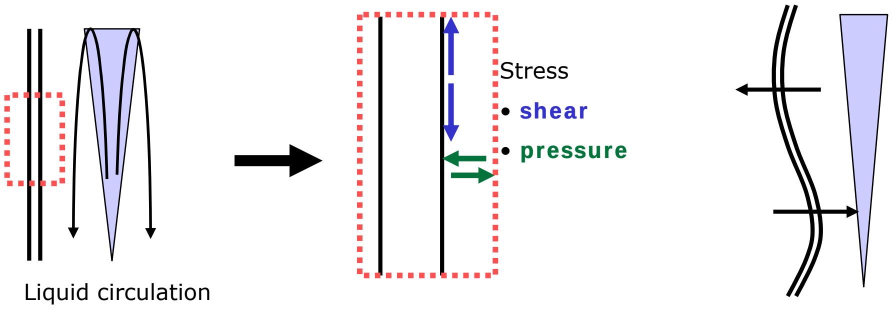
Injection of air near HF bundle

≠ aeration → ≠ hydrodynamics

Fine bubbles → Continuous Flow

Spherical cap → Intermittent flow

Phenomena induced by 2-phase flow hydrodynamics



Liquid circulation

Stress
- **shear**
- **pressure**

Possible fibre motion

1- Influence of aeration on hydrodynamics

Experiments, CFD	**Fines bubbles** **Spherical cap**

2- Influence of aeration on filtration performances

Filtration experiments	**Fines bubbles** **Spherical cap**

3- Link between hydrodynmaics and filtration performances

Influence of wall shear stress

Influence of liquid flow induced by aeration

M & M | **Hydrodynamics** | **Filtration**

Lab Scale pilot

Filtration tank: Glass tank (90 L)

HF-Bundle

5 hollow-fibres (polysulfone)

S_f = 0.032 m²

Fibres Tightness adjusment

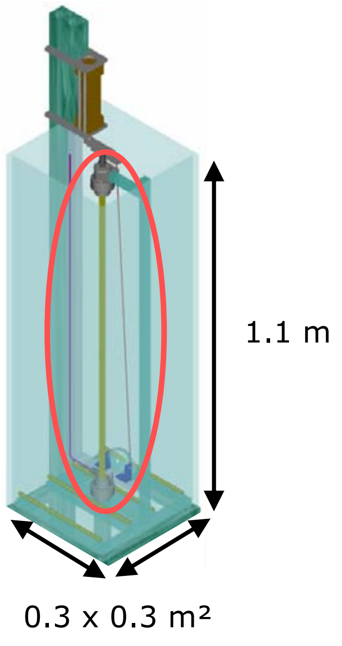
Tight fibres

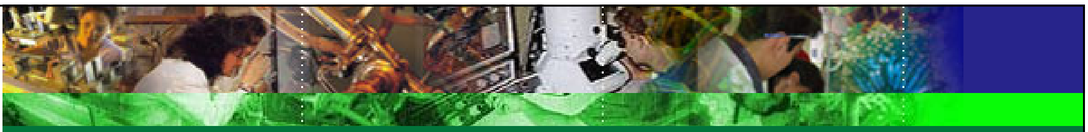
Loose fibres

Aeration system

Fines bubbles (3mm)

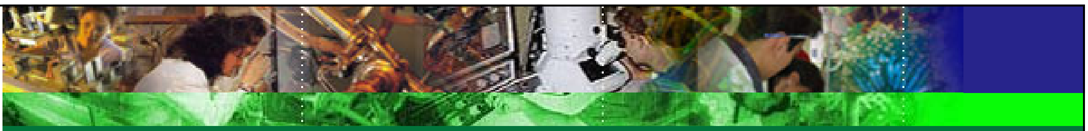
Spherical cap bubbles (few cm)



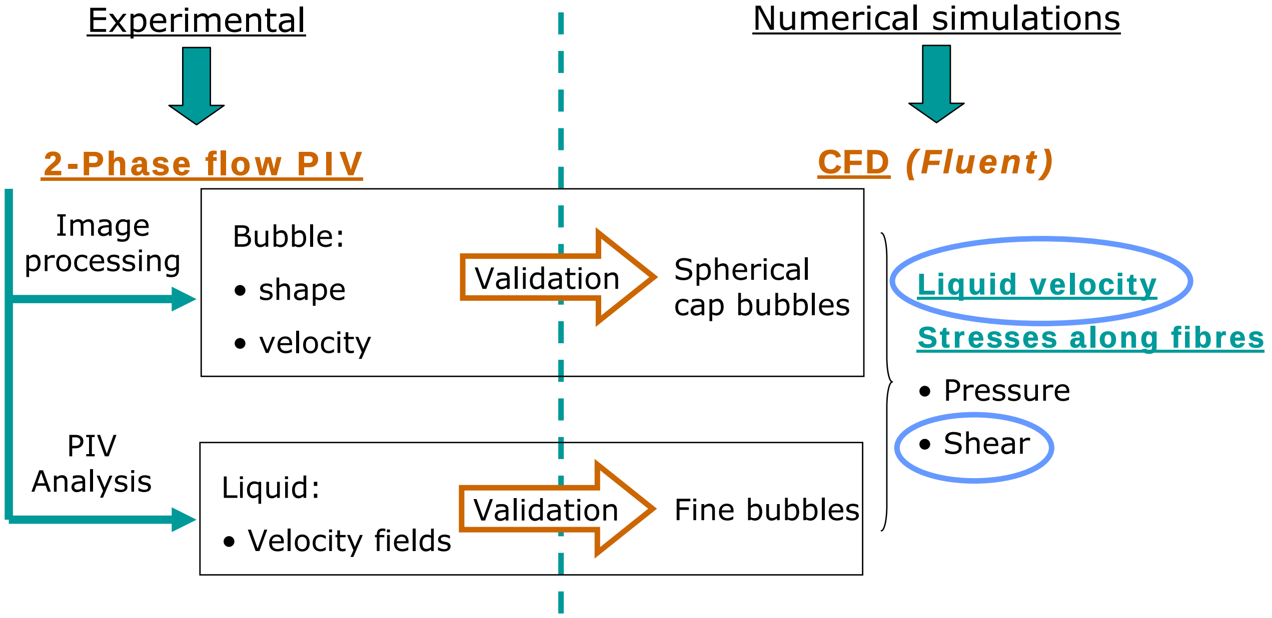


Aeration conditions

Bubble type	Global air flow rate		
Fine bubbles	30 $l.h^{-1}$		
	100 $l.h^{-1}$		
Spherical cap bubbles	Frequency = 1 / 6 s^{-1}	14 cm^3	8.4 $l.h^{-1}$
		27 cm^3	16.2 $l.h^{-1}$
		55 cm^3	33 $l.h^{-1}$



Characterisation of 2-phase flow hydrodynamics



Experimental

2-Phase flow PIV

Image processing

Bubble:
- shape
- velocity

Validation

Spherical cap bubbles

PIV Analysis

Liquid:
- Velocity fields

Validation

Fine bubbles

Numerical simulations

CFD *(Fluent)*

Liquid velocity

Stresses along fibres
- Pressure
- Shear

CFD *(FLUENT)*

Two types of bubbles

Spherical cap bubbles | Fine bubbles

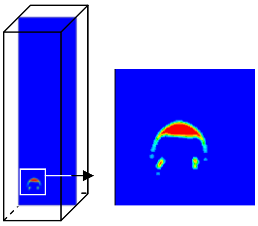
Two hydrodynamics

One bubble
Intermittent flow

Bubble swarm
Continuous flow

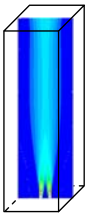
Two 2-phase flow models

Volume Of Fluid | Euler-Euler



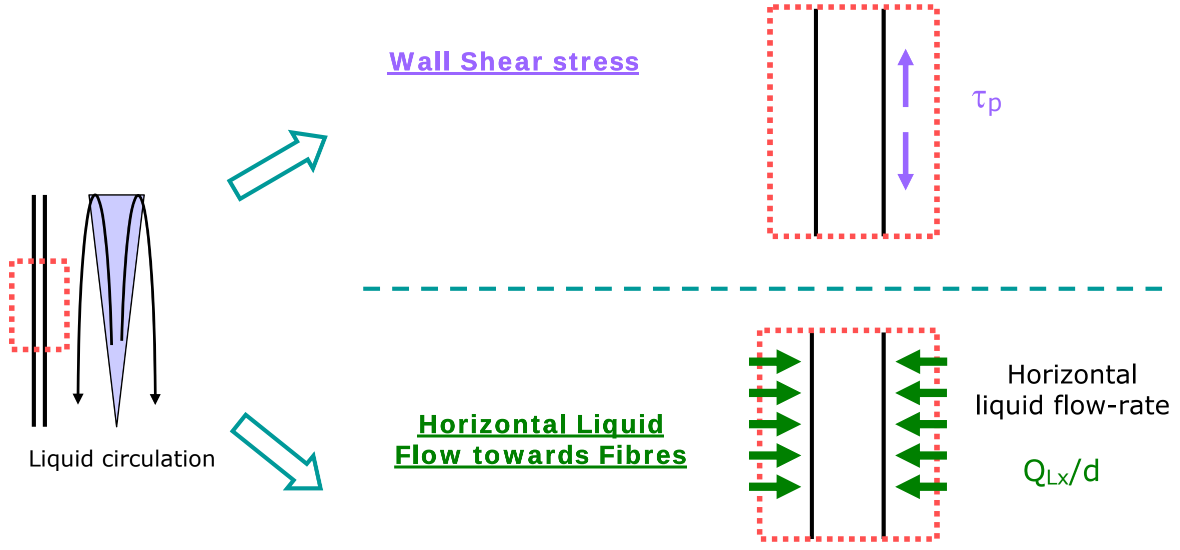
Numerical simulations

2D



CFD - Hydrodynamics results

- **Wall shear stress**
  Fine bubbles
  Spherical cap bubbles
- **Liquid flow towards fibres**
  Fine bubbles
  Spherical cap bubbles



Wall Shear stress

τ_p

Horizontal Liquid Flow towards Fibres

Horizontal liquid flow-rate

Q_{Lx}/d

Liquid circulation

2D numerical simulations → Calculated per depth unit

Horizontal liquid flow toward fibres

Bubble type	Global air flow rate			τ_p (Pa)	Q_{Lx} / depth $cm^3.s^{-1}.m^{-1}$
Spherical cap bubbles	Frequency = 1 / 6 s^{-1}	14 cm^3	8 $l.h^{-1}$	0.07	134
		27 cm^3	16 $l.h^{-1}$	0.1	308
		55 cm^3	33 $l.h^{-1}$	0.25	402
Fine bubbles	30 $l.h^{-1}$			0.015	144
	100 $l.h^{-1}$			0.075	302

Filtration experiments

Operating conditions

Outside/in Filtration: Constant filtration flux

Supercritical conditions: 50 l/h.m²

4 Hours

Performances = Fouling Hydraulic Resistance (Rc) $R_c(t) = \frac{\Delta P(t)}{J\mu} - R_{membrane}$

Suspension : Washed Baker Yeast *(Saccharomyces Cerevisiae)*

Rewetted (pH7, [NaCl] = 9 $g.l^{-1}$)

Concentration: 0.56 ± 0.02 $g.l^{-1}$

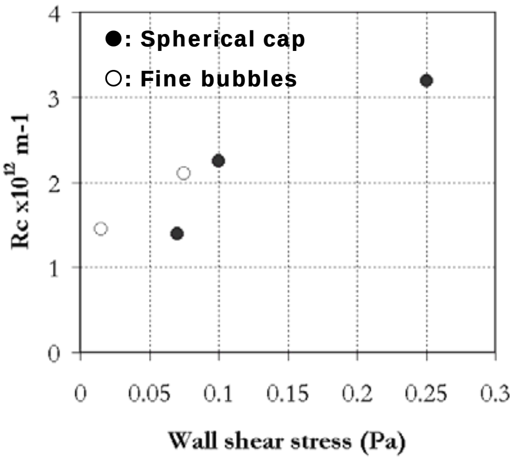
Size : $d_{0.5}$ = 4.8 ± 0.2 µm

Filtration results

Bubble type	Global air flow rate		Local air flow rate
Fine bubbles	30 $l.h^{-1}$		5 $l.h^{-1}$
	100 $l.h^{-1}$		16 $l.h^{-1}$
Spherical cap bubbles	Frequency = 1 / 6 s^{-1}	14 cm^3	8 $l.h^{-1}$
		27 cm^3	16 $l.h^{-1}$
		55 cm^3	33 $l.h^{-1}$

Filtration vs Hydrodynamics - Tight Fibres

Influence of wall shear stress



Wall shear stress remains low

< 1 Pa

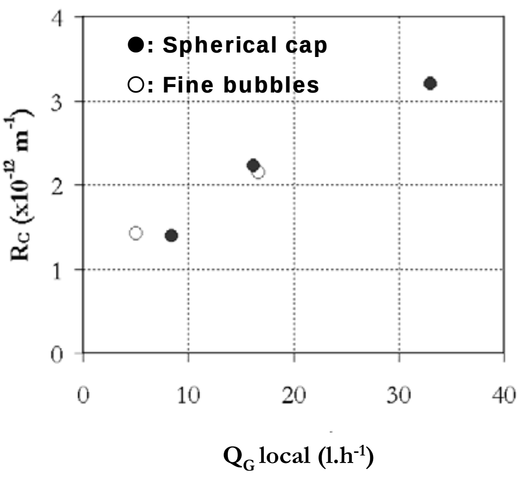
Filtration performances decrease when wall shear stress is increased

Tight fibres :

No influence of wall shear stress

Filtration vs Hydrodynamics - Tight Fibres

Influence of local air flow rate



Tight fibres :

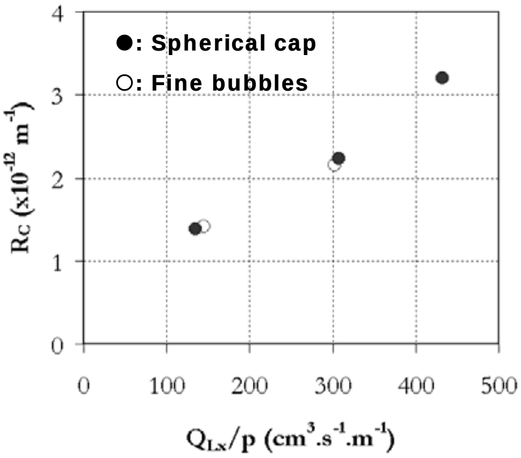
Which aeration conditions controll filtration performances ?

Air flow rate in membrane area

M & M > Hydrodynamics > **Filtration**

Filtration vs Hydrodynamics - Tight Fibres

Influence of liquid flow-rate towards fibres



Filtration flux:

50 $l.h^{-1}.m^{-2}$ ⟷ 35 $cm^3.s^{-1}.m^{-1}$

Tight fibres :

Mecanisms controlling filtration performances:

Matter deposit induced by liquid flow towards fibres

CONCLUSION

Influence of aeration on the fouling of tight HF-Membrane

- Characterisation of 2-phase flow: **PIV** (experimental) and **CFD**
- Hydrodynamic analysis to explain filtration performances

  No influence of wall shear stress

  Matter deposit induced by liquid flows towards fibres

Case of loose fibres

Competition

- Matter deposit induced by liquid flows towards fibres
- Fibre shaking (induced by **spherical cap**)

Results with tight fibres Communication in SFGP (French conference)

Publication being written (Journal of Mem. Sc.)

Results with loose fibres Publication being written (Journal of Mem. Sc.)

4. HYDRODYNAMIC CFD SIMULATION OF A TWO-PHASE FLOW IN A TUBULAR UF MEMBRANE IN A SIDE STREAM MBR AND PBM,

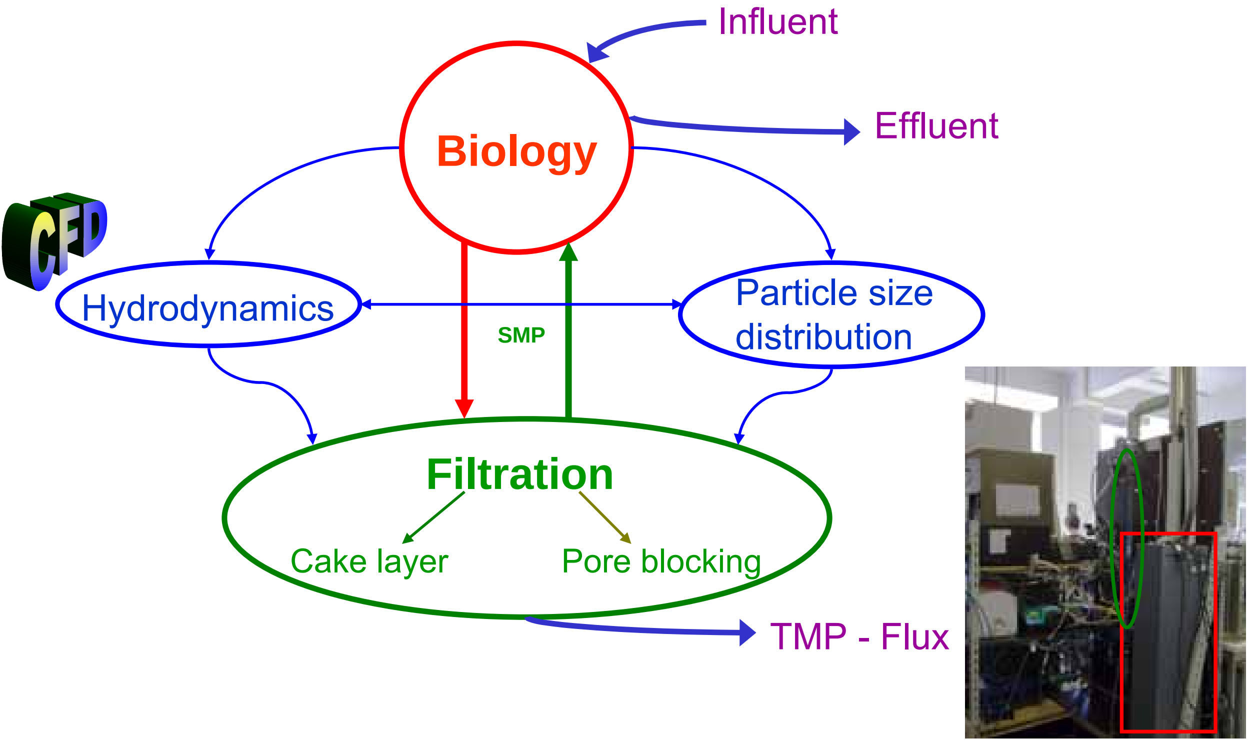
N. Rios, I. Nopens

Hydrodynamic CFD simulation of a two-phase flow in a tubular UF membrane in a side-stream MBR

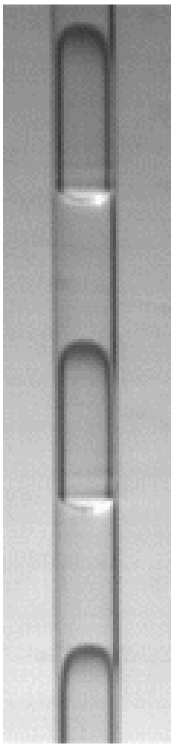
Nicolas Rios and Ingmar Nopens

CFD workshop
June 3rd 2007, Berlin - Germany

Biomath MBR research



Hydrodynamics CFD



Numerical model

- Software
  - Fluent®
- Methodology
  - Two-phase model (sludge + air)
  - Volume of fluid (VOF)
    - > Slug flow: large (Taylor) bubbles in a continuous liquid
  - Laminar model
  - Constant physical properties
  - Shear stresses → membrane surface
  - No filtration

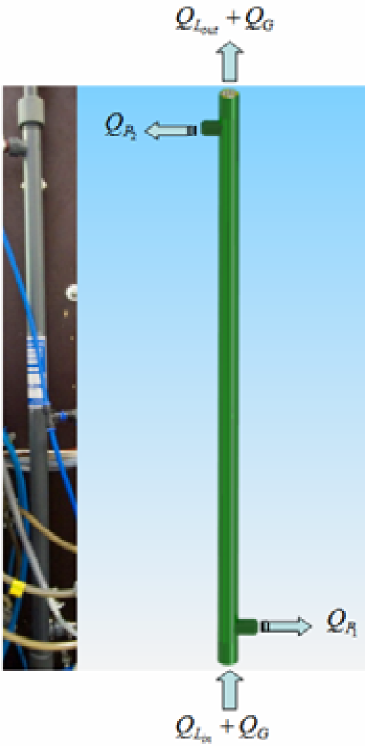
Hydrodynamics CFD

Membrane

- Ultrafiltration membrane
- Manufactured by Norit: X-Flow
  - Tubular: 12 tubes
  - Length: 1 m
  - ID: 5.2 mm
  - Surface area: 0.17 m^2
  - Pore size: 30 nm
  - Material: PVDF

Hydrodynamics CFD

- Gas-liquid flow rates
  - Sludge: 7.6 l min^{-1}
  - Air: 7.6 l min^{-1}
  - Permeate flux: 31.8 LMH
  - Filtration: <1.2 %
  - Assumption:
    - In- and outlet sludge flow rates are the same



Hydrodynamics CFD

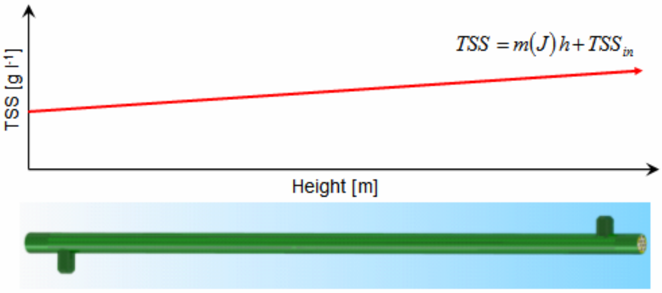
- Physical properties of the phases (at 15ºC)
  - Air (tables)
    - Density: 1.228 kg m^{-3}
    - Viscosity: $1.76 \cdot 10^{-5}$ Pa s
  - Sludge (TSS = 10 g l^{-1})
    - Density: 1002 kg m^{-3}
    - Viscosity: 0.0088 Pa s
  - Surface tension (Wilhelmy Plate)
    - Air-sludge: 0.073 N m^{-1} (≈ air-water)

Hydrodynamics CFD

Viscosity

- CVO Bohlin rotational rheometer
- Non-Newtonian behavior
- Shear stress-rate
- TSS
- Velocity (u_{SL})
- Diameter of the pipe (d)
- Fluid consistency index (k)
- Flow behavior index (n)

$$\mu_L = 8^{-1}\left(\frac{6n+2}{n}\right)^{n} k\, u_{SL}^{n-1}\, d^{1-n}$$

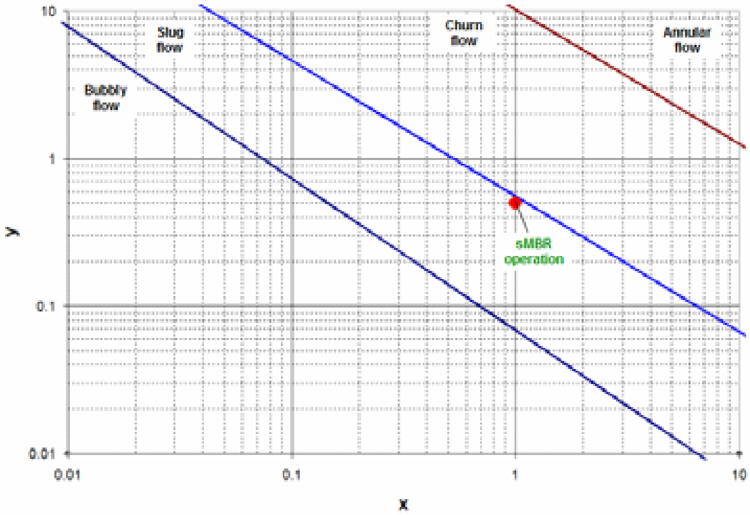


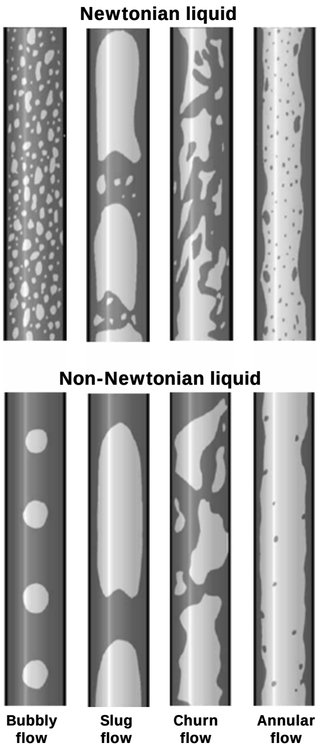
Hydrodynamics CFD

Flow pattern

- 4 flow patterns
- Newtonian or non-Newtonian fluid
- Velocity and density (gas-liquid)

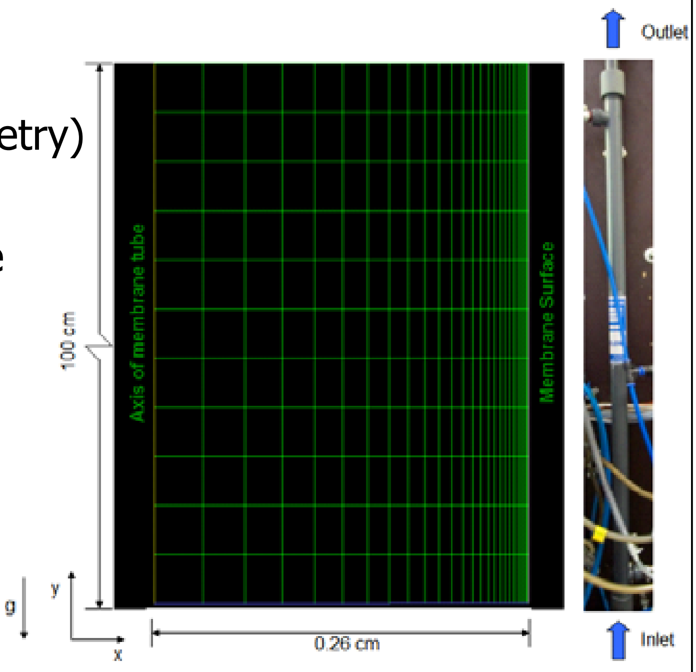
Flow pattern map for sludge-air





Hydrodynamics CFD

- Model geometry
  - Vertical symmetry
  - 2D model (axial symmetry)
  - Software: Gambit v2.2
  - Fine grid (shape of the bubble)
  - Grid: 26 x 2960



Hydrodynamics CFD

- Laminar or Turbulent regime?
  - Flow in a tube
    - Reynolds number: Identify the flow regime
    - For air:

$$\mathrm{Re}_{SG} = \frac{\rho_G u_{SG} d}{\mu_G} = 180$$

    - For sludge: Modification due to the fact that is a non-Newtonian fluid (Metzner and Reed Reynolds number)

$$\mathrm{Re}_{MR} = 8\left(\frac{n}{6n+2}\right)^n \frac{\rho_L u_{SL}^{2-n} d^n}{k} = 357$$

    - For the mixture

$$\mathrm{Re}_m = \frac{\rho_m u_m d}{\mu_L} = 492$$

  - Laminar (Re<2100)

Hydrodynamics CFD

CFD model

- Software: Fluent® v6.3
- Governing equations
  - Continuity equation (mass conservation)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

  - Momentum for VOF (Navier-Stokes)

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \left[\mu\left(\nabla \vec{v} + \nabla \vec{v}^{T}\right)\right] + \rho \vec{g} + \vec{F}$$

  - Volume fraction (interface liquid-gas)

$$\frac{\partial \alpha_G}{\partial t} + \vec{v} \cdot \nabla \alpha_G = 0 \qquad \alpha_G + \alpha_L = 1$$

  - Surface tension

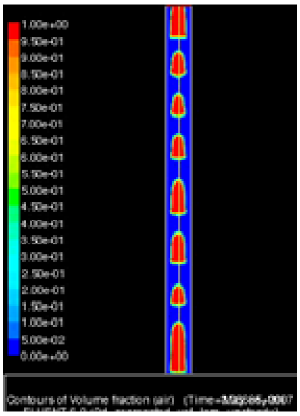
$$p = \sigma \kappa$$

- Isothermal (15ºC)
- Transient
- Solution (VOF)
  - Explicit interpolation
  - Geometric reconstruct discretization (surface tracking)
  - Momentum: 2nd upwind scheme
  - Pressure-velocity: PISO

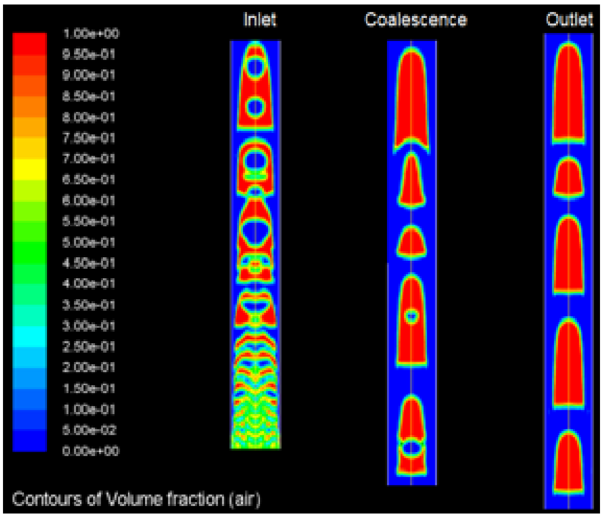
Hydrodynamics CFD

Simulation

- Bubbles have the specific Taylor bubble shape
- Bubbles have different sizes due to coalescence (wake generates acceleration on the previous bubble)



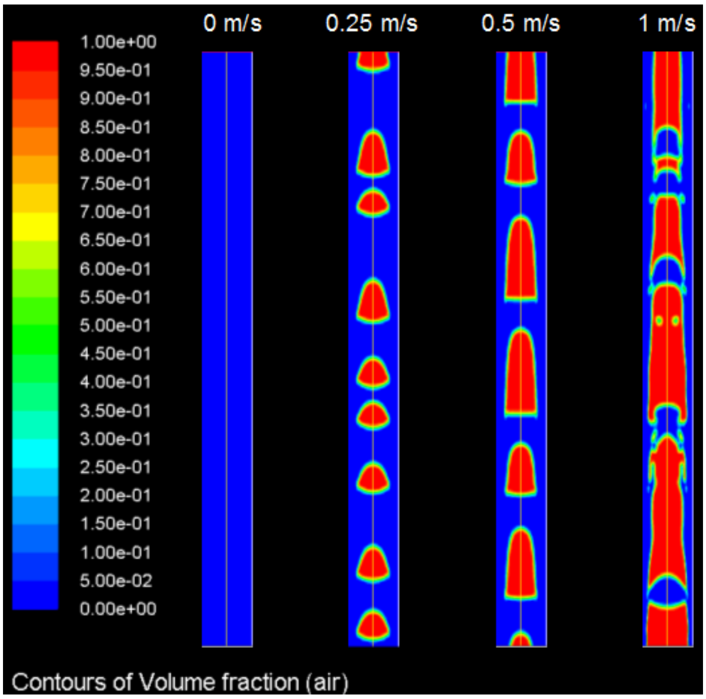
Sludge-air: 0.5-0.5 m/s



Hydrodynamics CFD

Simulation

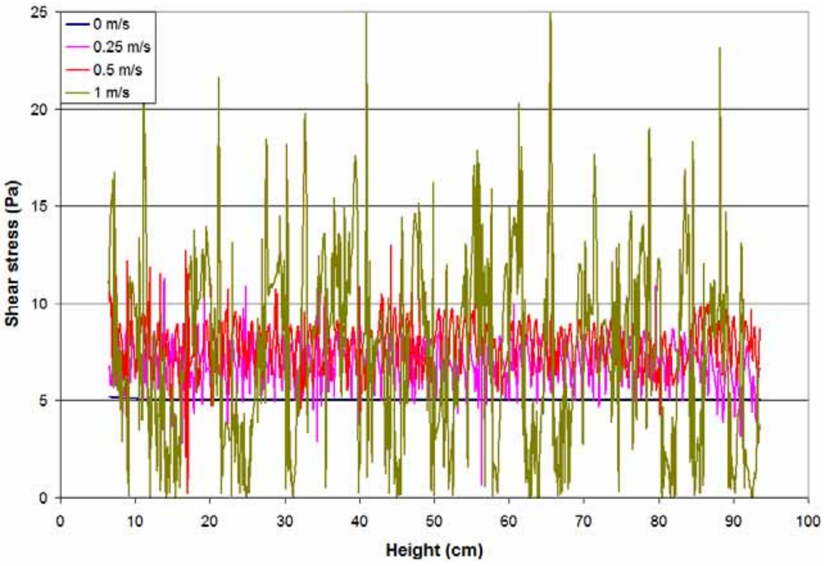
- Constant sludge velocity (0.5 m/s)
- Varying air velocity from 0 to 1 m/s

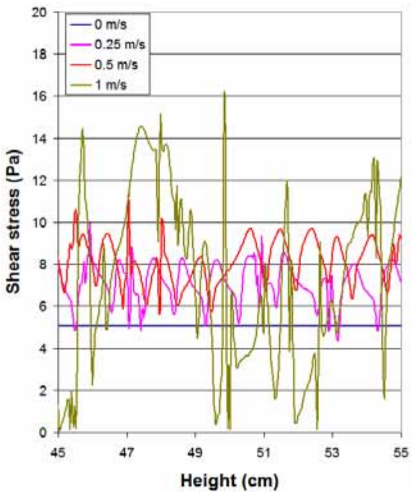


Hydrodynamics CFD

Simulation

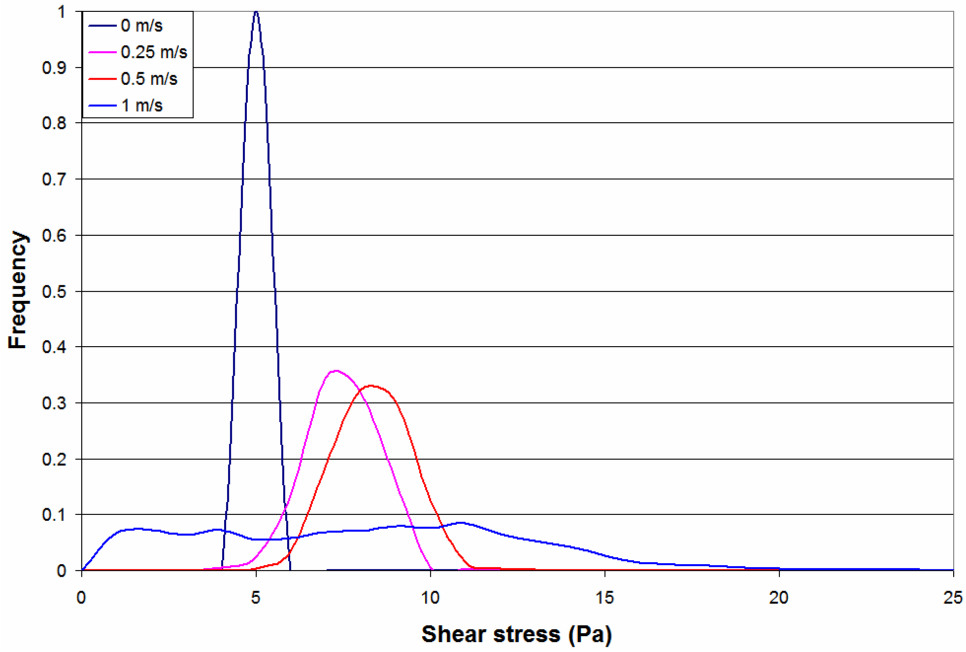
- Shear stress oscillates due to the continuous passing of bubbles near the membrane surface.
- At a determine location (and time) of the membrane, a variety of shear stresses occurs at a certain frequency





Hydrodynamics CFD

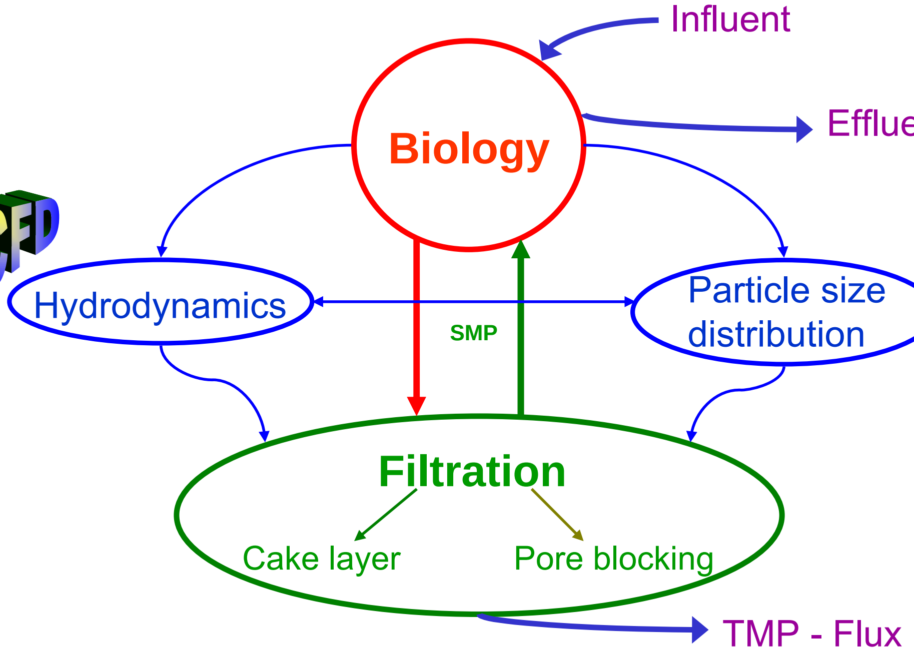
- Simulation
  - Histogram: range of shear stresses and frequency of this exposure

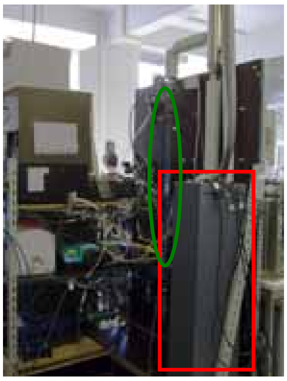


Conclusions Hydrodynamics CFD

- A two-phase flow model (sludge-air) inside a single membrane tube implemented in Fluent® using the VOF approach.
- A 2D-axisymmetric geometry used with the fine mesh to capture the bubble shape and the shear stress near the membrane surface.
- Preliminary simulations performed using constant physical properties resulting in a slug flow.
- Simulation with different air velocities performed to observe flow pattern and shear stress the membrane surface is exposed to, quantified as histograms.
- The bubble shape and the shear stress range changes significantly with increasing air velocities.

Biomath MBR research



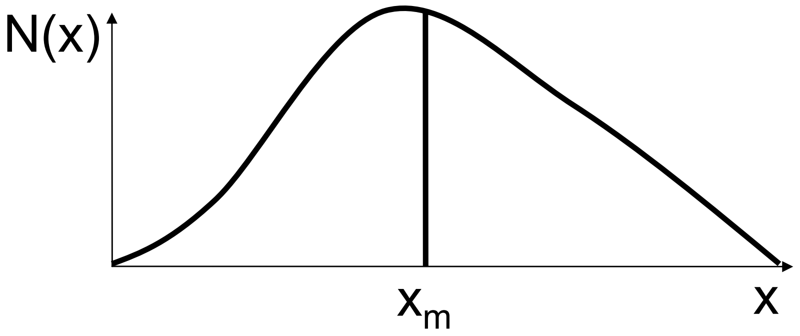


Modelling particle size distributions

- Many environmental systems contain *populations of individuals*
  - Population → particles, flocs, bubbles, organisms, cells, ...
- Properties of these populations
  - Properties → size, density, composition, cell age,...
  - hardly ever homogeneous → distributed

Modelling particle size distributions

- Is this individuality important?
  - Does property averaging affect the conversion model outputs?



Modelling particle size distributions

- How can individuality be important?
  - Do individuals with a certain level of a property react significantly different to environmental influences?
  - E.g. property = floc size
    - Shear, substrate availability, toxicity, DO, ...
  - Are particle-particle or multi-phase interactions important?
    - Flocculation, Flotation, Filtration, Hydrolysis
  - Simplifying assumption might lead to inaccurate results

➡ Suitable framework needed

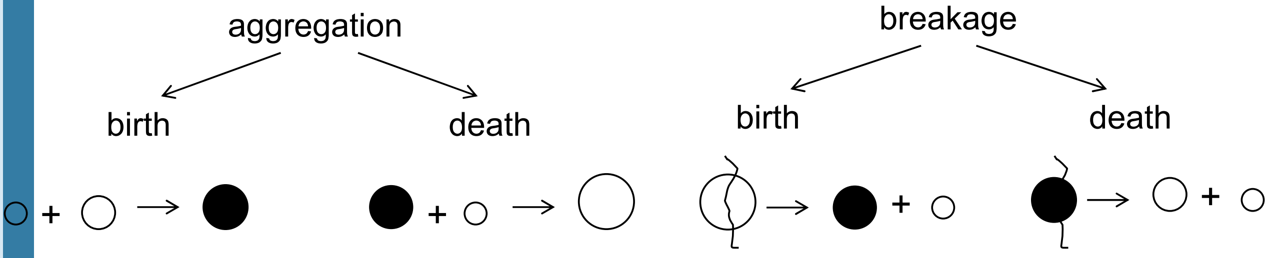
Population Balance Models

- General one-dimensional PBM (Ramkrishna, 2000) without growth

Floc of size x

$$\frac{\partial f(x,t)}{\partial t} = h(x,t)_{agg} + h(x,t)_{break}$$

- Birth and death concept



$$h(x,t)_{agg} = \int g(\alpha(x,x'),\ f(x,t),\ f(x',t))$$

$$h(x,t)_{break} = \int h(S(x),\ \Gamma(x',x),\ f(x,t))$$

Population Balance Models

- Challenges
  - Find kernels
  - Coupling with CFD
    - Indirect: compute fields and use in PBM
    - Direct: reduce number of classes

    - PBM-add-on available in Fluent 6.3

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- De Clercq, B., Nopens, I., Kinnear, D., Vanrolleghem, P. (2007). Low shear rheological behaviour of biological solids in secondary settling tanks. Wat. Res. (Submitted)
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- Rios, N., Nopens, I., Jiang, T., De Schepper, V., Verstraete, W., Vanrolleghem, P.A. (2007) A rheological model for activated sludge in a side-stream MBR. Proceedings for the international conference on membranes for water and wastewater treatment, May 15-17 2007, Harrogate, UK.
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- Nopens, I., Koegst T., Mahieu K.; Vanrolleghem, P.A. (2005) Population Balance Model and activated sludge flocculation: from experimental data to a calibrated model. AIChE J., 51(5), 1548-1557
- Nopens, I. and Biggs C. (2006) Advances in population balance modeling (editorial). Chem. Eng. Sci., 61(1), 1-2

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MARIE CURIE ACTIONS

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5. CFD APPLIED ON MBR SYSTEM

E. Nguyen Cong Duc, C. Levecq

MBR-TRAIN

CFD applied on submerged MBR system

Evelyne Nguyen Cong Duc, Céline Levecq
KompetenzZentrum Wasser Berlin

CFD/MBR workshop
03.06.07

ANJOU RECHERCHE
VEOLIA ENVIRONNEMENT

KOMPETENZZENTRUM Wasser Berlin

MBR-TRAIN

Content

- Context and Objective
- Materiel and Method
  - The submerged MBR pilot plan
  - The model
  - The measurement campaign
- First results
- Conclusion

Context and objective

Accumulation of particles in MBR system filtration

Understand and diagnose the two-phase flow inside a membrane cassette

Optimisation of existing filtration technologies

- Module and reactor geometry
- Aerator design
- Operation condition

Materiel and Method

Submerged MBR Pilot Plant

Module

✓ 3 commercial modules HF Zenon 500d

✓ 95 m^2 membrane surface

Aeration

✓ 2 Perforated pipes

✓ Ø hole 6mm – 8mm

Geometry

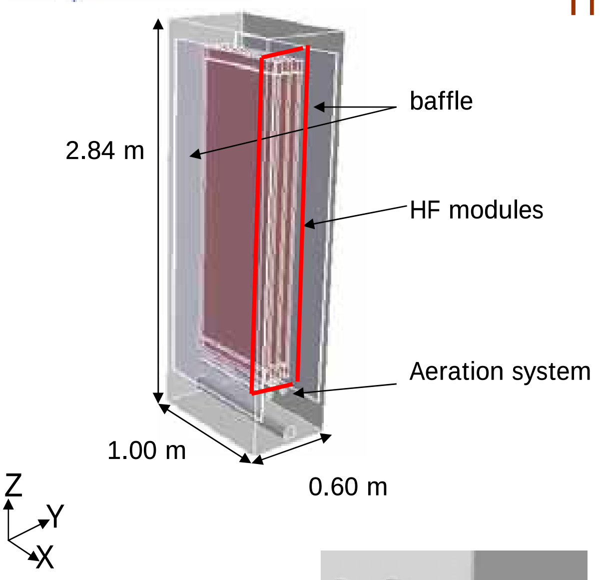
✓ Airlift

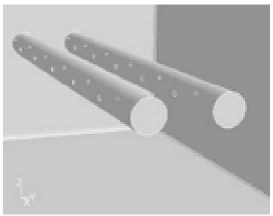
Operation

Gas Flow Rate m^3/h	20	50	90
SAD m^3/m^2/h	0.21	0.53	0.95

Materiel and Method

The Model





Mesh 560 000 cells

Multiphase model
- ✓ Euler-Euler

Turbulence model
- ✓ k-ε model

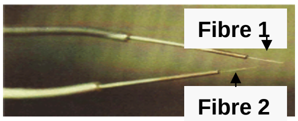
Force
- ✓ Drag force only

Filtration
- ✓ No Filtration model

Viscosity
- ✓ Water
- ✓ Sludge

Materiel and Method

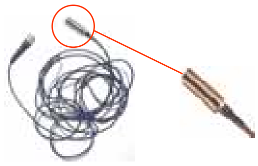
Measurement Campaign



Double optical probe

RBI

Gas phase •
- ✓ Bubble size
- ✓ Void fraction
- ✓ Vertical velocity
- ✓ Bubble frequency

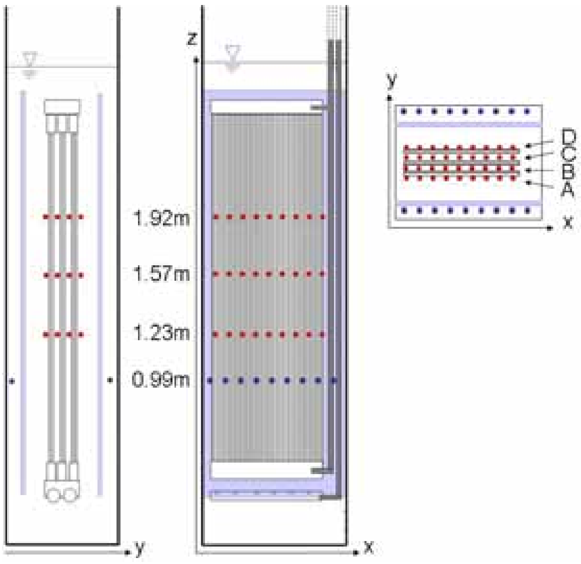


Acoustic Doppler Velocimeter

Met-Flow

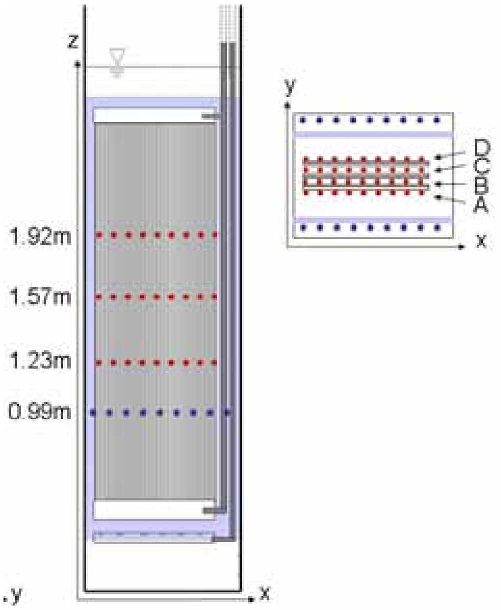
Liquid phase •
- ✓ Vertical velocity

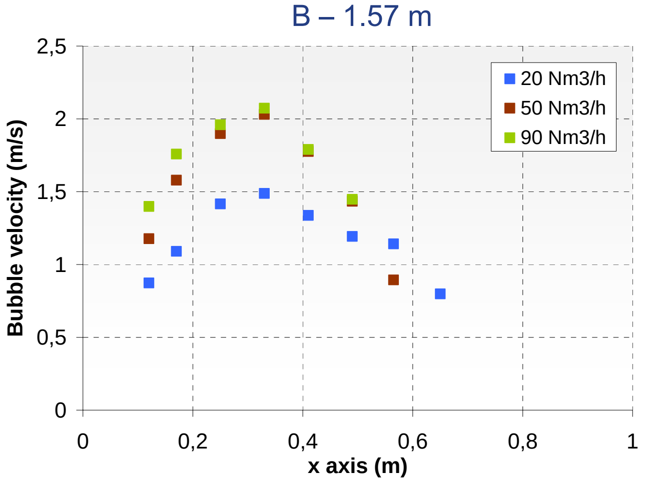
Where?



First Results

Gas velocity profile



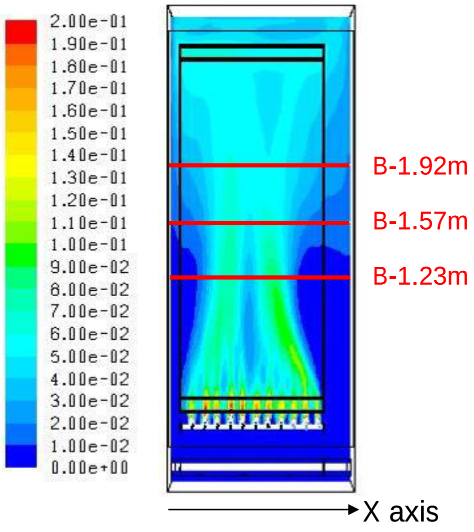


Optimum gas flow rate between 20 and 50 Nm³/h regarding the bubble vertical velocity

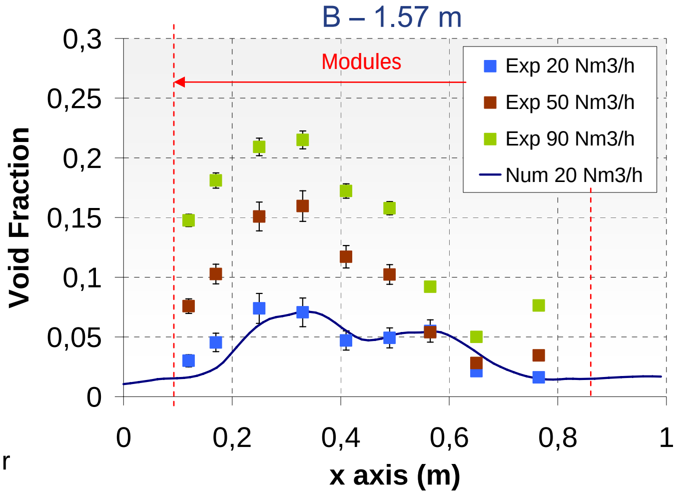
---

First Results

Gas hold-up profile



Contour of the averaged volume fraction of air



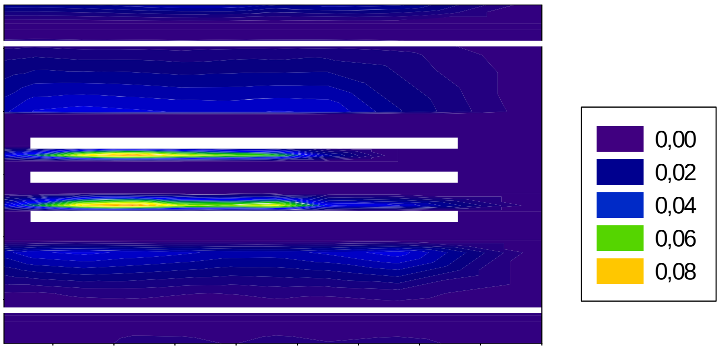
Non-uniform distribution of the air of the module surface

First Results

Air distribution

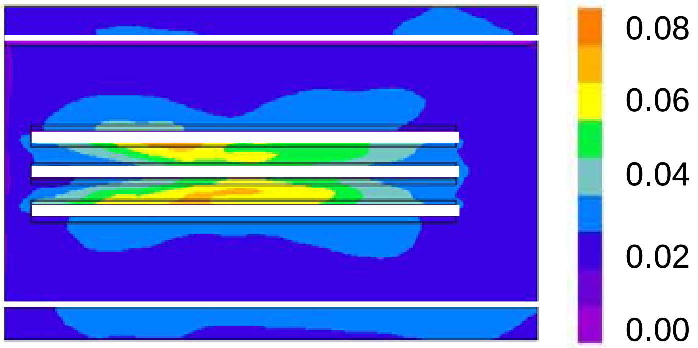
Experimental

Software : Sigmaplot



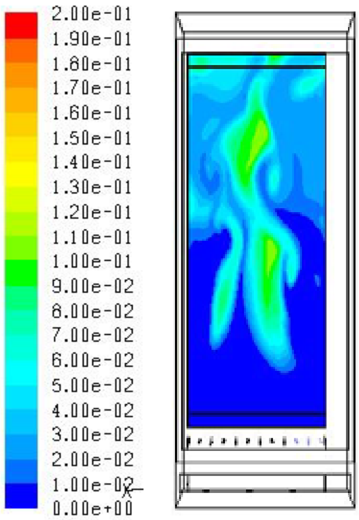
Level 3 top view fo the reactor

Numerical

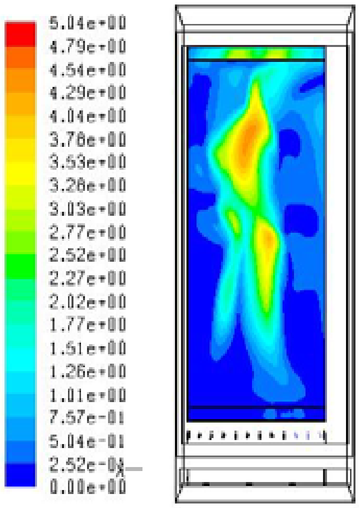


First Results

Wall Shear Stress



Contour of the **volume fraction of air**

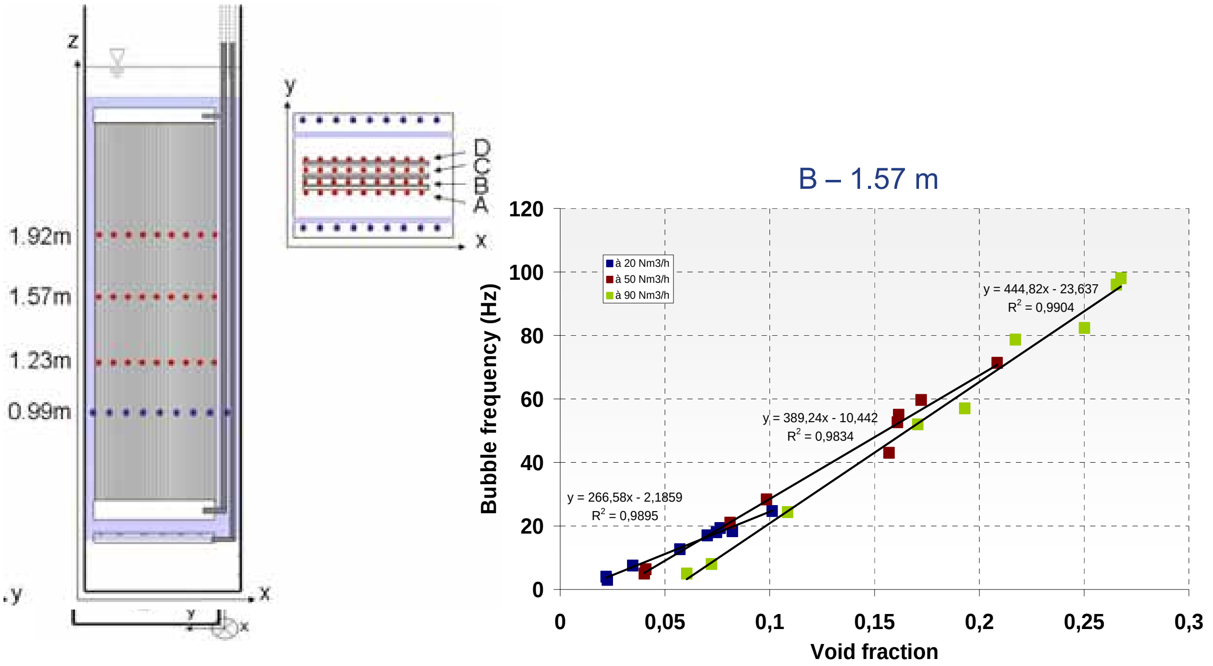


Contour of **water wall shear stress**

Wall shear stress seems to be linked to void fraction

First Results

Bubble frequency



Bubble frequency is proportional to void fraction

Conclusion

- Significant parameters (Wall shear stress, Bubble frequency) seem to be linked to void fraction
  - The knowledge of the effective distribution on module surface of the air is particularly challenging
- Experimental results show that air is not uniformly distributed on the module surface
  - Impact on membrane filtration behaviour
- The numerical model developped will help to diagnose the flow field inside submerged membrane cassette
  - Optimisation can be efficiently undertaken

Related Publications

- NGUYEN CONG DUC E., FOURNIER L., LEVECQ C., LESJEAN B. (2007) Hydrodynamic investigation of the aeration in a pilot immersed Membrane Bioreactor . *IWA Particle Separation Conference, 9-12 July 2007, Toulouse France*

- NGUYEN CONG DUC E., FOURNIER L., LEVECQ C., LESJEAN B., TAZI-PAIN A. (2007) Etude hydrodynamique d’un BioRéacteur à Membranes Immergées à l’échelle pilote . *Récents Progrès en Génie des Procédés – Numéro 96 – 2007 ISBN 2-910239-70-5, Ed. SFGP, Paris, France*

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6. INVESTIGATION OF THE VELOCITY FLOW PATTERN WITH THE HELP OF ACOUSTIC DOPPLER VELOCIMETRY (ADV)

D. Tacke, H. Prieske

Investigation of the Velocity Flow Pattern with the Help of Acoustic Doppler Velocimetry (ADV)

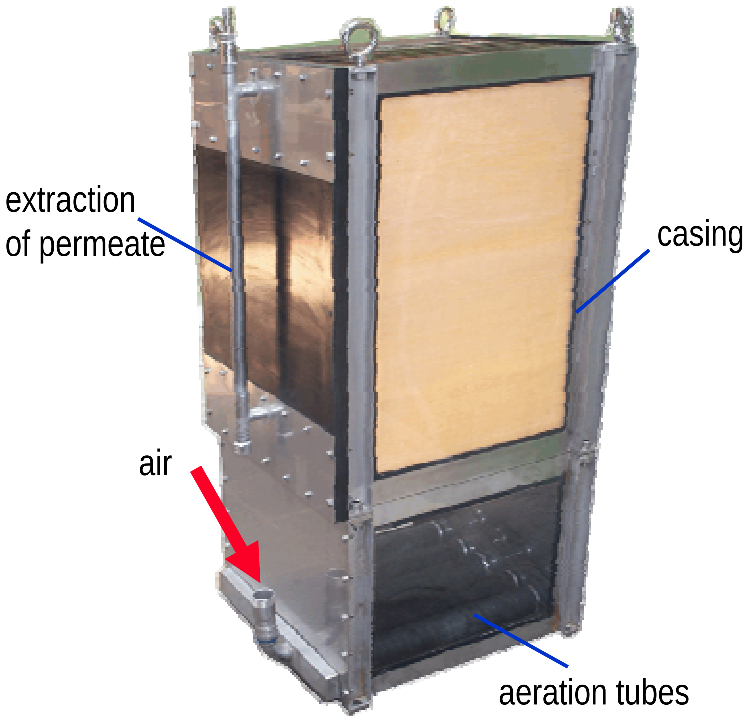
Dipl.-Ing. Daniela Tacke

Institute of Environmental Engineering

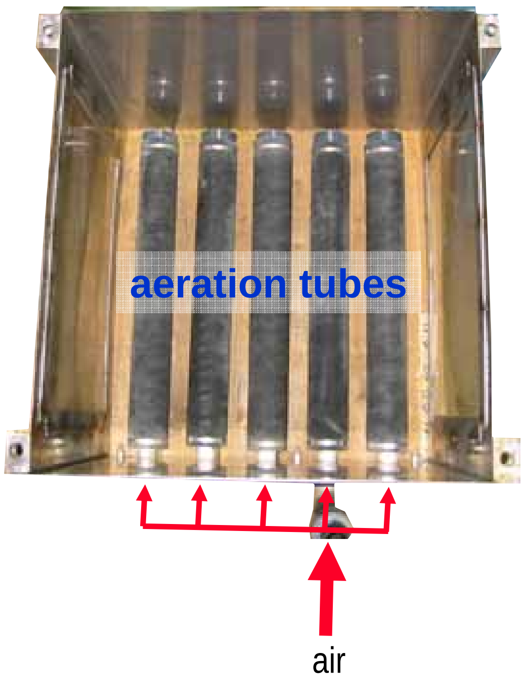
RWTH Aachen University, Germany

Flat Sheet Membrane Module A40

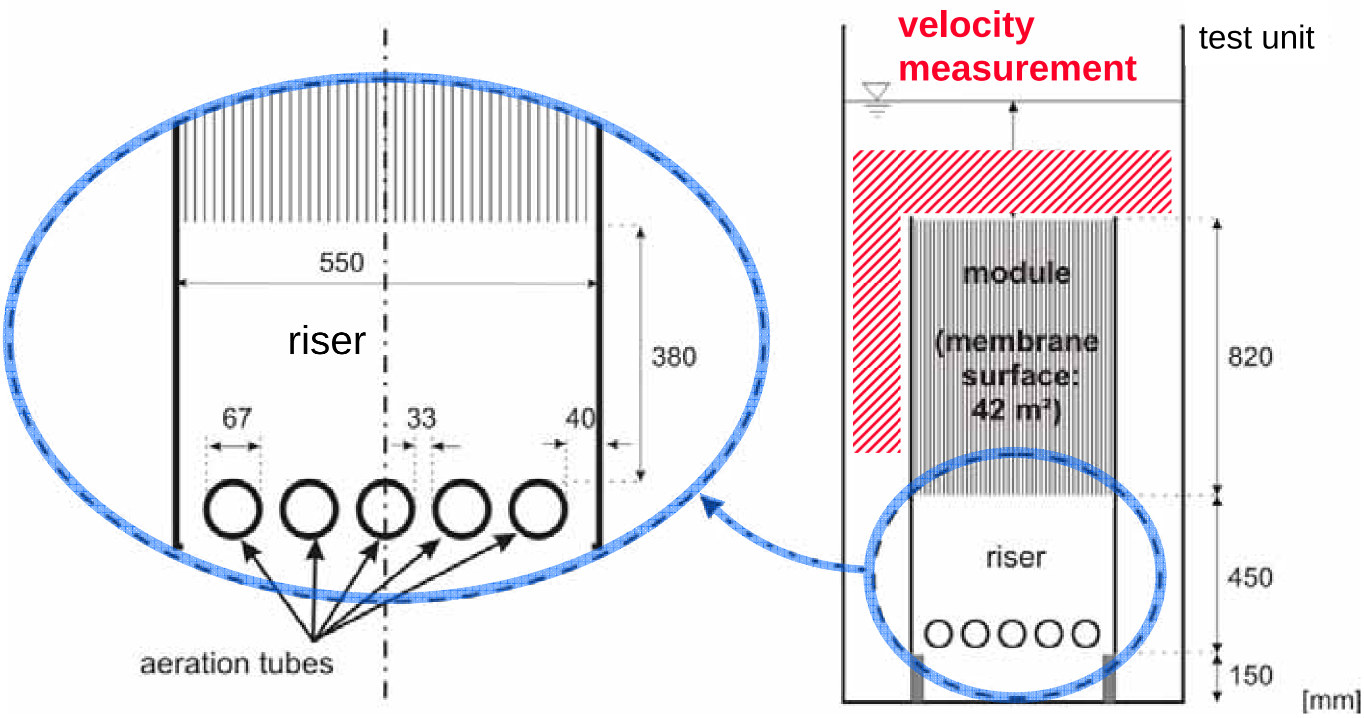
A3 water solutions GmbH



part of the riser (cross section)

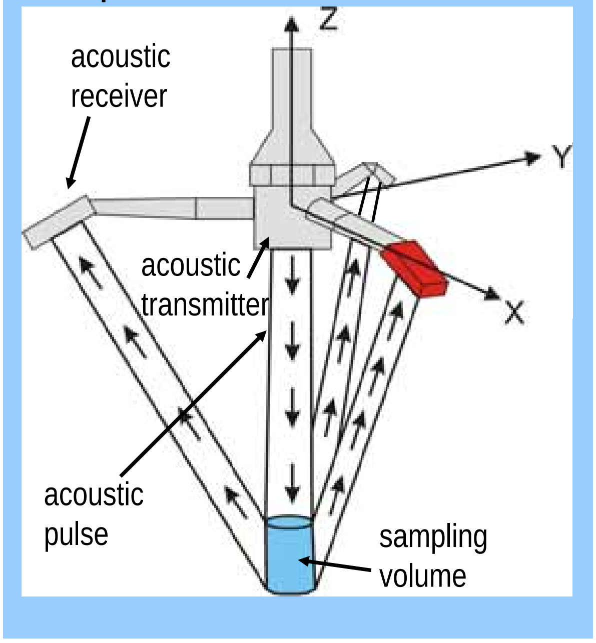


Example of an Experimental Setup (Schematic)



Acoustic Doppler Velocimetry (ADV)

adv probe:

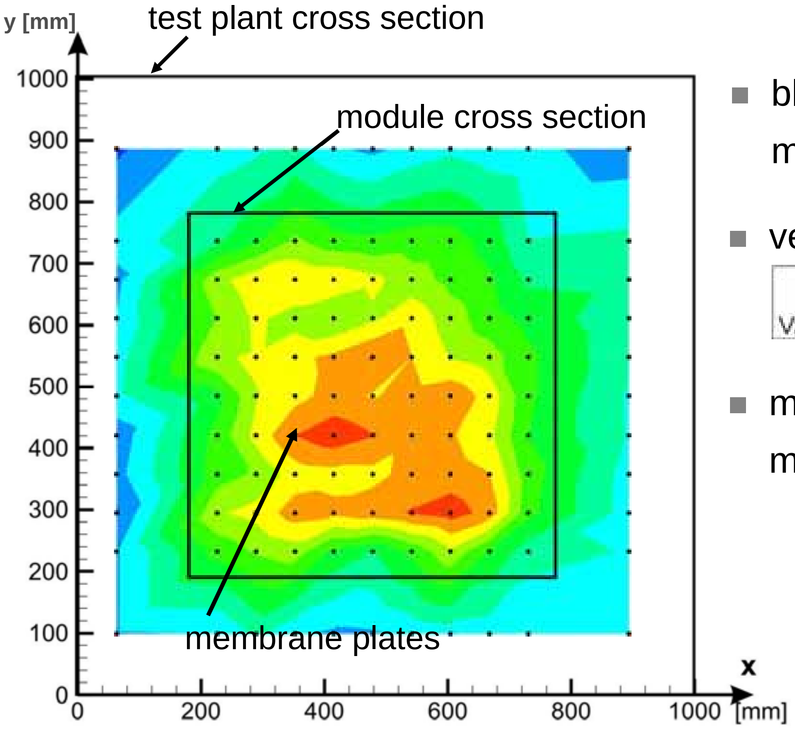


- transmission of a short acoustic pulse of known frequency
- the echo from the liquid is received in 3 transducer elements

water velocity

is proportional to the frequency shift between the transmit pulse and the received echo

Interpretation of ADV results



- black dots mark the points of measurement
- vertical cross flow velocities

- measurement 60 cm above the membrane module

General Objectives

1. Investigation of the velocity flow pattern in MBR
2. - reduction of sludge deposition on the membrane surface
   - avoiding of dead zones inside the whole reactor
   - homogeneous distribution of the dissolved oxygen

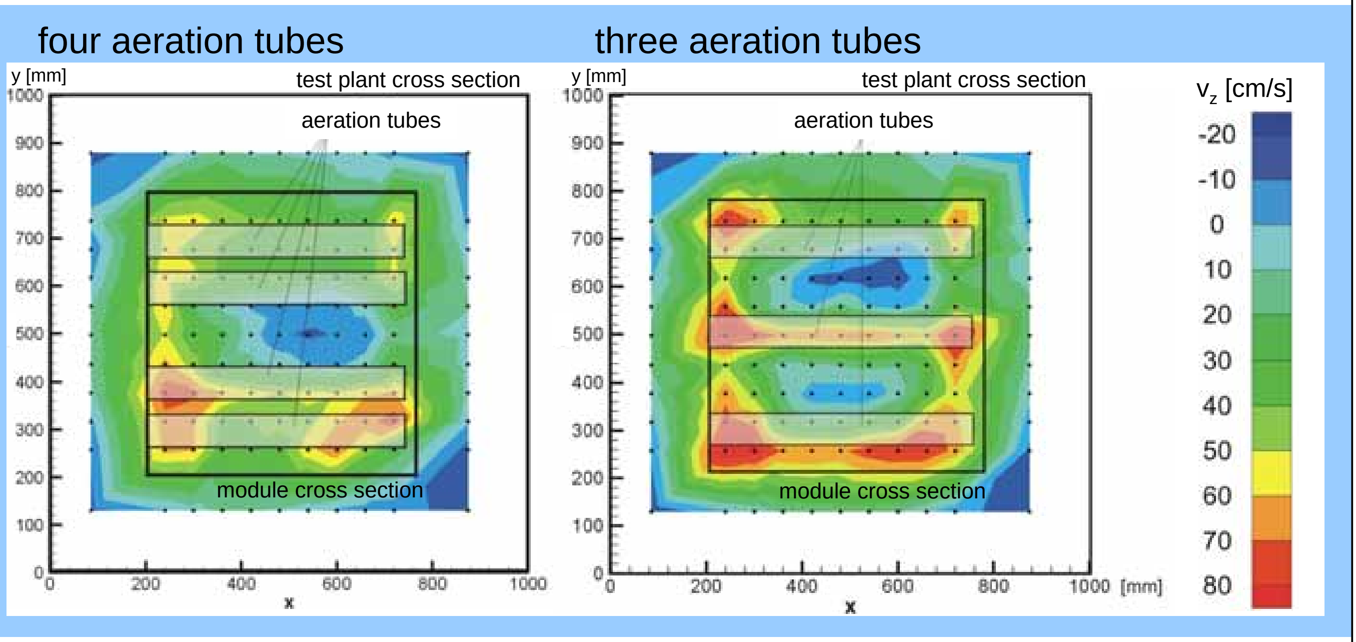
Measurement:

- investigation of the velocity flow pattern in MBR
- data for calibration of numerical models

Numerical Simulation:

- development of a simulation tool for easier membrane bioreactor design concerning aeration

Example of a Result: Aeration System


four aeration tubes

three aeration tubes

An homogeneous aeration of the module is important for a well operating membrane module

---

Publication

TACKE, D.; PINNEKAMP, J.; PRIESKE, H.; KRAUME, M. (2007): Membrane bioreactor aeration: investigation of the velocity flow pattern. Proceedings of 2nd IWA National Young Water Professionals Conference, 4.-6. Juni 2007, Berlin, ISBN 978-3-9811684-0-2

TACKE, D.; PINNEKAMP, J.; PRIESKE, H.; KRAUME, M. (2006): Improvement of Membrane Bioreactor Aeration. American Science Press, United States of America, ISBN 0-9768853-6-0

PRIESKE, H.; TACKE, D.; BAUMGARTEN, S.; PINNEKAMP, J.; KRAUME, M. WIEN (2006): Aeration of a Membrane Bioreactor in an Airlift loop configuration. 5th European Meeting on Chemical Industry and Environment (EMChIE), Vienna, Austria, 03.05.-05.05.2006

TACKE, D. (2005): Untersuchungen zur Moduldurch- und Modulumströmung als Werkzeug bei der Modulentwicklung. Membrantechnik - Begleitung zur 6. Aachener Tagung Siedlungswasserwirtschaft und Verfahrenstechnik, T. Melin, J. Pinnekamp, Aachen, 2005, P9-12, ISBN 3-86130-775-8

TACKE, D., STEPKES, H., BUER, T. (2003): Untersuchungen zu neuen Membranmodulen für die Trennung von Belebtschlamm und Wasser. Membrantechnik - Begleitung zur 5. Aachener Tagung Siedlungswasserwirtschaft und Verfahrenstechnik, T. Melin, M. Dohmann, Aachen, 2003, ISBN 3-921955-28-9

Hydrodynamic design of an MBR

Open points:

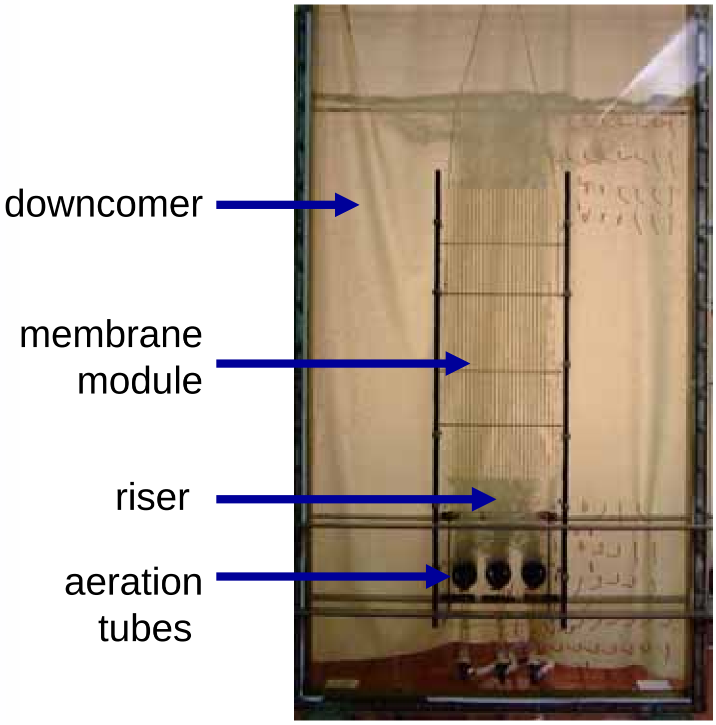
- Which (hydrodynamic) conditions are optimal?
  - cross flow velocity, aeration intensity, bubble size, ...
- How can these conditions can be achieved?
  - geometrical parameters, aerators, ...

General aim:

criteria for optimal (hydrodynamic) design to get

- high benefit (filtration flux)
- low effort (engergy input for aeration)

Selection of an airlift loop configuration



different gas holdup in the riser and downcomer

circulation velocity

advantage:

aeration is used for

- oxygen supply
- effective mixing
- increased cross flow velocity on the membrane surface

Experimental Setup

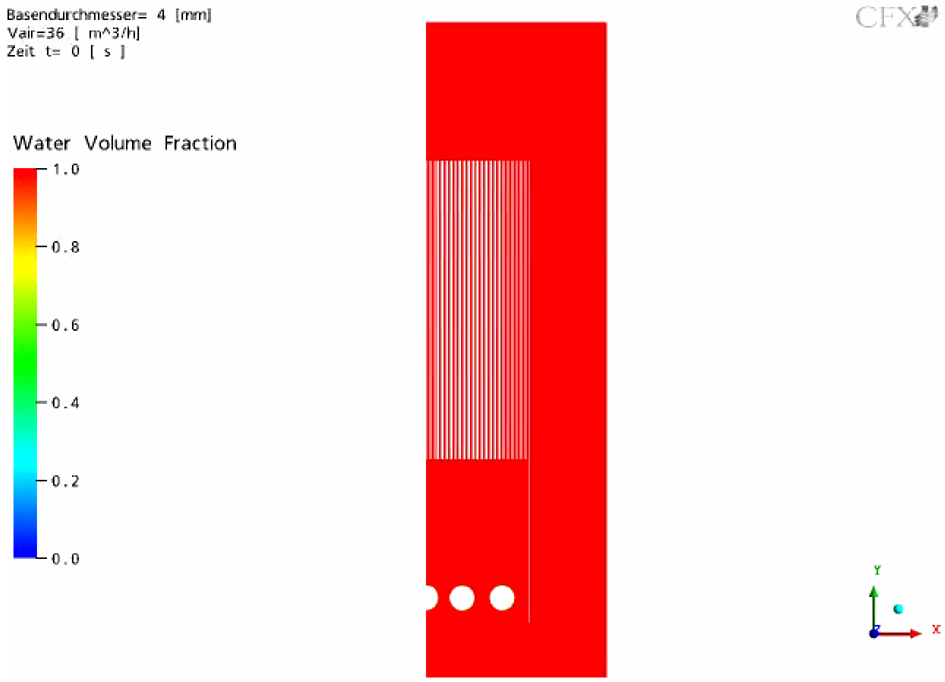
quasi 2d design

- height: 2.1m
- width: 1.2m
- depth: 0.1m

optical methods to measure:

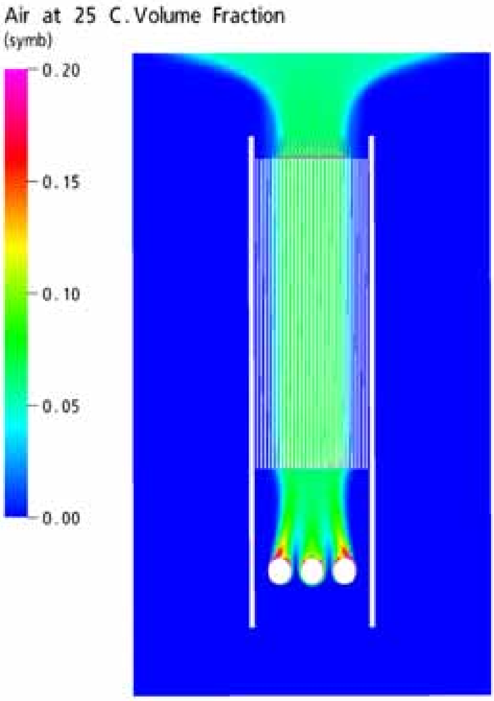
- gas holdup, bubble distribution
- velocity

Numerical investigations



- ANSYS CFX10
- Euler-Euler approach (Grace model)
- SST-turbulence model
- physical properties of water
- const. bubble diameter
- degassing boundary on the top

Experimental and numerical results for the gas holdup



superficial gas velocity in the riser U_{gr} = 0,0234 m/s

Comparison of the total gas holdup

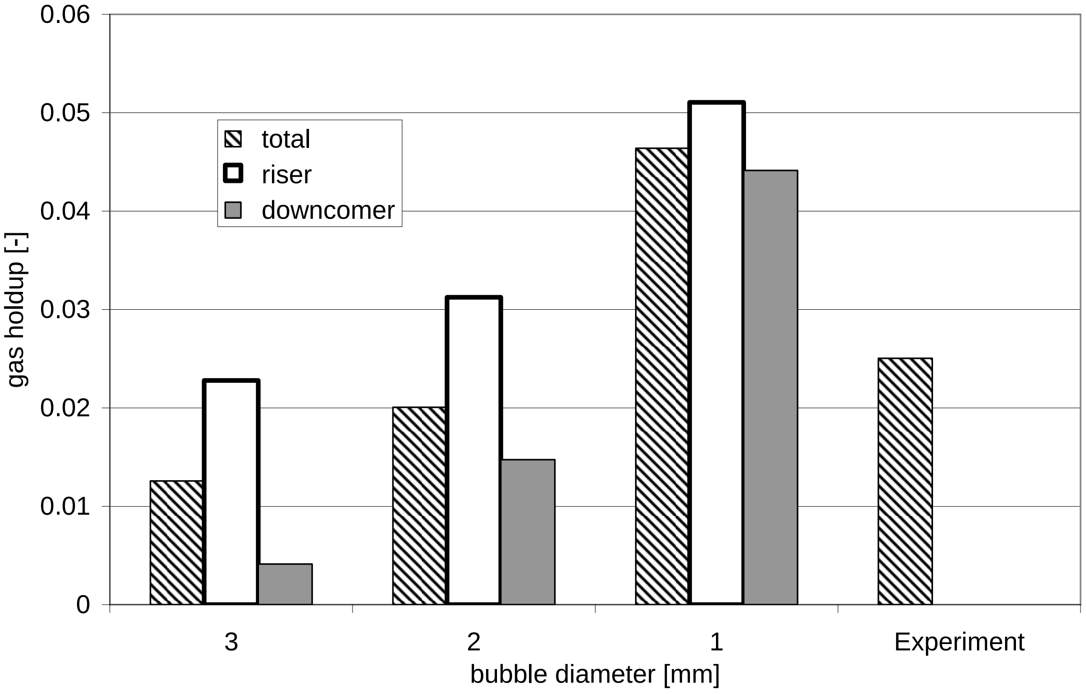
without internals

with membrane module

superficial gas velocity in the riser U_{gr} = 0,0234 m/s

Influence of the bubble size (MBR without internals)

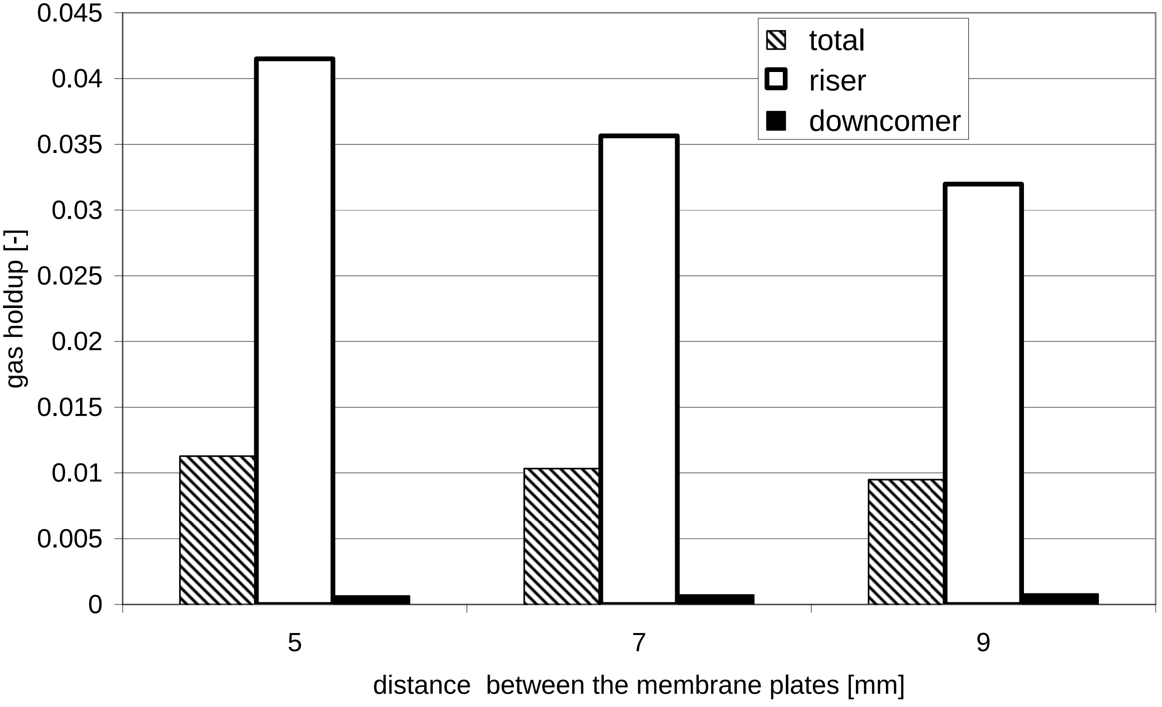
CFD results



superficial gas velocity in the riser U_{gr} = 0,0234 m/s

CFD results for different membrane modules

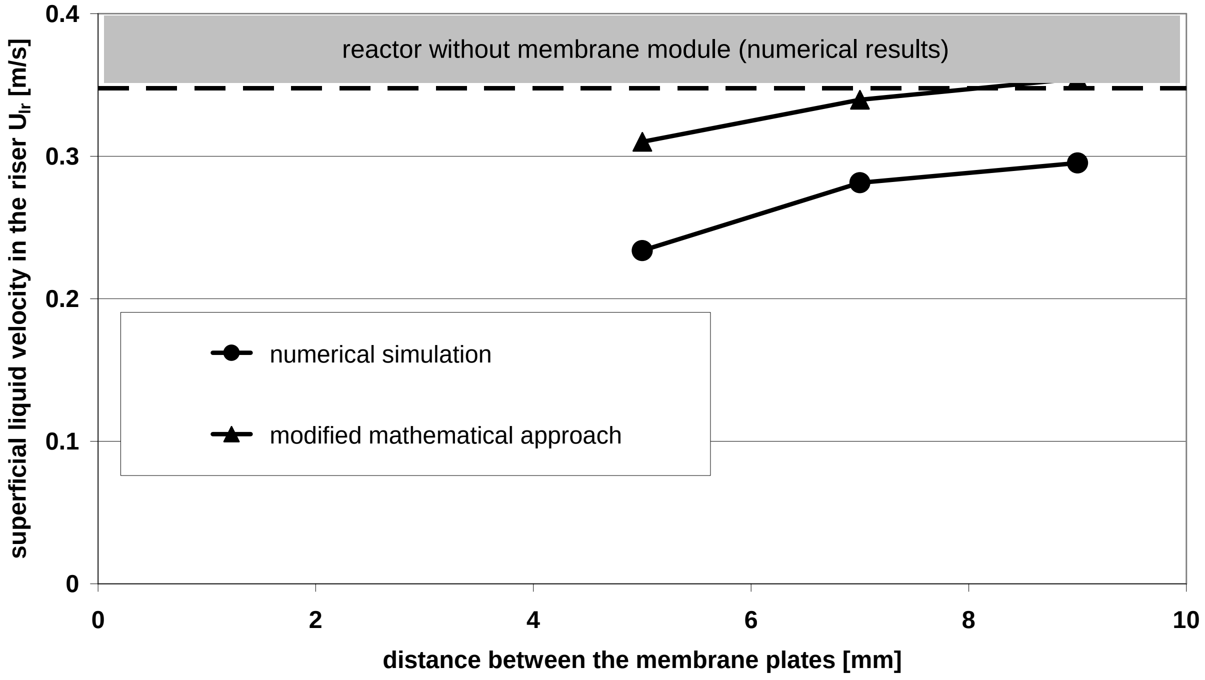
(2mm bubble diameter)



superficial gas velocity in the riser U_{gr} = 0,0234 m/s

CFD results for different membrane modules

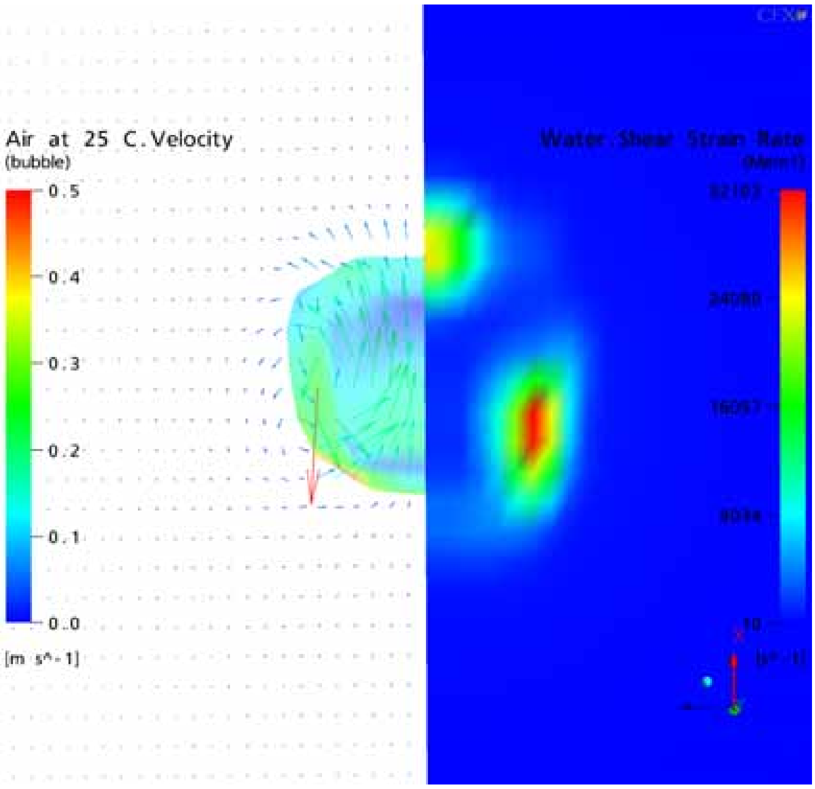
(2mm bubble diameter)



superficial gas velocity in the riser U_{gr} = 0,0234 m/s

Exprimental investigations of rising bubbles between membrane plates

Numerical investigations of rising bubbles between membrane plates



Acknowledgement

Thanks for your attention!

Deutsche Bundesstiftung Umwelt for financial support

A3 GmbH, Gelsenkirchen

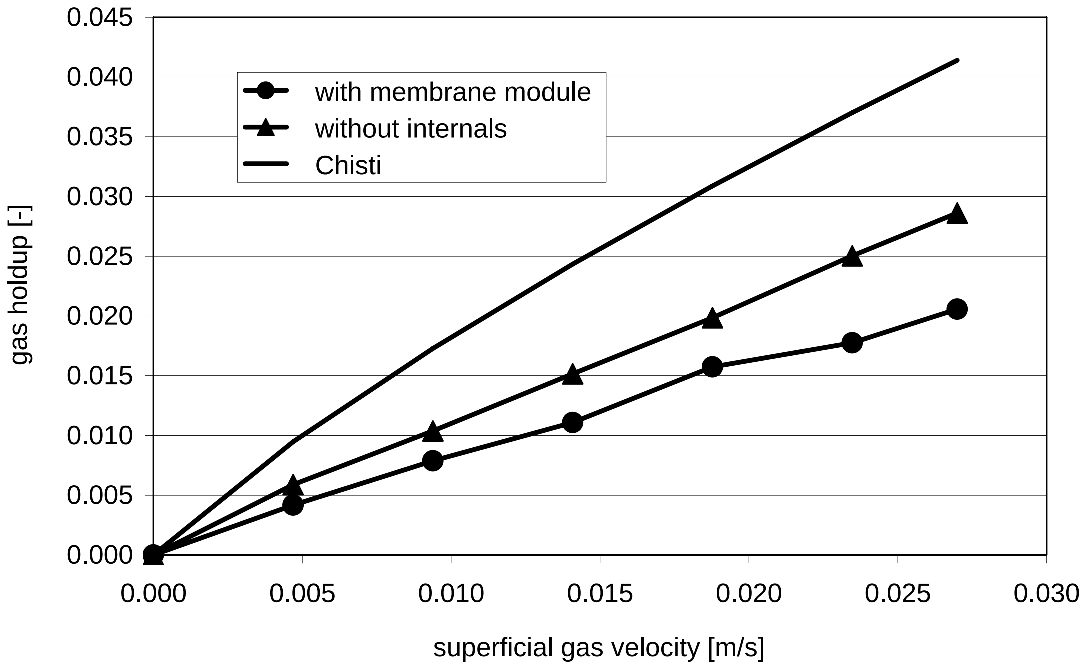
Institute of Environmental Engineering, Aachen

ISA - Institut für Siedlungswasserwirtschaft der RWTH Aachen

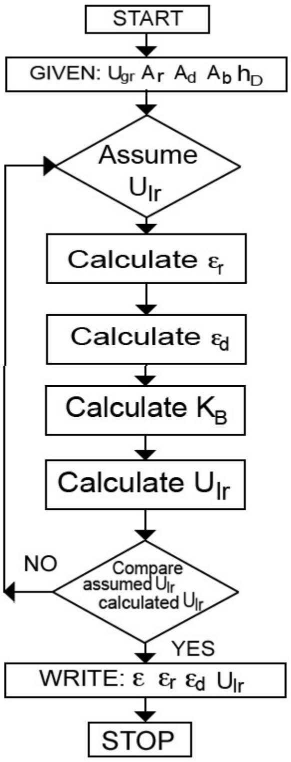
Summary

- Hydrodynamic can improve the economic efficiency of the MBR.
  - airlift loop configuration shoud be applied
  - geometrical optimization important
- A mathematical model was derived to calculate the liquid circulation velocity in the ALR with MBR.
- Further investigations are necessary to estimate the gas holdup in the downcomer.
- CFD simulations with a single bubble diameter are helpful to compare the effects of geometrical variations but not sufficient to fit the experimental results.

Comparison of experimental results with the calculation according to Chisti (1988)



Mathematical model for airlift reactors without internals


START

GIVEN: U_{gr} A_r A_d A_b h_D

Assume U_{lr}

Calculate ε_r

Calculate ε_d

Calculate K_B

Calculate U_{lr}

Compare assumed U_{lr} calculated U_{lr}

NO

YES

WRITE: ε ε_r ε_d U_{lr}

STOP

iterativ proceedure based on an energy balance

(Chisti, 1988)

$$\varepsilon_r = \frac{U_{gr}}{0.24+1.35\left(U_{gr}+U_{lr}\right)^{0.93}}$$

$$\varepsilon_d = 0.89\,\varepsilon_r$$

$$K_B = 11.402\left(\frac{A_d}{A_b}\right)^{0.789}$$

$$U_{Lr} = \left[\frac{2gh_D(\varepsilon_r-\varepsilon_d)}{K_B\left(\frac{A_r}{A_d}\right)^2\frac{1}{(1-\varepsilon_d)^2}}\right]^{0.5}$$

Mathematical model for airlift reactors with internals

Assumption:

pressure drop due to the liquid phase only

$$\Delta P_{MM} = K_{MM}\frac{\rho_l}{2}u_{MM}^2\frac{l_{MM}}{d_h}$$

$$d_h = 2\frac{d_{MM}\,T}{\left(d_{MM}+T\right)}$$

$$U_{Lr} = \left(\frac{2\,g\,h_D\,(\varepsilon_r-\varepsilon_d)}{K_B\left(\frac{A_r}{A_d}\right)^2\frac{1}{(1-\varepsilon_d)^2}+K_{MM}\frac{1}{2}\left(\frac{A_r}{A_{MM}}\right)^2\frac{l_{MM}\left(d_{MM}+T\right)}{d_{MM}\,T}}\right)^{0.5}$$

7. MODELLING IRREGULAR FIBRE DISPLACEMENT AND FIBRE MOVEMENT WITHIN SUBMERGED MEMBRANE MODULES

S. Buetehorn, C. N. Koh, T. Wintgens, T. Melin

EUROMBRA

Modelling Irregular Fibre Displacement and Fibre Movement within Submerged Membrane Modules

CFD Workshop “From the fibre to the plant”
Organised by the MBR-Network Cluster
Berlin, Germany, June 3, 2007

S. Buetehorn, C.N. Koh, T. Wintgens, T. Melin
RWTH Aachen University

D. Volmering, K. Vossenkaul
Koch Membrane Systems GmbH

RWTH AACHEN UNIVERSITY

RWTH AACHEN UNIVERSITY

Outline

- Motivation
- Research objectives
- Materials and methods
- Modelling approach
  - Modelling the rheology of activated sludge
  - Modelling the geometry of a single HF bundle
- Moving forward
- Acknowledgements

Motivation

- The permeability decline in activated sludge filtration in submerged mode is significantly affected by the air bubbling sequence within the filtration unit

- Higher operating costs due to costs for coarse bubble aeration are extensively discussed as being a major drawback of MBR technology in comparison to the CAS system

- Efforts have been made to reduce operating costs ...
  - ... by intermittent instead of continuous aeration
  - ... by repositioning aeration devices within the membrane tank
  - ... by improving the design of the gas sparging device
  - ... by improving the design of the membrane module
  - ... by reducing the aeration rate
  - ...

Research at RWTH

Research objectives

Objectives:

- Modelling the geometry of a single hollow-fibre bundle of the PURON® system provided by Koch Membrane Systems GmbH (KMS)

- Applying the geometry model to different operating conditions and module configurations

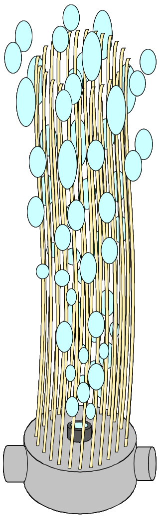
- Overall objective: Investigating the impact of fibre arrangement and air flow rate on the efficiency of air bubbling

Methods:

- Computational Fluid Dynamics (CFD) simulations
- Additional experimental investigations

Module configuration

PURON® module (Koch Membrane System GmbH):



- Hollow-fibre membranes arranged in bundles and submerged vertically into the activated sludge
- Lower ends are fixed, upper ends are individually sealed and are free to move laterally
- An air nozzle with an annular gas inlet is located in the centre of each bundle
- Flow channels facilitate sludge entrainment within the bottom part of the bundle

Membrane material	Nominal pore size	Fibre diameter	Fibre length	Membrane area (single bundle)
PES	0.04 µm	2.6 mm	1.2 m	2.2 m^2

Modelling approaches

CFD Workshop

Rheology:

- Contribution of suspended solids to the multiphase flow pattern is taken into account in terms of the dynamic viscosity of a model liquid
    - E.g. a polysaccharide solution (similar characteristics in comparison to the suspension)
    - Filtration is NOT taken into consideration [Wang *et al.*, 1994]

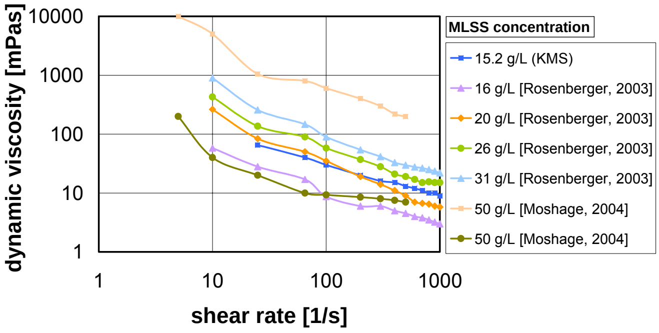
IWA Conference

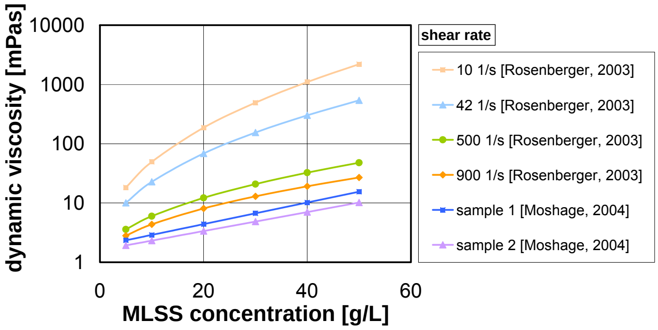
Geometry model:

- Modelling instantaneous fibre displacement in the bottom part of the membrane bundle ...
    - ... in terms of an accurate 3D representation (geometry model 1)
    - ... in terms of a heterogeneous porous medium (geometry model 2)

CFD Workshop

Sludge rheology - a brief overview





Published results:

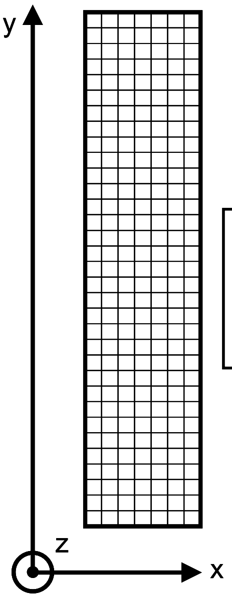
- Shear thinning character.
- MLSS ↑ ⇒ dyn. viscosity ↑
- Temp. ↓ ⇒ dyn. viscosity ↑
- Poor thixotropic behaviour

Problem:

- Model validation with published data difficult due to different test protocols used

⇒ Rheological measurements will be conducted at RWTH

Geometry model 2: Abstract representation



Porosity:
ε = (x, y, z)

Drag coeff.:
ξ = (x, y, z, ε, ...)

IWA Conference

- Representation of the fibre arrangement within a single hollow-fibre bundle in an abstract manner (firstly in steady-state conditions)

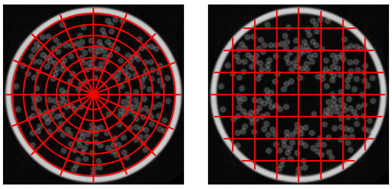
Modelling approach:

- Implementation of a heterogeneous porous medium with a local porosity and local flow resistance
  - X-ray Computer Tomography (CT) analysis of a single HF bundle with not moving fibres
  - Subsequent image processing in MATLAB® to generate the porous medium

Image processing in MATLAB®

Work flow:

- Import of raw CT images and conversion to matrix form
- "Filling" the permeate channels in each cross-section in order to distinguish between flow channels and hollow-fibres
- Creating a mesh
  - annular/rectangular
  - multiple structured blocks???



- Calculating the 2D voids fraction within each cell
- Computing the spatial porosity by connecting all cross-sections via image processing

⇒ 3D representation of the local porosity ε = (x, y, z) within a single hollow-fibre bundle

---

Experimental investigations

Correlating the local flow resistance with the local porosity:

- Filling identical pipes with a varying number of hollow-fibres
- Measuring the pressure loss over a defined length of the column
- Estimating the local drag coefficient ξ = f (x, y, z, ε, ...) as a function of the porosity ε ≠ f (y)

Tracking fibre movement (if feasible):

- Direct observation [Fane *et al.*, 2006]

NMR imaging:

- Cake layer formation/removal
  ⇒ Transfer of CFD results
- Bubble-induced fibre movement???

Moving forward

- CFD tools will be used to investigate the impact of fibre arrangement on the cleaning efficiency of air bubbling in submerged HF systems
- A rheology model will be established taking into account the influence of suspended solids on the flow characteristics of the activated sludge
- CT imaging has been performed as a basis for the generation of an abstract description of a single HF bundle with an instantaneous fibre displacement
- Experiments will be conducted in order to determine the relationship between local fibre concentration and local flow resistance within the bundle
- Efforts will be made to track continuous fibre movement induced by air bubbling (extended model with transient characteristics???)

Own publications

- Buetehorn S., Koh C.N., Wintgens T., Melin T., Volmering D., Vossenkaul K.: Investigating Hydrodynamics in Submerged Hollow-Fibre Membrane Filtration Units in Municipal Wastewater Treatment usinf Computational Fluid Dynamics (CFD). Platform presentation at the 2nd IWA National Young Water Professionals Conference, Berlin (Germany), June 4-6, 2007

- Buetehorn S., Koh C.N., Wintgens T., Melin T., Volmering D., Vossenkaul K.: Hydrodynamics in Submerged Hollow-Fibre Membrane Filtration Units: A Computational Fluid Dynamics (CFD) Approach. Platform presentation at the 6th International Membrane Science and Technology Conference (accepted),Sydney (Austrialia), November 5-9, 2007.

Acknowledgements

- The authors would like to thank Bastian Mahr and Martin Behling from the Institute of Multiphase Processes at the Leibniz University of Hannover, Germany, for kindly providing their CT device

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  Contract No. 018480 - EUROMBRA

  Duration: 01/10/05 - 30/09/08

  EUROMBRA is part of the MBR-NETWORK Cluster

  More info: www.mbr-network.eu

Thank you very much for your attention!

8. CFD MODELLING OF MBR TANK

J. Saalbach, M. Hunze

CFD-modelling of MBR-tanks

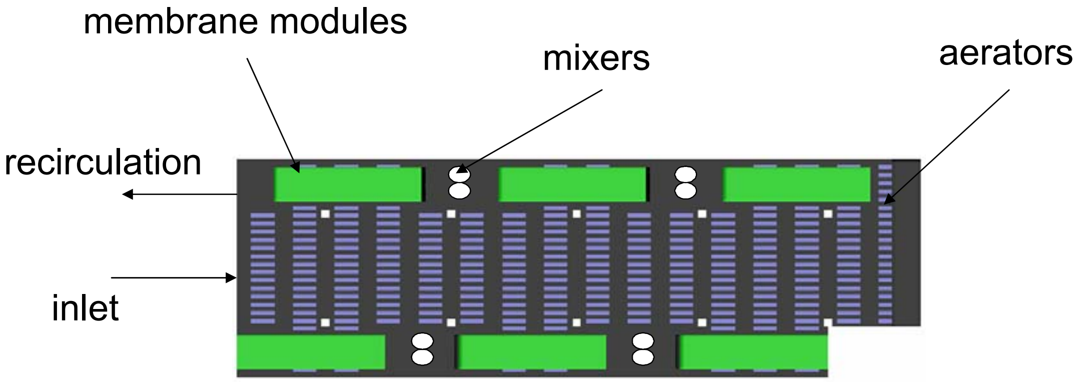
J. Saalbach, M. Hunze
Berlin, June 3rd 2007

Overview

Topics:

- Introduction
- Mathematical Model
- Case Studies
- Conclusions

Introduction: MBR-System Overview



membrane modules

mixers

aerators

recirculation

inlet

- flow
- turbulence
- transport
- energy input

- air input
- air rising
- interaction of water and air

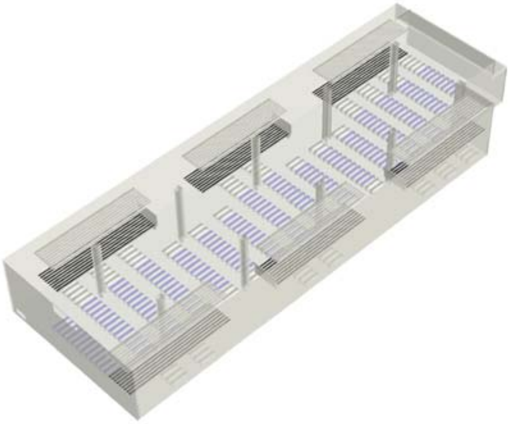
Challenges

- membrane related phenomena on micro-scale
- discretization would result in very high element number
- computational cost too high, not computable

(www.kochmembrane.com)

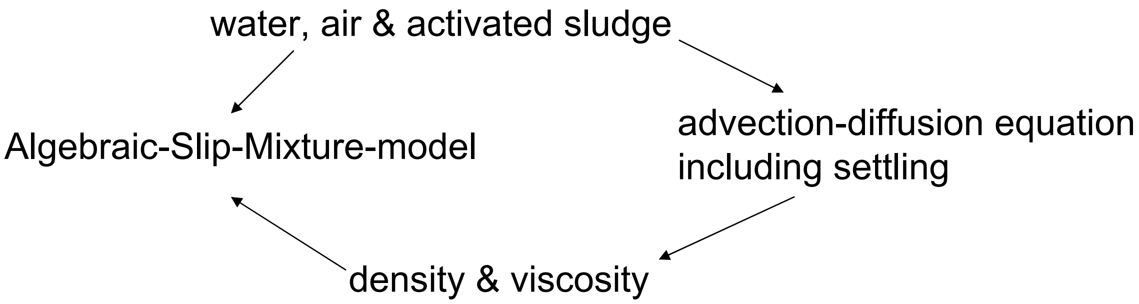
Approach

- macro-scale approach for modelling membrane modules
- membrane modules considered as porous zones
- relevant properties transferred to porous zone



Mathematical Model

- 3-dimensional flow field: Navier-Stokes and continuity equations
- advection-diffusion equation for transport of activated sludge
- rng-k-ε turbulence model
- multiphase system: water, air, activated sludge
- Algebraic-Slip-Mixture-model



water, air & activated sludge

Algebraic-Slip-Mixture-model

advection-diffusion equation including settling

density & viscosity

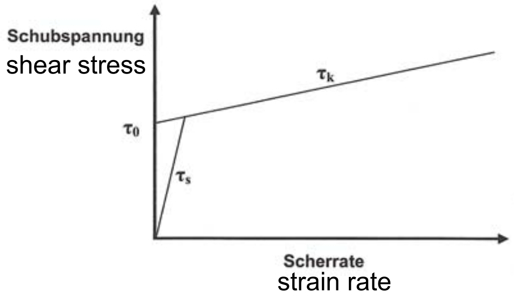
Mathematical Model: Density

- density depends on activated sludge concentration
- increased sludge concentration -> increased density
- coupling of water and sludge phase by constitutive equation

$$\rho = \frac{\rho_s - \rho_w}{\rho_s} \cdot C_s + \rho_w$$

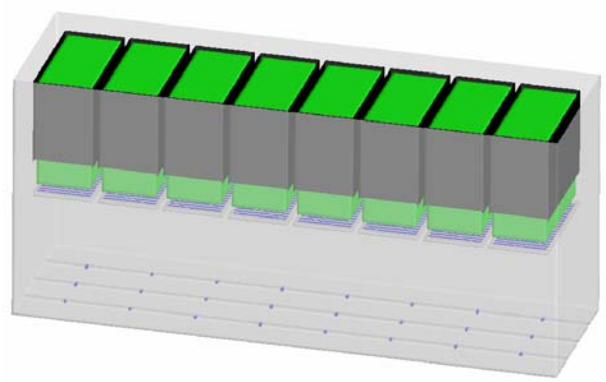
Mathematical Model: Viscosity

- viscosity depends on activated sludge concentration
- bi-linear approach by Schumacher (similar to Windhab)



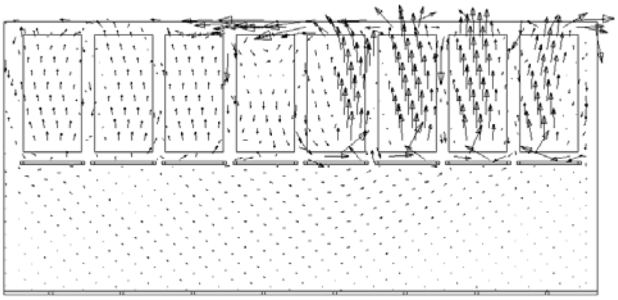
Case Study: Sobelgra

MBR-tank of WWTP Sobelgra (Belgium):
- hollow-fibre membrane modules by KOCH Membrane Systems
- 8 modules installed but only 4 in operation
- 90% air-load below modules 5-8



Case Study: Sobelgra

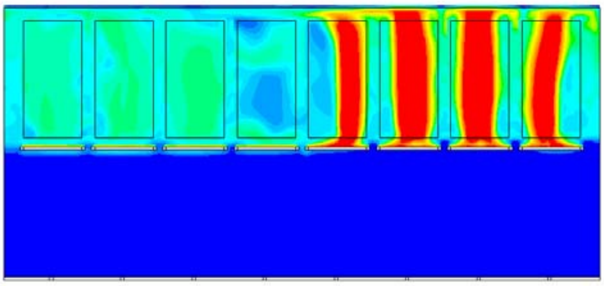
velocity distribution



air-phase distribution

volume fraction of air:

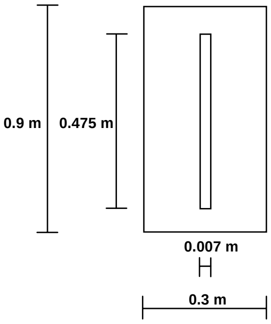
0.0 [blue] – 0.3 [red]

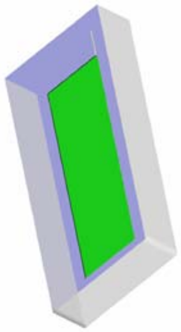


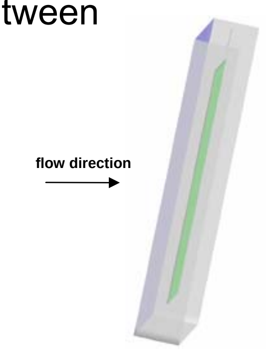
Case Study: Heenvliet

MBR-tank of WWTP Heenvliet (The Netherlands):

- sheet membrane modules by Toray Membrane
- flow resistance of sheet different than hollow-fibres
- single sheet membrane for calibration of resistance values
- two porous cover zones with a fluid zone in between





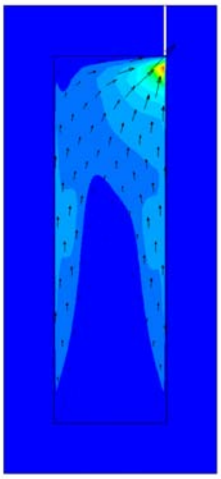


Case Study: Heenvliet

- flow field according to resistance posed by sheet
- water mainly directed around sheet
- flow field inside membrane unaffected by outside flow

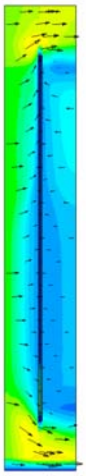
velocity magnitude [m/s]

0.0 [blue] – 1.0 [red]

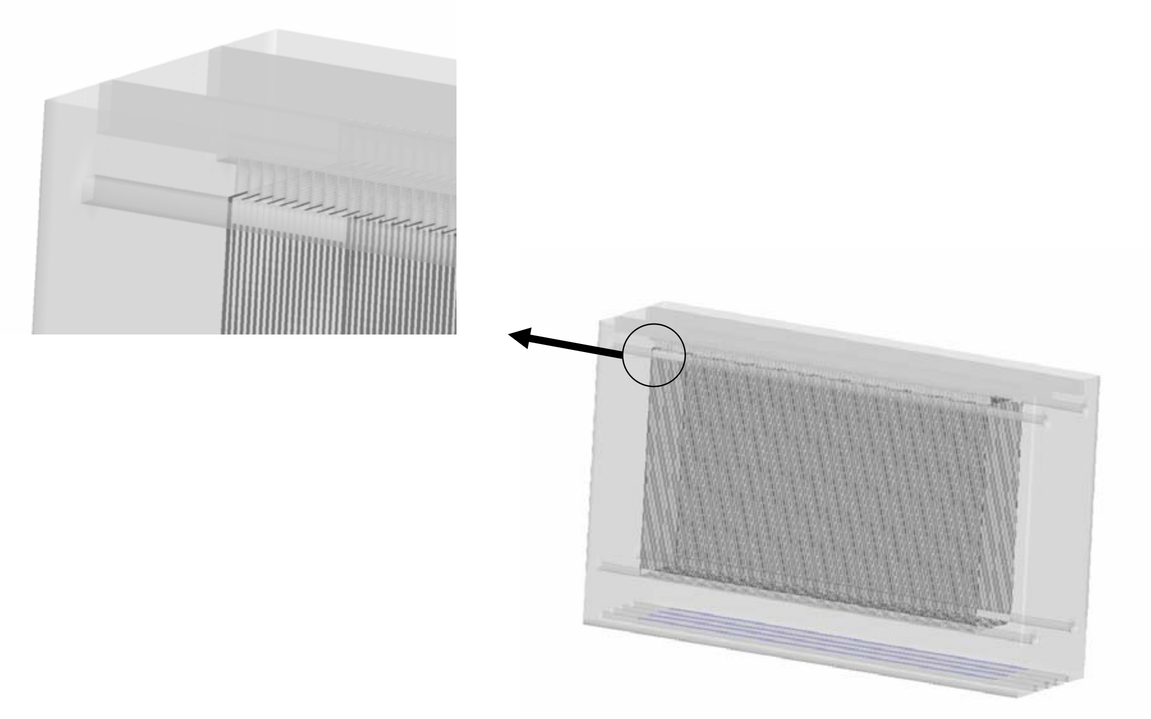


velocity magnitude [m/s]

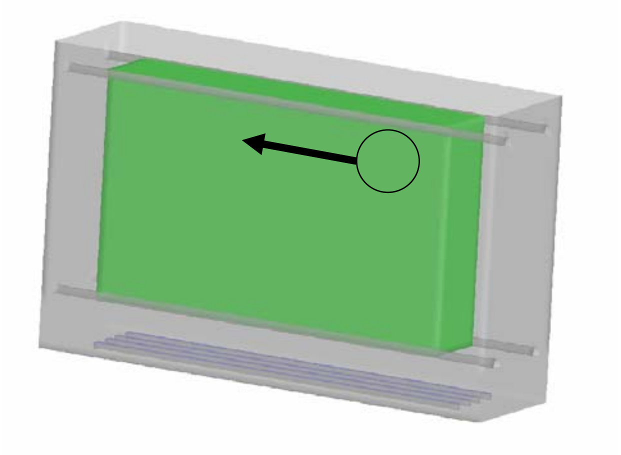
0.0 [blue] – 0.002 [red]



Case Study: Heenvliet



Case Study: Heenvliet



Conclusions

CFD as analysis tool:

- investigation of system conditions in MBR-systems
- micro – macro-scale processes

→ modules as porous zones

- consideration and interaction of water, air and sludge

approach has successfully been applied in practice

Publications

Hunze, M. and Schumacher, S. (2005). *Die Membranbelebung der Kläranlage Nordkanal – CFD-Modellierung – Ein Tool zur Analyse der Systemverhältnisse.* Proceedings of “6. Aachener Tagung Siedlungswasserwirtschaft und Verfahrenstechnik”, RWTH Aachen.

9. UNSW MBR HYDRODYNAMICS INVESTIGATIONS: CFD & TRACER STUDIES

M. Brannock, Y. Wang, G. Leslie

UNSW MBR Hydrodynamics Investigations: CFD & Tracer Studies

Matthew Brannock
Yuan Wang
Greg Leslie

UNSW MBR Hydrodynamics Project

- Project titled: “Evaluation of MBR performance via RTD analysis and process modelling”

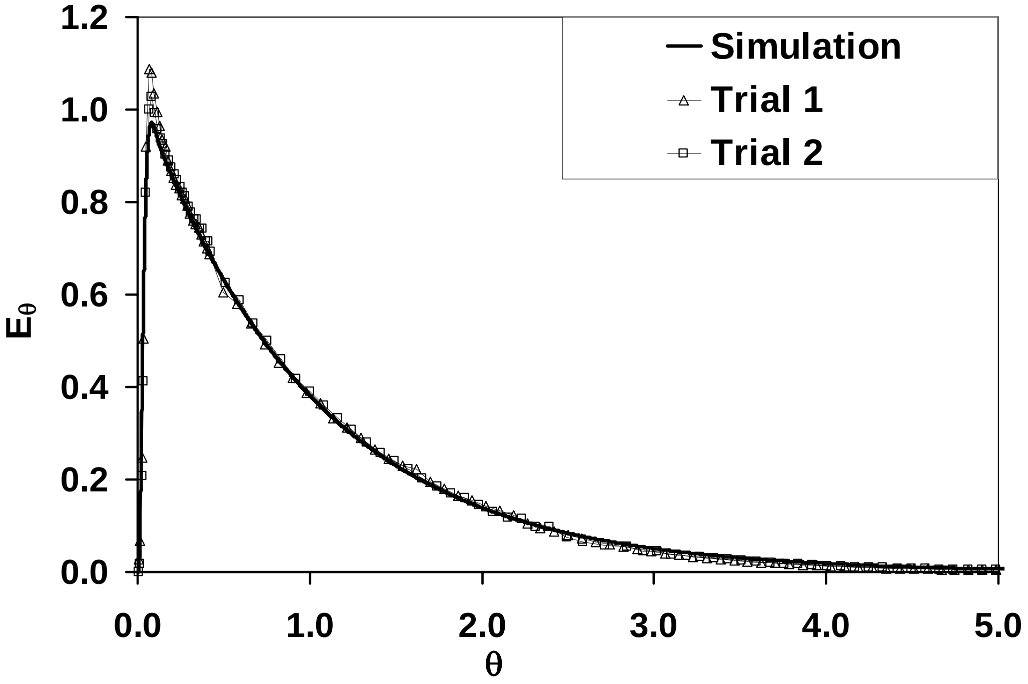
- Australian MBR Investigations:
  - Examination of 2 full-scale MBRs (FS & HF)
- EU (AMEDEUS) MBR Investigations:
  - WP6 – Inside submerged versus outside submerged
  - WP5 – Pre-sedimentation versus no pre-sedimentation

- Common tasks:
  - Tracer studies for “Residence Time Distribution Analysis” (RTDA)
  - Computational Fluid Dynamics (CFD) modelling

- End result ⇒ framework for an entire MBR CFD process model

Preliminary Full-Scale CFD Modelling – HF MBR

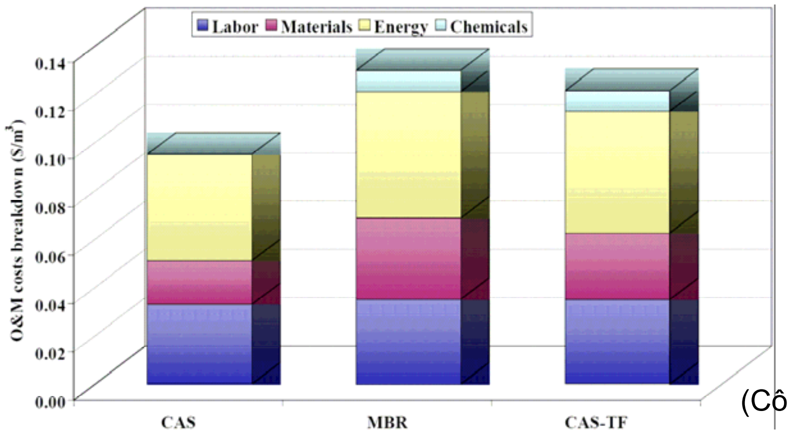
- Example of Recent Results



MBR Performance

- Performance can be measured by total cost to achieve a required pollutant removal rate:
  - Operating Costs ⇒ energy requirements etc
  - Capital Costs ⇒ volume requirements etc

- O&M costs for MBR @ 38ML/d – Energy ~50%



(Côté *et al*, 2004)

Factors Affecting MBR Performance

- *Biological* – Reaction rates etc
- *Membrane* – Flux (function of ΔP, Q_{AIR} etc)
- *Hydrodynamics/Mixing* – Fluid parcel movement through the reactor:
  - The mixing influences the pollutant removal
  - Macromixing can be assessed by measurement of the residence time distribution (RTD) of the reactor
  - Literature is silent on RTD analysis of MBRs

Why CFD Model an Entire MBR?

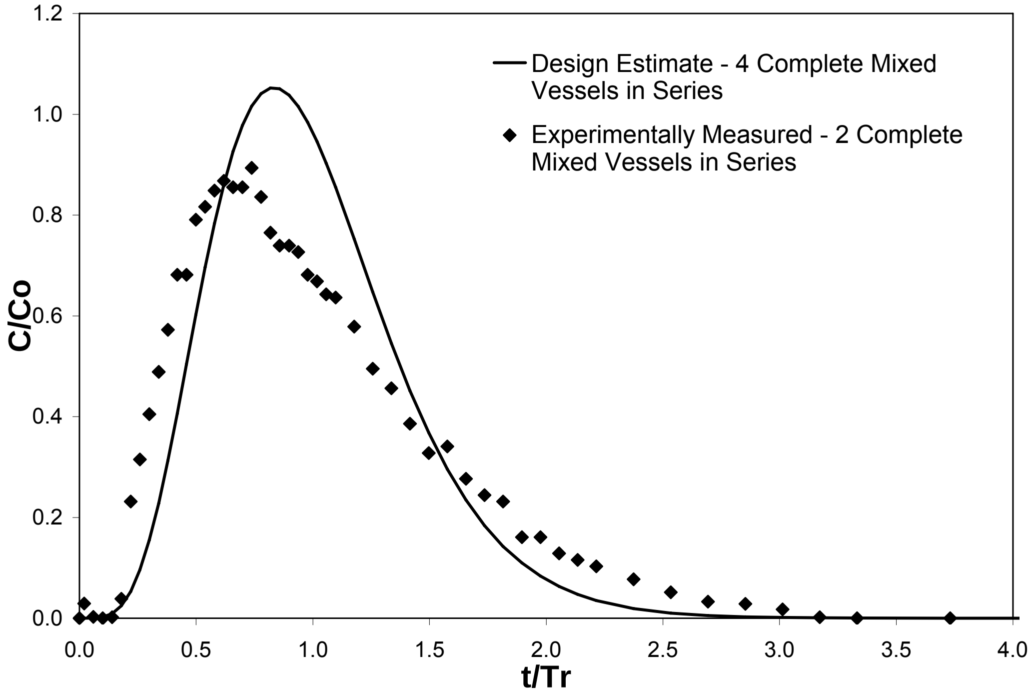
- Allows prediction of pollutant removal by including bioreactor zone
- Allows prediction of total energy usage
- Enables prediction of entire MBR RTD for comparison/validation against tracer studies
- Enables design & optimisation of entire MBR
- Sets up structure for inclusion of micro-scale & membrane zone models
- Not attempted before in literature

Hurdles:

- Difficult to predict fouling & membrane zone energy usage as these depend largely on microscale & transient effects
- Difficult to incorporate detailed micro-scale & membrane zone models

Why CFD Model an Entire MBR?

- Previous (PhD) Work - Anoxic Channel



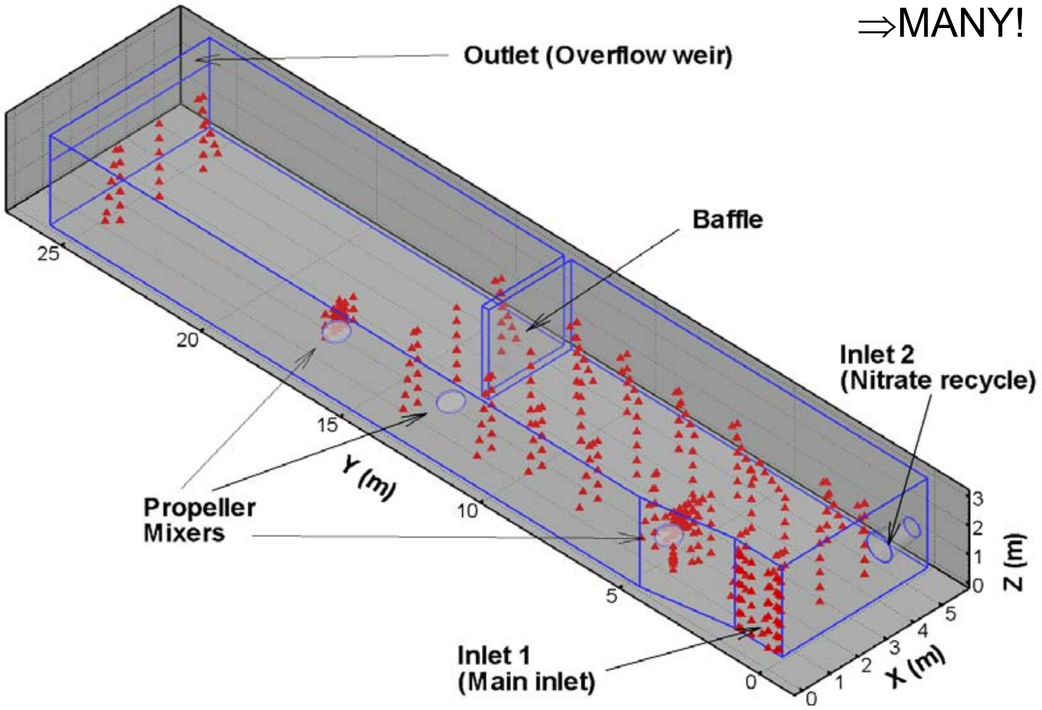
See reference Brannock (2003)

Why use Tracer Studies for CFD Validation?

- Reveals hydrodynamics in terms of macromixing
- Quick & easy onsite experiments compared to velocity measurements:
  - Tracer studies: errors are smoothed out
  - Velocity measurements: prone to errors onsite e.g. positional
  - Velocity measurements: ↑time to capture all scales of turbulence
- MBRs are designed/sized according to a required/predicted RTD
- Disadvantages:
  - Only examines macromixing
  - Only examines “whole” MBR not constituent parts (although this is possible through internal measurements & deconvolution)

Why CFD Model an Entire MBR?

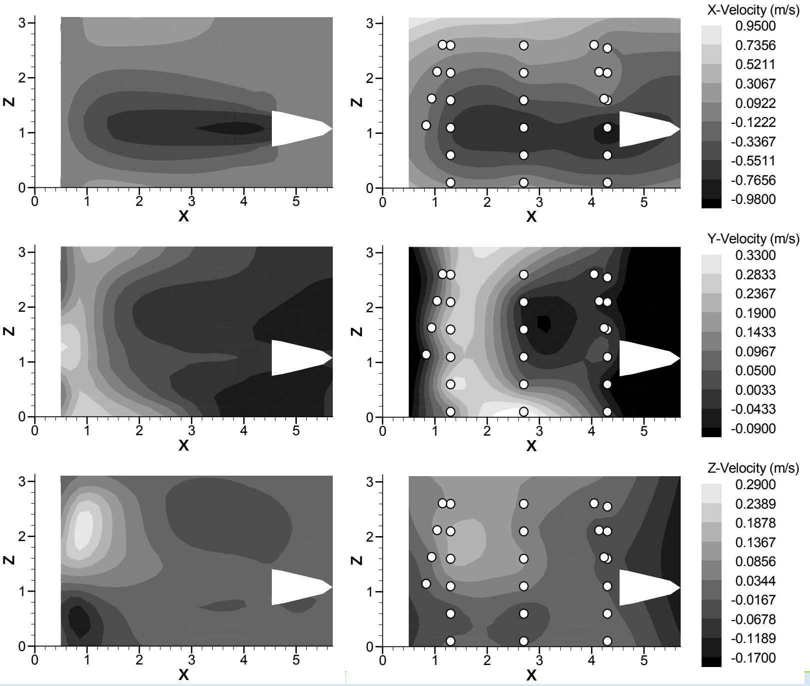
- Previous (PhD) Work - Anoxic Channel: Velocity Meas. Pts ⇒MANY!



See reference Brannock (2003)

Why use Tracer Studies for CFD Validation?

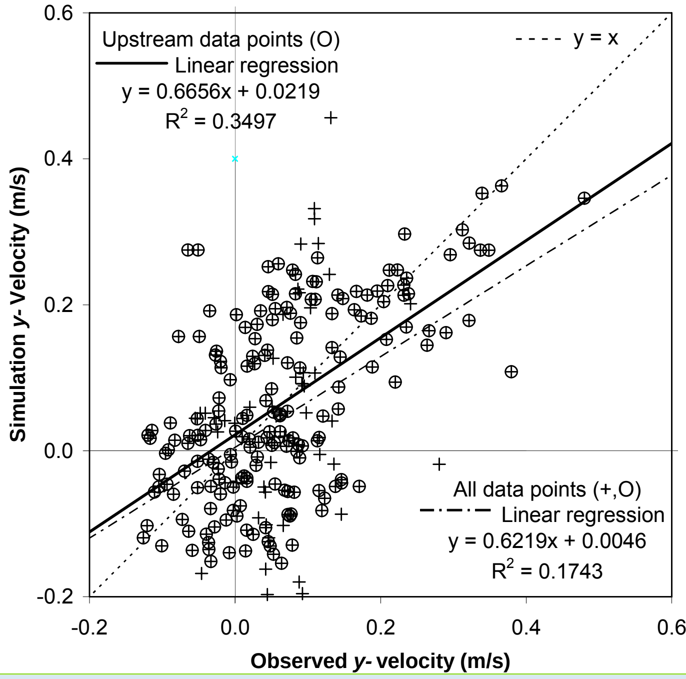
- Previous (PhD) Work - Anoxic Channel: Velocity Measurements
  - Qualitative CFD vs Exp Comparison ⇒ Rough comparison!



See reference Brannock (2003)

Why use Tracer Studies for CFD Validation?

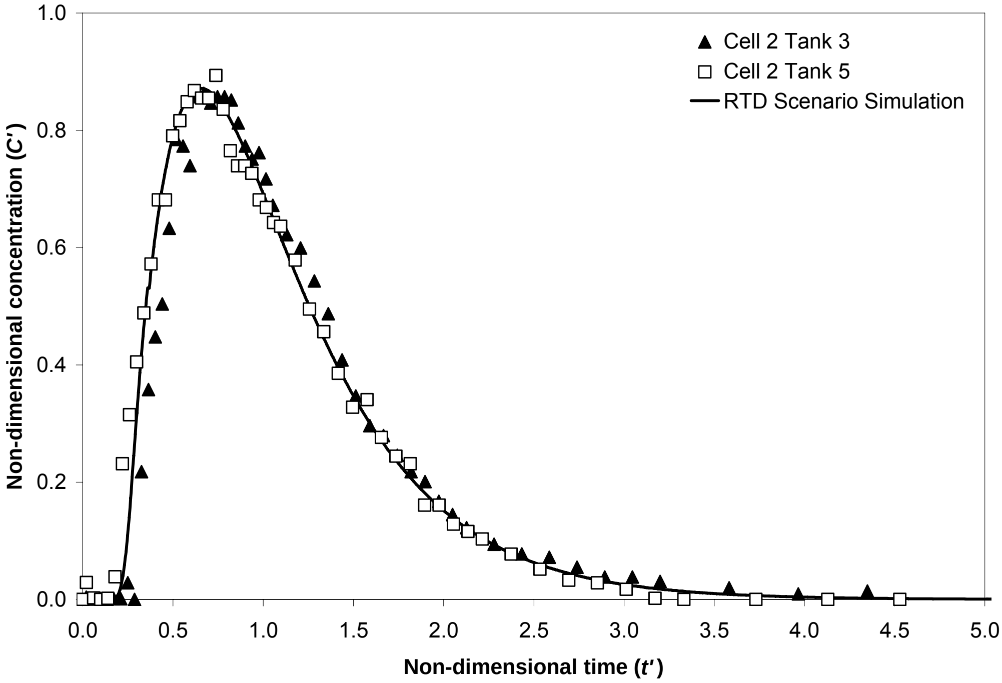
- Previous (PhD) Work - Anoxic Channel: Velocity Measurements
  - Quantitative CFD vs Exp Comparison ⇒ Difficult for full-scale!



See reference Brannock (2003)

Why use Tracer Studies for CFD Validation?

- Previous (PhD) Work - Anoxic Channel: RTD Measurements
  - CFD vs Exp Comparison ⇒ Much easier, less error, main design parameter



See references Brannock (2002b, 2003)

UNSW MBR Tracer Studies

- Prior Research Tracer Studies:
  - Singapore: FS vs HF Trials – Large Pilot-scale ~300 m^3/d

- Current Research Tracer Studies :
  - Hollow Fibre MBR – Full-scale ~2000 m^3/d
  - Flat Sheet MBR – Full-scale ~5000 m^3/d
  - Anjou Recherche: Pre-sed vs No Pre-sed – Pilot-scale ~6m^3/d

- Cancelled Tracer Study:
  - VITO Belgium:Inside vs Outside Membranes – Pilot-scale ~6m^3/d

- Replacement Tracer Study:
  - Aquafin Belgium/Schilde HF – Full-scale ~5500m^3/d

Prior UNSW Research Tracer Studies

- Singapore MBRs:
  - Volume 75m^3, Flow 300m^3/d, Same Feed

- Mitsubishi (Hollow Fibre)
- Kubota MBR Plant (Flat Sheet)

See reference Wang (2007)

Prior UNSW Research Tracer Studies

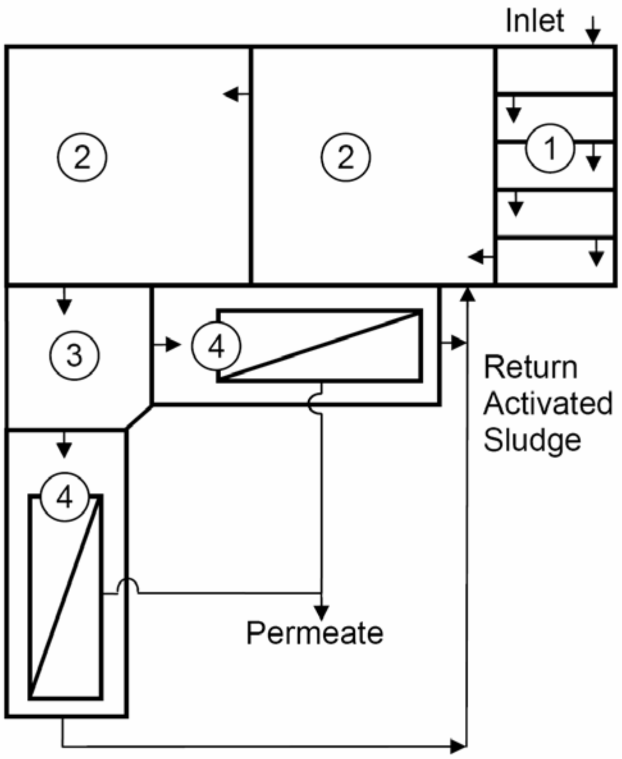
- Singapore Tracer Studies

	Kubota FS	Mitsubishi HF
BOD/COD Conversion	96%/93%	96%/94%
Dispersion Number (D/uL)	0.81	0.78
Number of tanks in series (N)	1.45	1.47
Anoxic Tank Mixer Power (kW)	1.3	0.4
MLR Pump (kW)	7.5	2.2
Aeration Blowers Aerobic Tank (kW)	4.0	11.0
Aeration Blowers Membrane Tank (kW)	11.0	
Total Power (kW)	23.8	13.6
Velocity Gradient (G)	2099 s^{-1}	849 s^{-1}

See reference Wang (2007)

Site 1 – Flat Sheet Membrane MBR

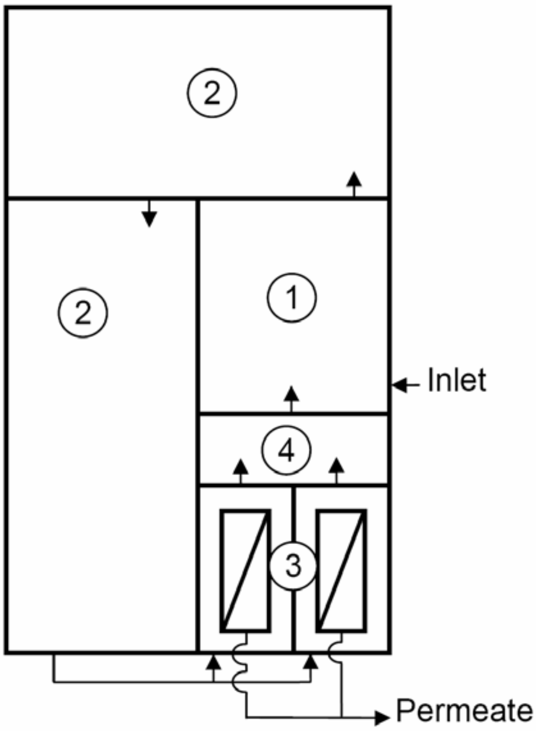
1. Bioselector (anoxic/anaerobic)
2. Swing aeration zones
3. Aerobic zone
4. Membrane filtration vessel



See reference Brannock (2007b)

Site 2 – Hollow Fibre Membrane MBR

1. Anoxic zone
2. Aerobic zones
3. Membrane filtration zone
4. De-aeration zone



See reference Brannock (2007b)

Site 1 – Flat Sheet Membrane MBR

See reference Brannock (2007b)

Site 2 – Hollow Fibre Membrane MBR

See reference Brannock (2007b)

Design Process Parameters

Parameters	Units	FS MBR	HF MBR
ADWF	ML/d	1.7	2.0
PDWF	L/s	48	-
PWWF	L/s	60	-
ADWF Net Membrane Flux	$L/m^2/hr$	18.5	29.0
PDWF Membrane Flux	$L/m^2/hr$	33.2	-
PWWF Membrane Flux	$L/m^2/hr$	45.8	-
Volume of Bioreactor Vessels	m^3	852	435
Volume of Membrane Filtration Vessels	m^3	392	36
Mixed Liquor Return Flowrate	m^3/hr	461	433

See reference Brannock (2007b)

Tracer Study Process Parameters

Parameters	Units	FS MBR	HF MBR
Average Influent Flowrate	ML/d	1.1	1.1
Net Membrane Flux	L/m^2/hr	11.8	16.0
Bioreactor Aeration	Nm^3/hr	109	419
Membrane Filtration Vessel Aeration	Nm^3/hr	992	918
COD Removal	%	92.0	94.0
BOD Removal	%	99.2	97.8

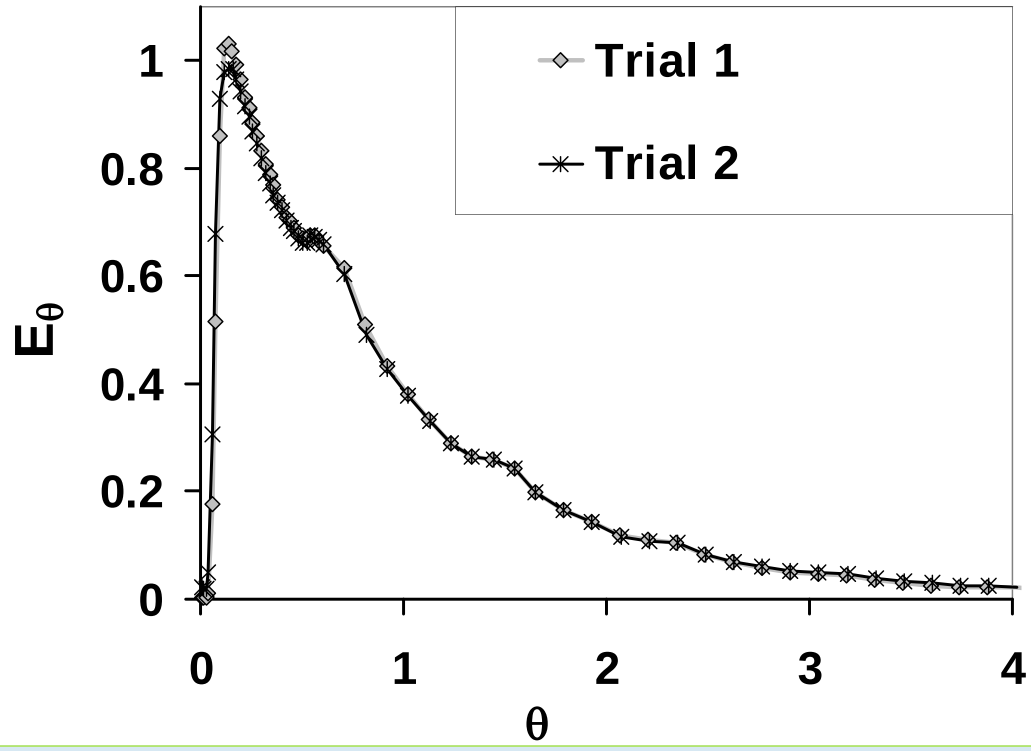
See reference Brannock (2007b)

Current Research Tracer Study Methodology

- Pulse inert tracer at inlet & measure response at outlet
- Tracer material used: Lithium
  - Lithium is relatively inert – does not readily adsorb onto surfaces & not readily taken up by bacteria
  - LiCl used – very soluble (640g/L at 0^{O}C) & solution density is low
- Dosage technique:
  - Bulk concentration of 1.5mg/L Li ~ response peak
  - Dosage solution 400-600g/L LiCl
  - ~15-25L solution dosed over 20s (<0.1% of HRT) into inlet stream with a momentum diffuser
- Response measurement:
  - 40-50 samples taken over 4HRTs & prepared on site immediately
  - ICP-AES – minimum detection limit <0.01mg/L (<1% of peak & ~20% of typical background level)

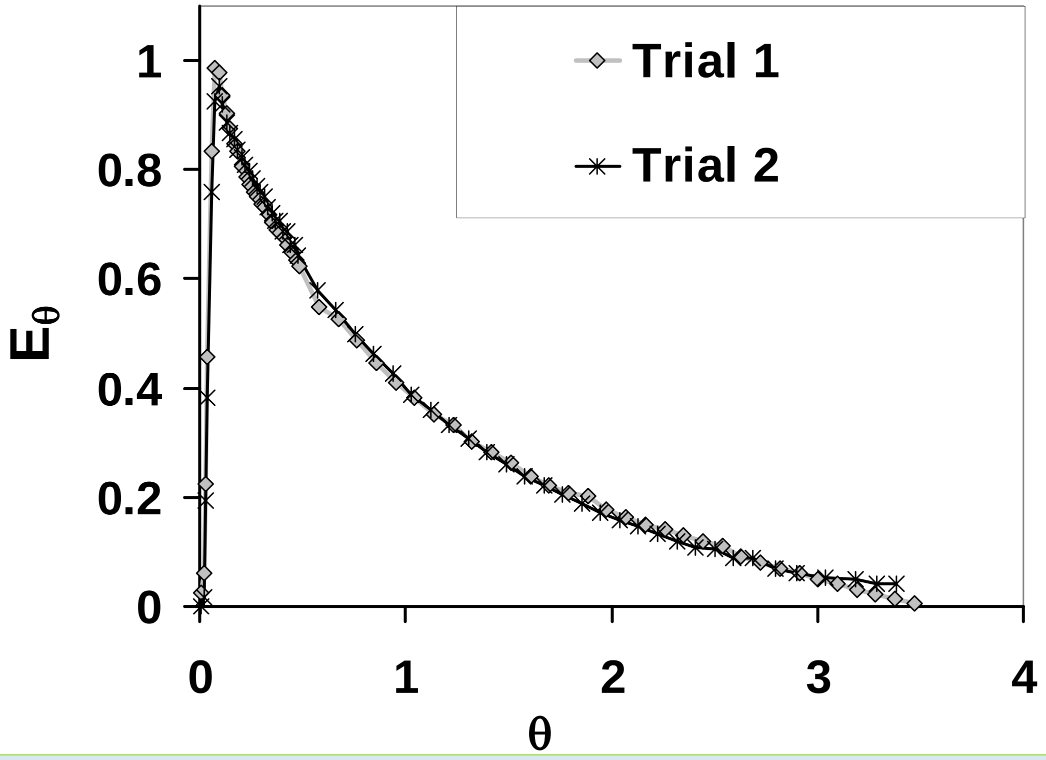
See reference Brannock (2007b)

RTD – Flat Sheet MBR



See reference Brannock (2007b)

RTD – Hollow Fibre MBR

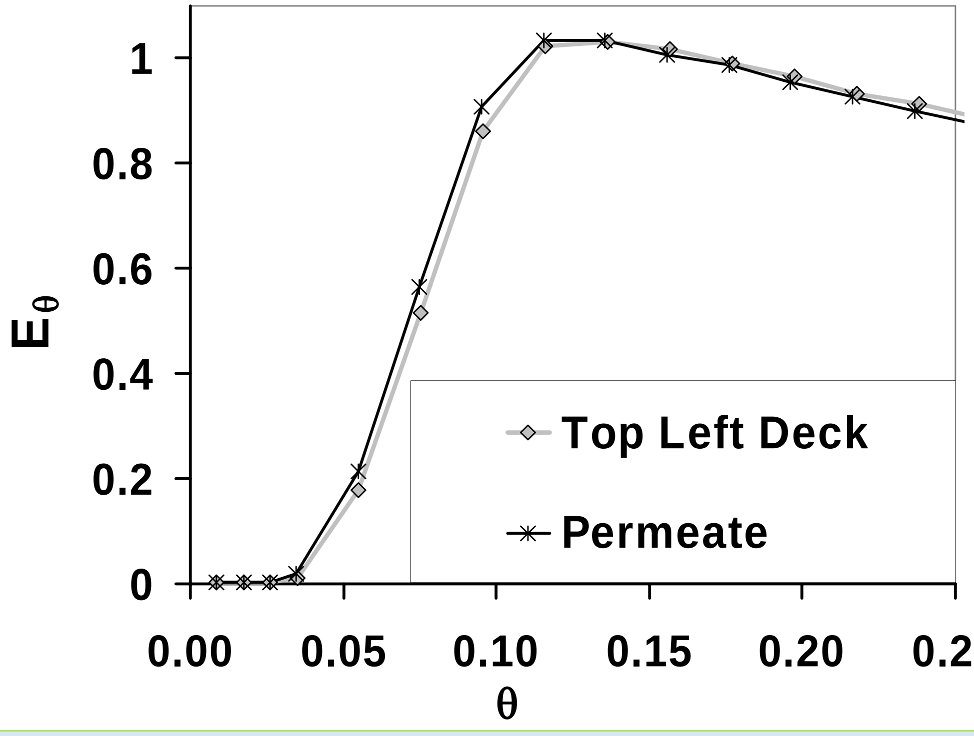


See reference Brannock (2007b)

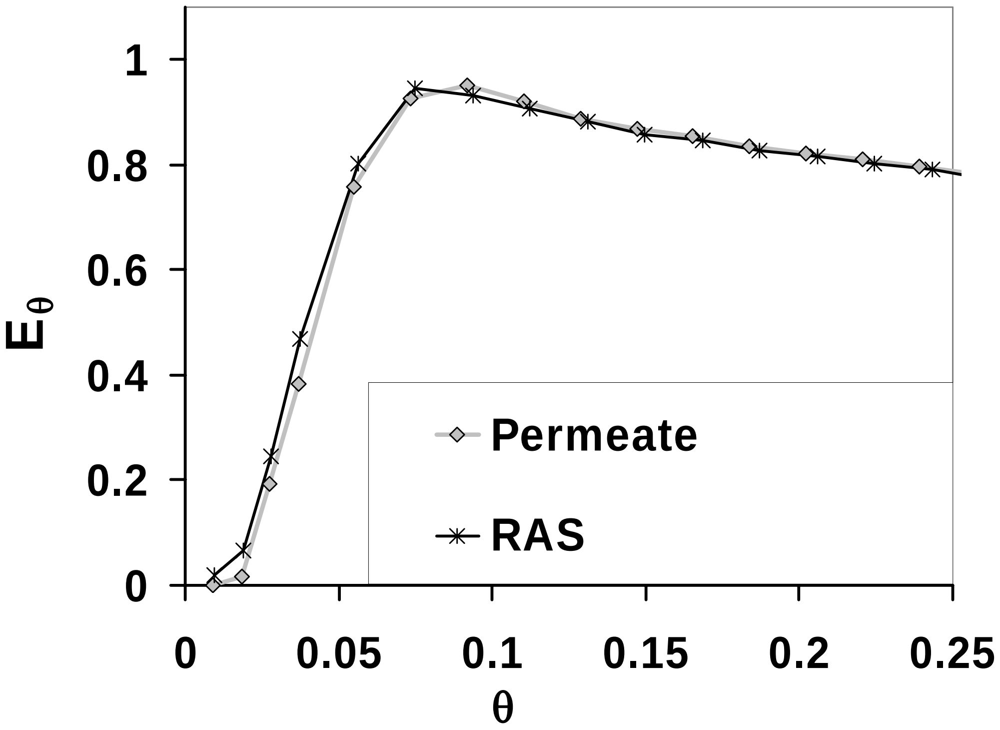
Residence Time Distribution Properties

Site			1. Flat Sheet	2. Hollow Fibre
Trial			2	2
Tracer Recovery	-	[-]	99.5%	96.0%
Hydraulic Residence Time	T	[h]	27.5	10.3
Mean Residence Time	t_m	[h]	28.7	9.07
Peak Time	t_p	[h]	3.92	0.83
Plug Flow Index (⇑→1)	t_p/T	[-]	0.142	0.081
Dead Zone Index (⇑→0)	t_m/T	[-]	1.04	0.88
Short-Circuit Index (⇑→1)	$(1-t_p/t_m)$	[-]	0.863	0.908
Peclet Number (⇑→PFR)	Pe_r	[-]	1.29	1.75
Number of Tanks in Series	n	[-]	1.44	1.35

Membrane Filtration Vessel Mixing - Site 1 (FS)



Membrane Filtration Vessel Mixing - Site 2 (HF)



See reference Brannock (2007b)

Australian MBR Tracer Studies

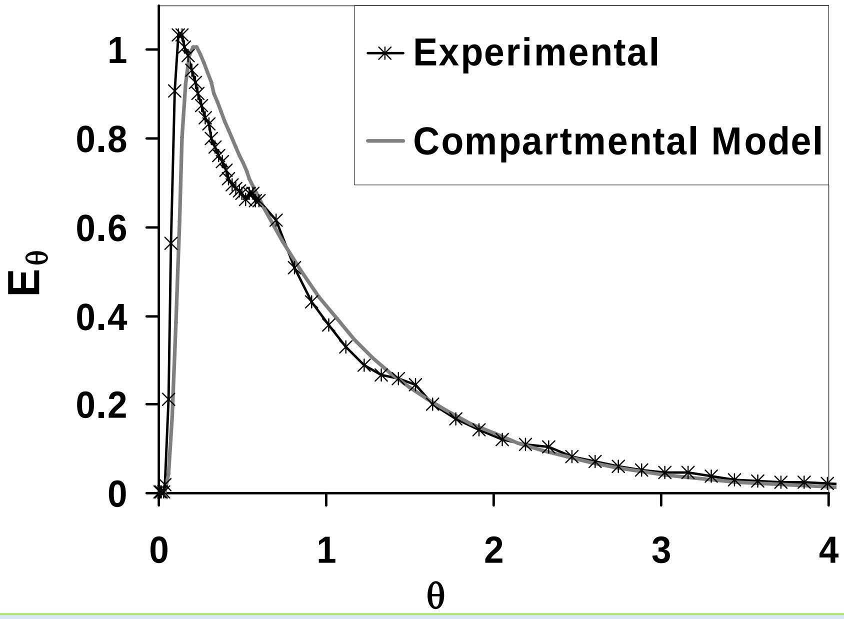
Relative Power Requirements:

Parameters	Units	FS MBR	HF MBR
Power - Mixer	kW	7.1	2.2
Power - Bioreactor Blower	kW	3.3	8.5
Power - Membrane Vessel Blower	kW	29.5	13.8
Power - Recirculation Pump	kW	16.0	18.5
Power - Total	kW	55.8	42.9
Total Specific Power Input – Volume Basis	*W/m^3*	***44.8***	***91.2***
Total Specific Power Input – Flowrate Basis	*kWh/m^3*	***1.23***	***0.939***
Memb. Blower Power Input – Volume Basis	*W/m^3*	***75.2***	***235***
Memb. Blower Power Input – Flowrate Basis	*kWh/m^3*	***0.651***	***0.301***

See reference Brannock (2007b)

Compartmental Modelling

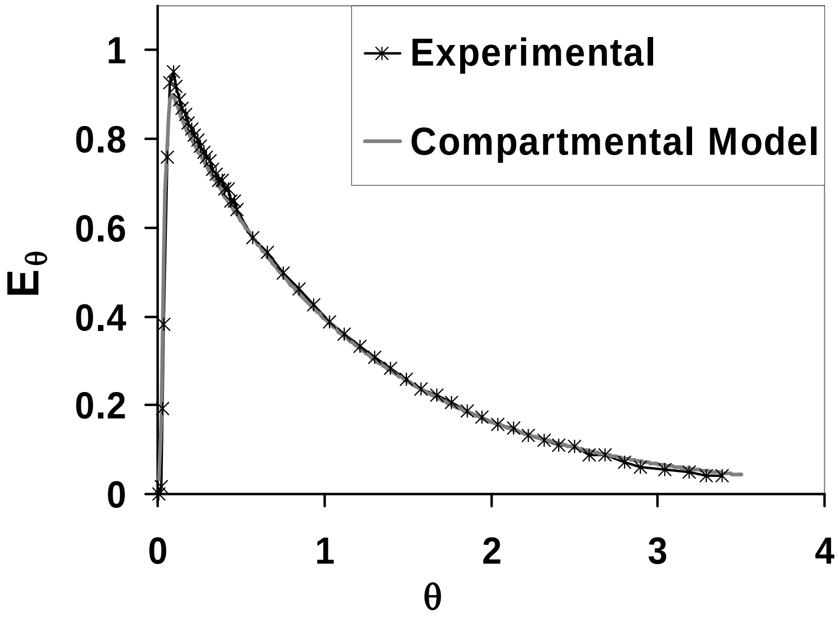
- Site 1 – Flat Sheet MBR
  - Cannot predict energy requirements!
  - Relies on CSTR assumption – not valid for channels/complex flow



See reference Brannock (2007b) & Howes (2003)

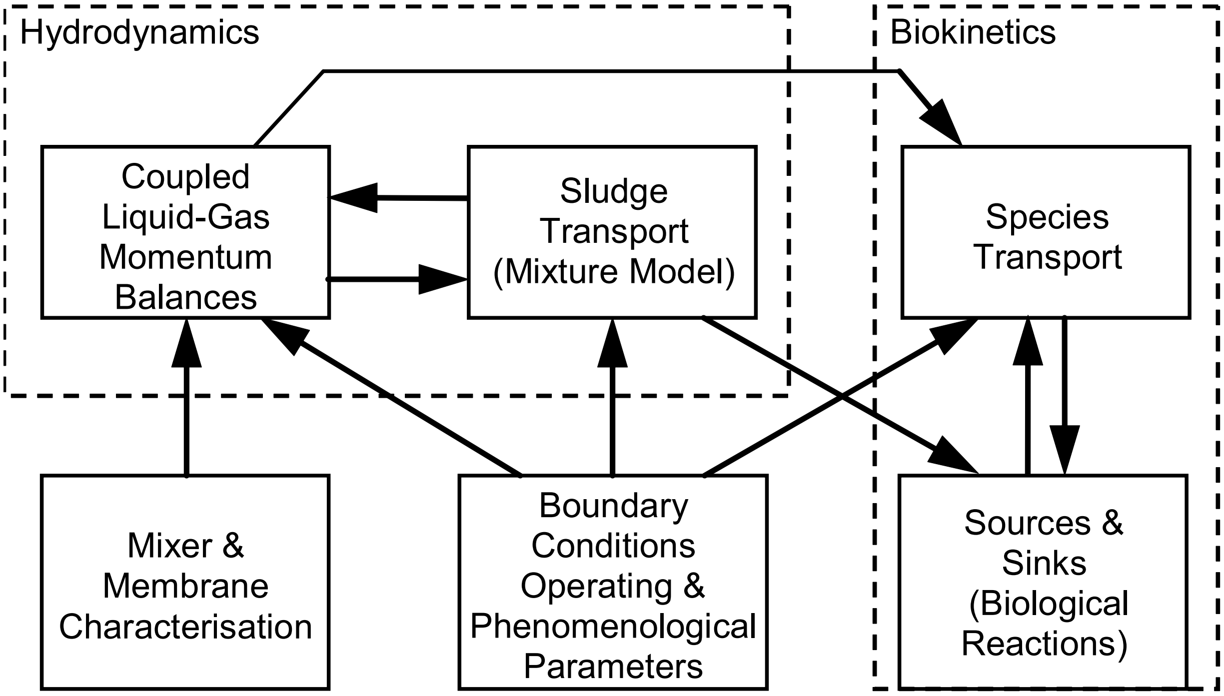
Compartmental Modelling

- Site 2 – Hollow Fibre MBR
  - Cannot predict energy requirements!
  - Relies on CSTR assumption – not valid for channels/complex flow



See reference Brannock (2007b) & Howes (2003)

MBR CFD Model Components



Hydrodynamics

Coupled Liquid-Gas Momentum Balances

Sludge Transport (Mixture Model)

Biokinetics

Species Transport

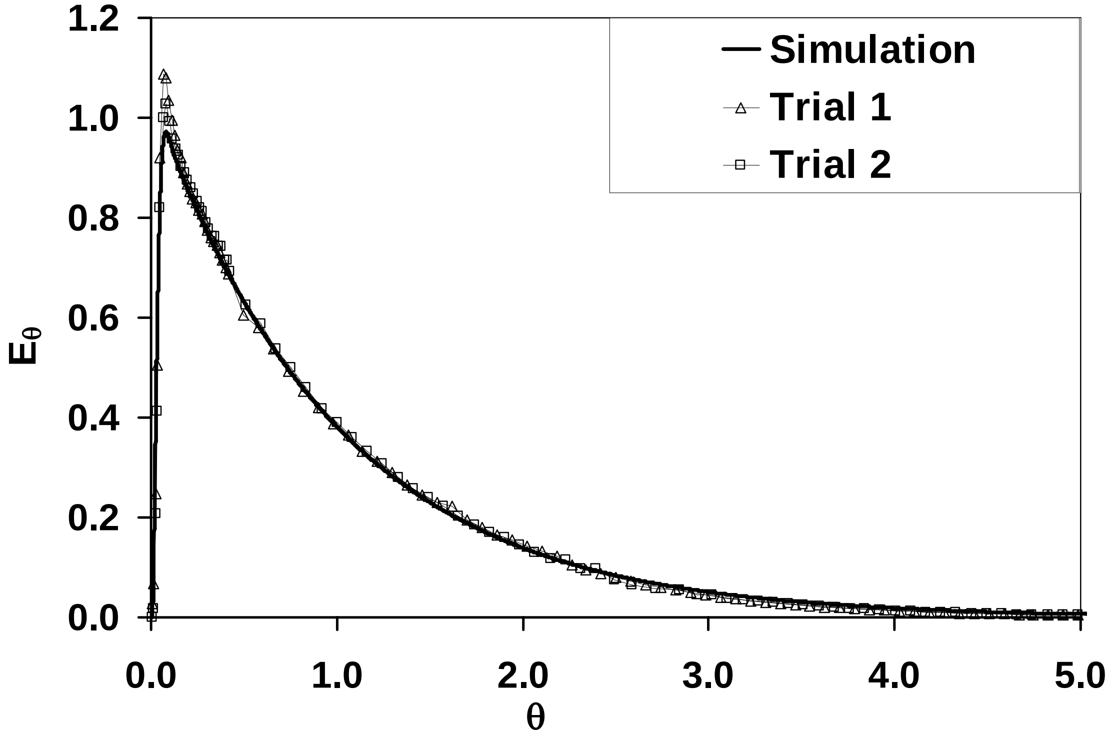
Mixer & Membrane Characterisation

Boundary Conditions Operating & Phenomenological Parameters

Sources & Sinks (Biological Reactions)

See reference Brannock (2007a)

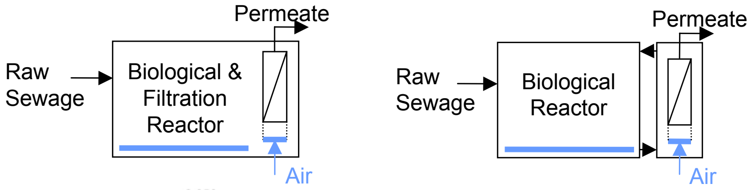
Preliminary Full-Scale CFD Modelling – HF MBR



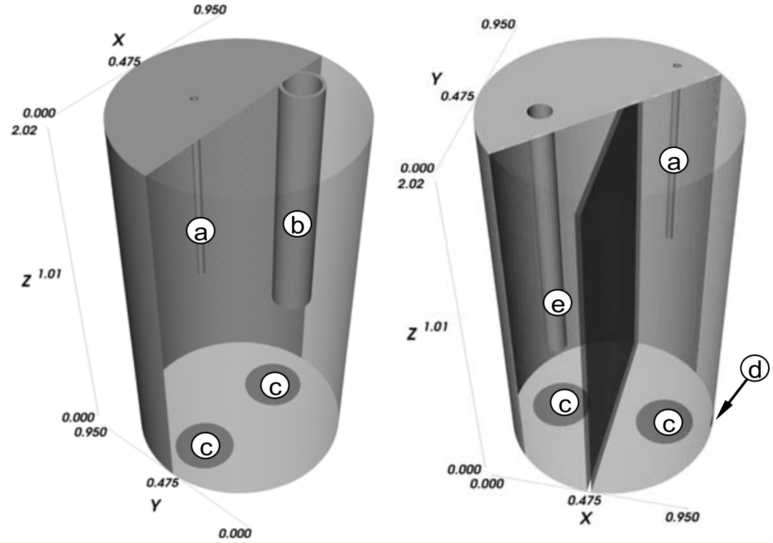
CFD Modelling of IN/OUT MBR Pilot Plant

MBR Setup:-

Left - inside submerged
Right - outside submerged



- a) inlet
- b) membrane module
- c) aerators
- d) outlet to external membrane module
- e) recycle from the external membrane module

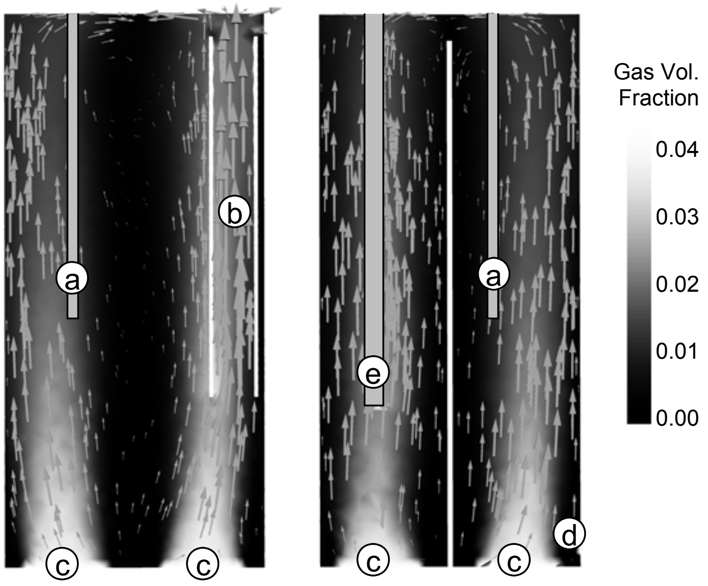


See reference Brannock (2007a)

CFD Modelling Applied to IN/OUT Setup

Volume fraction and velocities (slice at y = 0.475m) for the inside (*left*) and outside (*right*) at aeration 12.5% of max (20cfm):

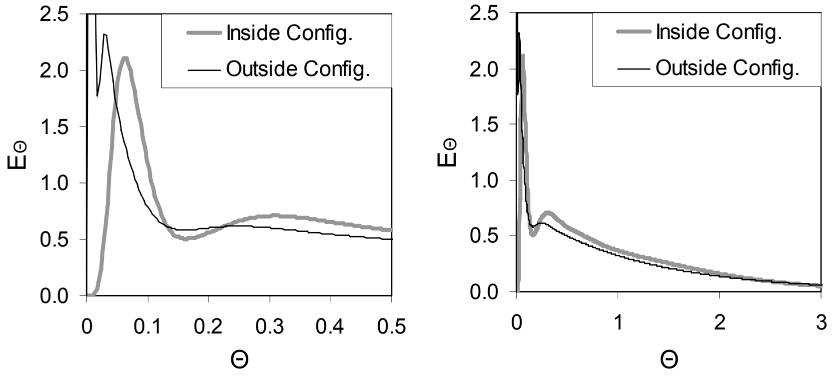
- a) inlet
- b) inside membrane module
- c) aerators
- d) outlet to the external membrane module
- e) membrane recycle.



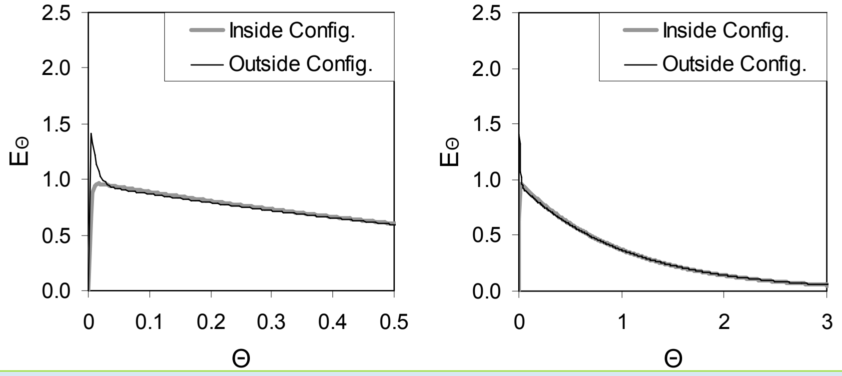
See reference Brannock (2007a)

Simulated Residence Time Distributions

- 0% of maximum aeration $(20ft^3/min)$



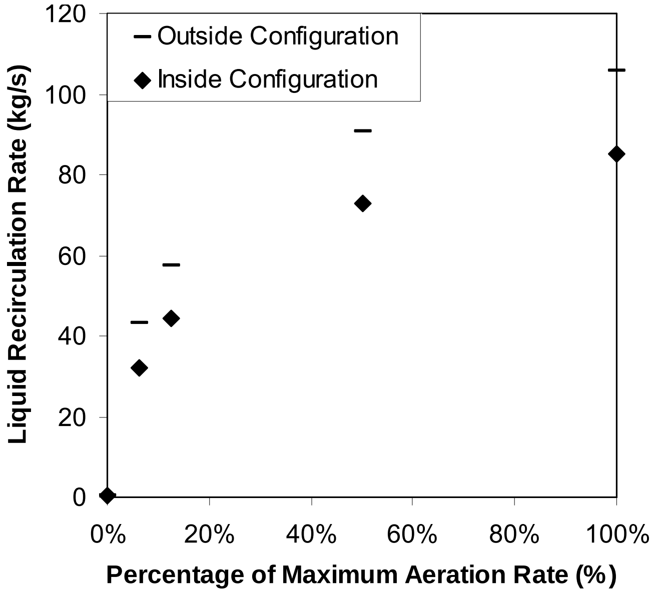
- 12.5% of maximum aeration $(20ft^3/min)$



See reference Brannock (2007a)

CFD Modelling Applied to VITO Setup

Liquid internal recirculation rate at z = 1.02m (inlet z = 1.01m) versus percentage of maximum aeration rate $(20ft^3/min)$:



See reference Brannock (2007a)

CFD Modelling of MBR Pilot Plant

Residence time distribution properties:

Config.	Property	No Aeration (0%)	V.Low Aeration (6.25%)	Low Aeration (12.5%)	High Aeration (100%)
Inside	Residence No.	0.650	0.641	0.641	0.638
	Plugflow Index	0.0629	0.0140	0.0175	0.0140
Outside	Residence No.	0.434	0.640	0.640	0.638
	Plugflow Index	0.00673	0.00337	0.00337	0.00337

Note:

Residence Number is a measure of ‘closeness to plug flow’ where:

Residence No. = 1.00 ≅ Plug flow (i.e. ∞ complete mixed reactors)

Residence No. = 0.74 ≅ 2 complete mixed reactors in series

Residence No. = 0.63 ≅ 1 complete mixed reactor

Plugflow Index = 1 for plugflow & Plugflow Index = 0 for complete mixing

See reference Brannock (2007a)

Conclusions

- Singaporean/Australian MBR Tracer Studies:
  - Enabled development of a methodology with high reproducibility & tracer recovery ⇒ validation “whole” MBR CFD models
  - Overall MBR RTD approach completely mixing – full-scale & pilot-scale MBRs
  - FS membranes require ↑ aerator kWh/m^3 permeate than HF likely due to ↓packing ρ, ↑depth, baffle effects, etc ⇒ CFD optimisation
- Full-scale MBR CFD Modelling:
  - Preliminary modelling undertaken but still in development
- Inside/Outside Membrane CFD Modelling:
  - As expected, main mechanism of mixing is aeration
  - Baffle & recycle of “Outside” configuration resulted in more “mixing“
  - Low level of aeration achieved almost complete mixing, ∴ aeration level should be determined by biological &/or fouling minimisation requirements

The Future of MBR Design?

Future CFD Design Procedure:

1. Required pollutant removal specified
2. Develop range of scenarios using established empirical & heuristic techniques
3. Simulate scenarios using validated CFD model
4. Evaluate each i.e. cost (volume required & energy usage)

Far Future CFD Design Procedure – Optimisation Routine:

Objective function: Costs – capital (e.g. volume) + O&M (e.g. energy)

Constraints: Pollutant removal & practical limitations

Parameters: a myriad!

Related Publications

- BRANNOCK, M., HOWES, T., JANSONS, K., JOHNS, M. & KELLER, J. (2002a) Development of a computational fluid dynamic design technique for mixed wastewater treatment vessels. *Environmental Engineering Research Event.* Sydney, Australia.
- BRANNOCK, M., HOWES, T., JOHNS, M., DE CLERCQ, B. & KELLER, J. (2002b) CFD modelling of particle transport and biological reactions in a mixed wastewater treatment vessel. *International Conference on Scientific & Engineering Computation (IC-SEC) 2002.* Singapore, Imperial College Press.
- DE CLERCQ, B., BRANNOCK, M., LANT, P. & VANROLLEGHEM, P. A. (2002) In situ particle size characterization on a circular clarifier of a wastewater treatment plant. *World Congress on Particle Technology 4.* Sydney, Australia.
- BRANNOCK, M. W. D. (2003) Computational fluid dynamics tools for the design of mixed anoxic wastewater treatment vessels. *School of Environmental Engineering.* Brisbane, The University of Queensland., PhD, ISBN: 186 499 741 9
- HOWES, T., M. BRANNOCK, & CORRE, G. (2003). Development of simplified flow models from CFD simulations. *Third International Conference on CFD in the Minerals and Process Industries*, CSIRO, Melbourne, Australia.
- BRANNOCK, M. W. D., DE WEEVER, H., WANG, Y. & LESLIE, G. (2007a) Evaluation of membrane bioreactor performance via computational fluid dynamics modelling: effect of membrane configuration and mixing. *IWA 4th International Membrane Conference.* Harrogate, UK, IWA.
- BRANNOCK, M. W. D., KUECHLE, B., WANG, Y. & LESLIE, G. (2007b) Evaluation of membrane bioreactor performance via residence time distribution analysis: effects of membrane configuration in full-scale MBRs. *Membrane Technologies for Wastewater Treatment and Reuse.* Berlin, Germany, IWA., ISBN: 978 3 9811684 0 2
- WANG, Y., BRANNOCK, M., ONG, K. & LESLIE, G. (2007) Evaluation of membrane bioreactor performance via residence time distribution: effects of membrane configuration in pilot-scale MBRs. *IWA 4th International Membrane Conference.* Harrogate, UK, IWA.

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10. MINUTES AND DISCUSSION

Minutes of “Workshop on CFD modelling for MBR applications: From the fibre to the plant”

Introduction

The meeting brought together groups from Europe (and even beyond) working on several aspects of CFD related to MBR. Most of the groups are involved in one of the projects under the MBR-Network Umbrella.
Boris Lesjean addresses a brief welcome word and points out the objectives:

- Review and exchange of international experience on CFD modelling and hydrodynamic measurement methods for MBR applications
- Discussions with system suppliers and plants constructors and operators to identify the needs of the MBR industry

Technical part

Most groups give an overview of their respective activities followed by brief discussion/question slots. To structure the whole this part was broken down in different parts based on the process scale studied:

- Modelling of the interaction of bubbles on membrane (microscale)
- Modelling of the membrane modules and aeration system (mesoscale)
- Modelling of the entire MBR station

The content of the contributions will not be discussed here. The presentations are provided in this book of handouts.

Wrap up and discussion

Boris Lesjean listed some “hot” topics to initiate discussion:

- Most relevant parameters in modelling MBR-fouling
  Studies have focused on wall shear stress, bubble frequency, bubble size/shape, liquid velocities,… It is unclear which is the most important one. Also some “contradictory” results are obtained with regard to the optimal gas velocity and its ability to reduce fouling. A link between these parameters and the actual fouling potential needs to be addressed.

- Viscosity model to be used?
  Many groups have attempted to model sludge viscosity, again with several outcomes that are not always “in line”. Some questions were raised: (1) does viscosity really has a large impact on the calculation outcome? Especially at micro-scale it is needed, whereas at meso- and macro-scale the solution would not be too sensitive and the impact would not be that large The question here is: how accurately do we need to understand the effect of the shear on the flocs and to model the viscosity of the sludge? At micro-scale the knowledge should be accurate enough to represent the particle size distribution and mass transfer. However at meso- and macro-scale, to model the behaviour of the sludge with too much accuracy would not affect that much the result and can be computationally expensive. (2) could a transparent model solution be found that

mimics the sludge in terms of viscosity? This is deemed difficult as the behaviour is not known, (3) Do we need the viscosity in the entire range of shear and if not what would be the range where we do need it? This remained without any clear answer suggesting that more work in this area is still needed. (4) How are we sure that the non-Newtonian rheological behaviour of the sludge usually reported are not due to a destruction of the sludge structure during the measurement and non representative of the comportment in the plant?

- Experimental tools/sensors for validation
  A lot of experimental methods are out there. In general these methods work fine as long as you know what you are doing and interpret the results with the necessary care. Experimental method should be defined according to the objective of the study. Models validated at meso- or macro-scale cannot deliver any conclusion at microscale and vice-versa. It is agreed that still more advanced techniques are needed to measure in these complex systems (esp. measures in particular media such as sludge) and that this point should be addressed to the sensor providers. Model validation is generally agreed to be of high importance. Bench-scale experiments would be useful to calibrate / validate the sensors.

- CFD for fundamental or applied R&D
  Here it was raised that the detail in the CFD-model can clearly be different (viscosity is a good example here). To justify the inclusion of any aspect to a certain degree of complexity should be based on some kind of sensitivity analysis. The idea was raised to create a kind of benchmark for the different levels of systems (with different degree of complexity: CFD model calibration with column bubble, with water / coalescence, with sludge or model solution).

  Simon Judd proposed to launch a questionnaire in order to collect the typical settings used when modelling at the different scales.
  Also the coupling between different scales is an issue that should receive attention (e.g. influence of macro-mixing on specific problems observed at meso- or microscale).

- Bubble size?
  Sensitivity analyses could be performed using CFD models.

Although only one participant from the supplier/end users was present, this lead to a summary of questions/needs from their side which were discussed.

- Distribution of in- and outgoing flows: can this be simulated? This in view of design (bottom-top, bottom-bottom, top-bottom, top-top) and short-circuiting.
- Optimum between cleaning effectiveness and energy demand
- Dealing with clogging. Pre-treatment, module design, system design, testing procedure.
- System specific fouling control/cleaning strategy
- Cover biological tanks to avoid external pollution (e.g. leaves)
- Mechanical stability
- Module lifetime assessment

Some of these questions could be fairly easily addressed by the current state-of-the-art but have up to now not been the object of research. On the other hand the end-users could not assess the feasibility of the current state-of-the-art to answer these questions. This proves the importance of this “joint” meeting.

Next meeting

A next meeting will be organised in Ghent (BIOMATH – Ghent University; Belgium) during July/August 2008 in junction with the MBR-Train training week.

Participants

Matthew Brannock (University of New South Wales)
Steffen Buetehorn (RWTH Aachen University)
Ingmar Nopens (Ghent University)
Nicolas Rios (Ghent University)
Christelle Guigui (INSA Toulouse)
Jan Saalbach (Flow Concept)
Simon Judd (Cranfield University)
Daniela Tacke (RWTH Aachen University)
Helmut Prieske (Technical University of Berlin)
Céline Levecq (Anjou Recherche)
Laure Martinelli (INSA Toulouse)
Samuel Pollet (INSA Toulouse)
Evelyne Nguyen Cong Duc (Berlin Centre of Competence for Water)
Boris Lesjean (Berlin Centre of Competence for Water)
Colleen Chan (University of British Columbia)
Roger Ben Aim (INSA Toulouse)
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Mathias Kraume (University of Technology, Berlin)
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Gudrun Winkler (Cranfield University)
José Luis Santos (FCT-UNL, Lisbon)
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