Institution: Swansea University
Unit of Assessment: 15 - General Engineering
Title of case study: Optimisation of membrane systems and its benefit to water treatment, food processing and medicine - from characterisation and fabrication to control.
1. Summary of the impact

Researchers at Swansea University were the first in the world to apply Atomic Force Microscopy (AFM) to membrane separation in the field of process engineering. Membrane optimisation processes have emerged as one of the most significant recent developments in chemical engineering, with a range of applications in, for example, the food industry and medicine/therapeutics. Research undertaken by the University has led to significant commercial and health benefits, including

- improved food processing techniques, with induced investment of £11m and operational savings of over £2m.
- novel antibacterial alginate therapeutics, now in clinical trials, that have been proven in the treatment of cystic fibrosis, inducing investment of £7m.
- exploitation of proprietary membrane modification techniques, with $2m impact.
- development of two novel membranes used worldwide in the process industries, generating sales of £500k for each.

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2. Underpinning research

The underpinning research relates to the establishment of membrane process optimisation techniques with advanced rigour, based on the novel surface characterisation, membrane modification and theoretical frame works developed at Swansea.

Staff within the Centre for Complex Fluids Processing (CCFP) and Centre for Water Advanced Technologies and Environmental Research (CWATER) including **Prof N Hilal** (Editor in chief Desalination Journal) (at Swansea 1998–2001; 2010 – date), **Dr C J Wright** (1998 – date), **Dr R W Lovitt** (1998 – date), **Dr P M Williams** (1998 – date), **Dr D Oatley** (1998 - 2001, 2010 – date) and **Prof W R Bowen** (emeritus professor since 2003), continue to be at the forefront of research that has enabled the industrial application of membrane technologies.

Atomic Force Microscopy (AFM) was originally used by physicists and bioscientists for imaging biomaterials. In the early 1990s, researchers at Swansea began to consider other applications for AFM and were **the first to use the technique in process engineering**, where two primary advantages were found: i) the ability to image materials in a liquid environment, and ii) the ability to measure colloid/cell-to-colloid/cell and colloid/cell-to-surface interactions, again in a liquid environment.

Our research consequently established AFM as an essential tool for the membrane technologist. Initially, the techniques to directly visualise membranes and measure interaction forces responsible for process behaviour were limited by relevance and resolution [G3]. We demonstrated that AFM not only provides unparalleled definition of membrane structure, when compared to other imaging techniques, but also permits the direct measurement of forces that control the operation of membranes [R1-R3]. Our **breakthrough innovations** in the development of AFM for application in process engineering include the:

- first demonstration that nanofiltration membranes have pores [R1];
- smallest reported AFM colloid probe [R3];
- first AFM coated colloid probe technique [R3];
- first AFM cell probe technique [R2];
- first direct measurements of the interaction of single live cells with surfaces [R2] [G4].

These AFM techniques allow unrivalled capabilities in terms of characterisation for membrane process optimisation, which have been exploited in the development of membranes **now used worldwide** in the process industries [R2, R3].

Optimisation of membrane systems by surface characterisation is an integral part of the development of new membranes and the modification of membranes to improve process performance. We have used membrane modification techniques extensively to create novel membranes, such as a positively charged nanofiltration membrane permitting an increased range of process control when the majority of current membranes are negatively charged. We have also demonstrated through characterisation and membrane flux studies that a novel UV-initiated graft polymerisation technique was able to optimise membrane processes by substantially reducing the fouling of nanofiltration membranes [R4]. This is highly desirable as fouling of membranes and the consequent compromise of the separation process is a substantial cost to all industries that use membranes.

Under EPSRC platform grant funding, from physics to process [G1], the group has developed theoretical frameworks for optimisation which features *ab-initio* predictions of membrane process performance with no adjustable parameters avoiding complex and elaborate descriptions that would not be adopted by industry [R5]. In the theoretical description of membrane filtration we have advanced the rigour of the technique substantially by the account of nanoscale variation of solvent dielectric properties and viscosity. The Donan-Steric-Partitioning-Model first developed at Swansea, continues to be recognised as **the most advanced model describing nanofiltration** [R1]. Our modelling of ultrafiltration/nanofiltration involves prediction of nanofluid properties in membrane separation; this optimisation capability has been adopted for improved production.

Under EPSRC funding we have also developed AFM techniques to examine the colloidal surfaces interactions and mechanical properties of biological particles including bacteria. This not only improved the rigour of membrane optimisation processes based on characterisation of fouling resistance of membranes but also had tremendous potential in other disciplines. Thus, the initial AFM work led to a new research theme for the Swansea membrane group, with cross over into medical research. We applied the novel AFM characterisation techniques to study the mechanical properties of small quantities of biological materials and this research has been used to study and optimise the application of alginate particles that control bacterial biofilms [R6]. New methods for controlling biofilms are increasingly being recognised as essential for the future of healthcare as antibiotic resistant strains are predicted to become predominant.

3. References to the research

Our international lead in membrane technology and application of AFM in Engineering was recognised as 4* in the RAE2008 General Engineering Panel summary and has led to the publication of two high profile handbooks (ISBN 978-1856175173, 978-1439866351). The research has featured in over 170 peer reviewed papers in the past 15 years (over 4600 citations with an average of 27 citations per paper) and an ‘h’ index of 38 (Thompson Web of Knowledge).

R1. Bowen WR; Mohammad AW; **Hilal N** (1997) “Characterisation of nanofiltration membranes for predictive purposes - Use of salts, uncharged solutes and atomic force microscopy” Journal of Membrane Science, 126(1) pp 91-105. (IF 4.357 Citation 402.)

R2. Bowen, WR; **Hilal, N; Lovitt, RW, Wright, CJ** (1999), Characterisation of membrane surfaces: Direct measurement of biological adhesion using an atomic force microscope. Journal of Membrane Science, 154**:** 205-212 (IF 4.357 Citation 67.)

R3. Bowen, WR; **Hilal, N; Lovitt, RW, Wright, CJ** (1998), A new technique for membrane characterisation: Direct measurement of the force of adhesion of a single particle using an atomic force microscope. Journal of Membrane Science 139 pp 269-274. (IF 4.357 Citation 65.)

R4. Abu Seman M.N, Khayet M., Bin Ali Z.I., **Hilal N.** (2010) Reduction of nanofiltration membrane fouling by UV-initiated graft polymerisation technique Journal of Membrane Science 355 pp 133-141. (IF 4.357 Citation 26.)

R5. Bowen WR, Cassey B, Jones P; and **Oatley DL**, (2004) Modelling the performance of nanofiltration membrane — application to an industrially relevant separation, Journal of Membrane Science 242, pp 211-220. (IF 4.357 Citation 43.)

R6. Powell LC, Sowedan A, Khan S, **Wright CJ**, Hawkins H, Onsøyen E, Myrvold R, Hill KE and Thomas DW (2013) The effect of alginate oligosaccharides on the mechanical properties of Gram-negative biofilms, Biofouling, 29, 4, pp.413 (IF 4.488.)

R1, R2 and R5 best represent the quality of the research. *(Citations obtained from Google scholar)*

Major Relevant Research Grants

G1 EPSRC Platform grant. Complex fluids and complex flows – from physics to processes (2000-2003 Renewed 2003-2008; £687K) W.R.Bowen, PR Williams CJ Wright. (The Centre for Complex Fluid Processing at Swansea was the first at any UK Chemical Engineering Department to be awarded an EPSRC Platform Grant.)

G2 Centre of Excellence for Technology and Industrial Collaboration (CETIC). Complex Fluids Processing Centre (2002- 2009; £700K) (CETIC, NAfW, HEFCW, WDA) WR Bowen (PI), R. Bryant, M Jones, RW Lovitt, PM Williams, PR Williams (PI) and CJ Wright

G3 EPSRC Visualisation, verification and quantification of physiochemical interactions in bio(separation) processes (1994-1997; £240K) WR.Bowen (PI) RW Lovitt (PDRAs N.Hilal and CJ Wright)

G4 EPSRC Advanced Research Fellowship, C.J. Wright: Elucidation, quantification and control of bio-surface interactions – exploiting the potential of AFM (2001–2006 £250K). Reviewed at completion '*overall as tending to outstanding with internationally leading research'*

G5 EPSRC Advanced Research Fellowship 2001-2006, PM Williams: *Ab Initio* methods for the prediction and optimisation of separation processes (2004-2009 £250K).

4. Details of the impact

Swansea's research in membrane optimisation processes has delivered international economic, societal, environmental and health impacts through the novel application of membranes and AFM to food processing, water treatment and medicine. Close engagement with industry has informed the research throughout the period, ensuring the development, implementation and adoption of new technologies by industrial organisations in the UK, Europe and Middle East. The unit's record of active industrial engagement is evidenced by its recognition as a Centre of Excellence for Technology and Industrial Collaboration and subsequently a Knowledge Transfer Centre.

In the **food processing industry**, our membrane optimisation technology has been exploited through the development of *ab initio* modelling techniques, novel processes and systems [R1, R5]. An example of a novel industrial process arising from the research is the separation of lactose from whey by Volac, a leader in the application of dairy nutrition, manufacturing and supplying performance nutrition products globally. In 2008, with reference to our membrane and process systems, Volac used this membrane separation as a process innovation and **invested £8 million** into its plant, establishing a new lactose refining and drying system said to be "*the only kit of its kind in Europe*". [Group Technical Manager, Processing & Technology, Lampeter UK]

In 2009, First Milk were able to base an audit on their current processing stream on our membrane process optimisation research [R1, R5]. As a result, they replaced evaporators with reverse osmosis membrane technology, with an **investment of £3 million** in new whey processing equipment, which has delivered more than £500,000 of energy savings at the site in Haverfordwest each subsequent year, as well as improving the quality of whey produced at the creamery. These process improvements impact on an international scale as First Milk supply milk, cheese and ingredients to an international market.

> *"In total, the membrane optimisation procedure at First Milk has induced an **investment of £3m, with a net saving of over £2m** since 2009"* (Site Manager First Milk Cheese Co Ltd)

Alongside commercial impacts, our research is delivering societal and environmental impacts through the production of novel membranes and processes to **improve water and waste water treatment** with respect to the environmental impact of industry. For example, our research on membrane fouling combined with novel membrane modification was used to improve nanofiltration for production of clean water [R4]. A membrane modification technique based on UV-initiated graft polymerisation was used by Water Nano to produce a new series of membrane systems for desalination and household water in the Gulf.

> *"the membrane research at Swansea University, in particular the development of the membrane modification technique based on UV-initiated graft polymerisation, led to the creation of* ***9 jobs at Water Nano and sales of the small scale unit were in the order of 1.2M US$."*** (Managing Director, Advanced Water Nano Ltd, Saudi Arabia)

Health impact is evidenced in the development of **novel antibacterial alginate therapeutics.** The development of AFM methods to study the mechanical properties of cells and biofilms is being exploited in the development of the next generation of antibacterial agents [R6]. Research on the disruption of bacterial biofilms associated with cystic fibrosis by alginate particles used AFM techniques in conjunction with microbiology, rheology, particle characterisation and structural modelling, and was used by the Norwegian company AlgiPharma to support the case for clinical trials across Europe. This led to further investment both from industry and government for the development by AlgiPharma **of a novel polymer therapeutic (Oligo G) for the treatment of cystic fibrosis and chronic obstructive pulmonary disease** (COPD).

> *"The visualisation of OligoG on membrane surfaces has provided (and will continue to provide) valuable evidence in support of the product development, characterization, and funding for OligoG in human disease [...] and in applications for biomedical device coatings. OligoG is currently in Phase IIa clinical trials for cystic fibrosis. We currently estimate that this research has facilitated the investment for further research in AlgiPharma from the Norwegian Research Council and the UK Technology Strategy Board* ***in the region of £7m****"* (Research and Development Director, Sandvika, Norway.)

Membrane optimisation by surface characterisation was also exploited to identify **novel membranes for the process industries** [R2, R3] [RG3]. The novel membranes and their characterisation were used by PCI Membrane Systems, now part of Xylem Inc. Xylem are a global supplier of fluid technology and equipment for fluid processing, including water management. The membranes developed included two that have been supplied globally on a large scale to the process industries since 1999. Xylem Inc have identified that the volume of sales continues with sales in the REF period totalling £500K for each membrane [Technical Manager Xylem Water Services Ltd, Basingstoke, UK]. The emerging process of nanofiltration reached a global market size of $310.5 million by 2012, contributing to a market of established ultrafiltration technology that is in the US alone currently worth $635 million. [BCC research.]

5. Sources to corroborate the impact

1. Group Technical Manager, Processing & Technology, Volac International Limited - the impact of membrane optimisation procedures for lactose processing
2. Site Manager, First Milk Cheese Co Ltd - the impact of membrane process optimisation on whey processing
3. Managing Director, Water NanoLtd - the impact of the development of a membrane modification technique for reduced fouling and improved treatment of water
4. R&D Director, AlgiPharma AS - the impact of AFM biofilm research on the development of new therapeutics
5. Technical Manager, Xylem Water Services Ltd - the impact of AFM membrane characterisation on membrane development
6. Market Size - BCC Research http://www.prweb.com/releases/2013/8/prweb10978649.htm