Institution: University of Oxford

Unit of Assessment: 15, General Engineering

Title of case study: UOA15-08: Efficient, cost-effective membrane filtration

1. Summary of the impact

Research at the Department of Engineering Science has led to step changes in the way industrial membrane filtration plants are designed and operated . Based on some key research results that have successfully tackled membrane fouling problems, the work has triggered rapid uptake of membrane-based technologies that are more energy-efficient than traditional processes. Water companies are among those achieving both economic and the environmental benefits, and the research has played a key role in the membrane bioreactor (MBR) market, which is now growing at over 10% a year, and in the global desalination market which exceeds US$19 billion, according to GMR Data (2012) [13].

2. Underpinning research

Many industrial processes (e.g. water/wastewater treatment, food and drink manufacture) use filtration plants to separate macro-molecules or micro-particles from water. Although the benefits of using membrane technologies for separation had long been recognised, and their use was well-established, the issue of membrane fouling (and the associated costs of membrane cleaning) had inhibited the adoption of these technologies by industry. Two important breakthroughs achieved at the Department – the concept of 'critical flux' and the injection of air bubbles into membrane systems – have unlocked the potential of membrane technologies. Originating as separate work streams in the 1990s, the research was first brought together in 2002. Refinement of the methods is on-going [1] and international collaborations led by the Department over the past decade have included scientists in France, Australia, China and Singapore.

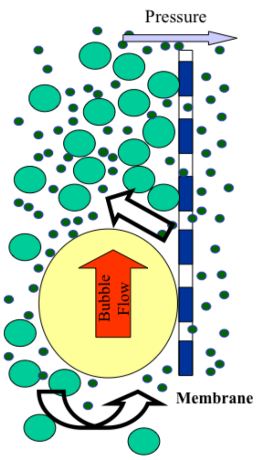

Fig. 1: Gas-liquid cross-flow membrane filtration.

Fig. 2: CFD modelling of the new process.

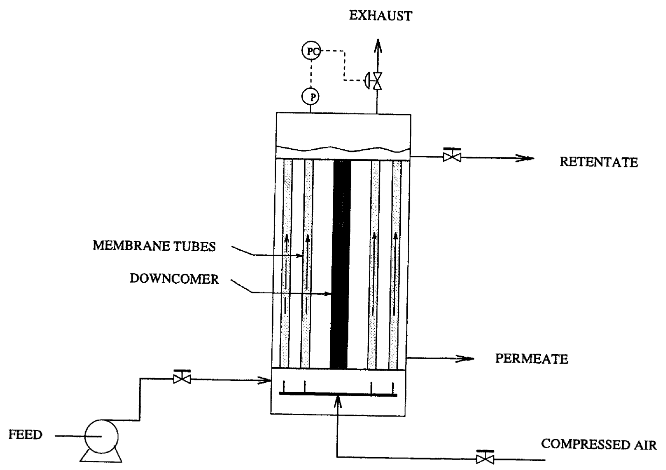

Fig. 3: Air-lift gas-liquid two-phase cross-flow filtration.

- **Air bubble injection**: Research began in 1994, led by Prof. Zhanfeng Cui (who joined the Department in 1994 as a University Lecturer and has been the Donald Pollock Professor of Chemical Engineering since 2000). To reduce membrane fouling, Cui proposed injecting air bubbles into membrane systems to create gas-liquid two-phase flow (see Figure 1) and bubble-induced local mixing. This concept was at first controversial: industrial users favoured degassing solutions and believed that bubble injection would make fouling problems worse. Cui therefore carried out a detailed analogue analysis, based on heat transfer enhancement, and also conducted proof-of-concept experiments. Between 1994 and 2005, he secured nine major research grants to develop computational fluid dynamics (CFD) models demonstrating the benefits of this new approach (e.g. see Figure 2) and to develop industrial applications; one process developed was air-lift gas-liquid two-phase cross-flow filtration (Figure 3) [2]. Cui has published a series of extensively cited major papers on this research (e.g. [3, 4]) and supervised work in this area by 12 doctoral students. Since 2009, his work on the topic has focused on using aeration to cut energy consumption in MBRs [1].

- **Critical flux:** First developed by Dr Robert Field (who joined the Department in 2001 as a University Lecturer and is currently Professor of Engineering Science), this concept has identified the conditions to minimise fouling; with large driving pressures and high cross-flow velocities no longer required, energy use and cleaning costs are both reduced. In 2002 and 2003, Field held workshops to explore the theory and undertook experiments to validate both the existence of a critical flux and his predictions [5]. In 2006, he co-authored a major review paper [6] (extensively cited, and rated by the Journal of Membrane Science one of the top five papers of 2006-2010). Since 2009, with wastewater applications to the fore, Field has proposed and developed (with industrialist Dr Graeme Pearce) the new concept of a 'threshold flux' to distinguish between low-fouling and high-fouling regimes and to guide the practical design of new membrane processes [1]; experimental research by Field has focused on identifying and predicting the threshold flux, with much of the work undertaken in collaboration with Singapore and China.

Cui and Field have published 16 joint papers describing their research (*e.g.* [1]). They also both played a key role in the Oxford University-led, EPSRC First Faraday 'Advanced Membrane Bioreactors for Leachate Treatment' project. Running from 2003 to 2005, this involved six UK universities and three UK companies (*e.g.* Yorkshire Water and Shell) and led to development of new technologies and establishment of a Knowledge Transfer Network.

3. References to the research (best indicators of research quality are marked ***'Q'***)

1. Zhang, K., Cui, Z. and Field, R.W. 'Effect of Bubble Size and Frequency on Mass Transfer in Flat Sheet' (2009). *Journal of Membrane Science*, 332(1-2), pp 30-37. http://dx.doi.org/10.1016/j.memsci.2009.01.033 ***'Q'***
2. Cui, Z.F., Bellara, S.R. and Homewood, P. 'Airlift Crossflow Membrane Filtration: A Feasibility Study with Dextran Ultrafiltration' (1997). *Journal of Membrane Science*, 128 (1), pp. 83-91. http://dx.doi.org/10.1016/0376-7388(96)00280-3
3. Cui, Z.F. and Wright, K.I.T. 'Flux Enhancements with Gas Sparging in Downwards Crossflow Ultrafiltration: Performance and Mechanism' (1996). *Journal of Membrane Science*, 117(1-2), pp 109-116. http://dx.doi.org/10.1016/0376-7388(96)00040-3
4. Cui, Z.F., Chang, S. and Fane, A.G. 'The Use of Gas Bubbling to Enhance Membrane Processes' (2003). *Journal of Membrane Science*, 221(1-2), pp 1-35. http://dx.doi.org/http://dx.doi.org/10.1016/S0376-7388(03)00246-1 ***'Q'***
5. Hughes, D. and Field, R.W. 'Crossflow filtration of washed and unwashed yeast suspensions at constant shear under nominally sub-critical conditions' (2006). *Journal of Membrane Science*, 280, pp 89-98. http://dx.doi.org/10.1016/j.memsci.2006.01.022
6. Bacchin, P., Aimar, P. and Field, R.W. 'Critical and Sustainable Fluxes: Theory, Experiments and Applications' (2006). *Journal of Membrane Science*, 281(1-2), pp 42-69. http://dx.doi.org/10.1016/j.memsci.2006.04.014 ***'Q'***

Grants supporting this research: (all awarded to Prof. Zhanfeng Cui as PI)

- EPSRC GR/506967/01: Membrane bioreactors for waste water treatment, £58k (part of AMBRAL-MBR Faraday), 2003 – 2005.
- BBSRC E15902 (with Dr J Urban, Physiology): On-line monitoring in tissue engineering using micromembrane probes, £229k, 2002 - 2005.
- EPSRC GR/R01729: Fractionation of macromolecules using carrier phase ultrafiltration, £63k, 2001 - 2004.

- EPSRC GR/N66438/01: Hydrodynamics and mass transfer in gas-liquid capillary flow, £23k, 2000 - 2002.
- BBSRC-DTI LINK BCE06424 (with Prof. BJ Bellhouse): Enhanced filtration of fine chemicals, protein and cellular solutions using tubular membranes and screw-thread inserts, £126k, 1997 - 1999
- BBSRC E05544: Protein fouling on ceramic membranes, £138k, 1996 - 1999
- BBSRC SPC05236: Protein fractionation with gas sparged ultrafiltration, £94k, 1996 – 1997
- BBSRC SPC02796: Virus removal using enhanced membrane filtration, £92k, 1994 – 1997
- EPSRC GR/J46388/01: Gas-liquid two-phase crossflow ultrafiltration of protein solutions, £75k, 1993 - 1995.

4. Details of the impact

This research has delivered a step change in industrial membrane filtration practices. For several decades, membrane-based filtration processes have been a staple technology in a range of sectors. From the 1970s to the 1990s, however, membrane fouling became a bottleneck limiting usage. The original research led by Cui and Field resulted in solutions that have enjoyed rapid, extensive industrial take-up and delivered substantial improvements in the efficiency and effectiveness of membrane filtration; for instance, injecting air bubbles into membrane systems has proved an economic, easy-to-implement fouling control technique that has now been adopted by many membrane manufacturers and water companies including Siemens, GE Water and Norit Membrane Technology BV, as well as securing widespread recognition among membrane researchers in academia.

Indeed, in the last decade, the research has led to a revolution in the way membrane plants in the water industry are designed and operated. For example, all MBRs now use low flux to achieve low fouling; and all MBRs are operated with big bubble, rather than small bubble aeration. Both are direct results triggered by the research undertaken by Cui and Field.

Several companies have now developed processes based on air bubble injection, for which Cui provided the design basis both through publications or direct consultancy. They include:

- The AirFlash®, AquaFlex™ and Airlift™ MBR (Fig. 4) developed by Norit Membrane Technology BV and now Pentair X-Flow. The underlying process was developed by Cui in the mid-1990s [2, 7] around 10 years before the products came to market.
- The MemPulse™ MBR system (Fig. 5) developed by Siemens Water Technologies (formerly US Filter and Memtec) [8]. The adoption of gas sparging in this was first described in [3].
- The ZeeWeed® MBR systems developed by GE Water (formerly Zenon Environmental). Cui's analysis helped to cut the energy cost of filtration in these systems [8, 9].

Fig. 4: X-Flow Airlift™ MBR – a commercially available system.

Fig. 5: Siemens' MemPulse™ MBR – a commercial installation.

In addition, Yorkshire Water has explored the use of Cui's concept for water and wastewater treatment. Introduction of fouling control for membrane processes used in food production has also significantly increased productivity at Cargill Inc., the largest private company in the US, by at least halving the downtime needed for cleaning during amino acid production, according to their Senior Vice President [10].

Similarly, Field's work on critical flux has created a paradigm shift in membrane process design:

- His contribution has been acknowledged by leading consultants. For instance, according to the Director of Membrane Consultancy Associates: "the 'direct-flow' method of designing membrane filtration drinking water plants (which is the new standard) was born out of critical flux theory" [11].
- International researchers, including the Director of the Singapore Membrane Technology Centre (SMTC), have widely recognised Field's contribution [12]. For nearly 10 years, Field has collaborated with the Singapore group and contributed to SMTC's development into the largest membrane research centre in the world today.

Cui and Field's work has therefore benefited both users and suppliers of membrane technology:

Economic Impact 1 – a growing market for membrane filtration

Rapid growth in membrane use is a direct outcome of the effective mitigation of membrane fouling, to which the research has made a significant contribution. Use of membranes within the water industry grew by 20% per year worldwide between 1998 and 2008, the MBR market is currently growing at 10.5% per year and the global desalination market now exceeds US$19 billion [13].

Economic Impact 2 – cost savings for industry

Users of membrane systems that incorporate findings from the research have secured economic benefits through reductions in, for example, membrane cleaning costs and the amount of energy consumed by membrane filtration processes. Compared to traditional filtration processes, membrane plants are also far more compact.

Environmental Impact – benefits of reduced energy demand

Reduced energy use equates to a reduced carbon 'footprint' for membrane filtration processes, helping water companies and other users to achieve their environmental targets.

5. Sources to corroborate the impact

7. Cui, Z.F. UK Patent: Membrane Filtration Apparatus, PCT/GB96/01854. Applicant: ISIS Innovation Ltd (1995). https://www.google.com/?tbm=pts#q=WO1997004857&tbm=pts
8. NL Chemical Technology Inc., Membrane Discussion Forum (1995). Contact details for President, corroborating the use of the processes.
9. Consultancy for Siemens, Australia (2006); Norit, the Netherlands; contact Senior Process Engineer, Pentair Advanced Water Technologies. Corroborates the use of the processes.
10. Consultancy for Cargill Inc., US (2008); contact Senior Vice President, Cargill Inc. Corroborates that Cargill has significantly increased productivity as a result of Cui's work
11. Oxford Membrane Fouling and Monitoring Workshop (2012); contact Director, Membrane Consultancy Associates Ltd. Supporting the work within case study.
12. Oxford Membrane Workshop on Critical Flux (2003); contact Director, SMTC, Singapore. Supporting the work within case study.
13. 'Desalination Market 2013-2023: Commercial, Technological & Strategic Developments in Global Desalination' (2012). GMR Data. http://gmrdata.com/the-desalination-market-2013-2023.html . Commercially available report posted 24/04/13. See also press release, http://www.free-press-release.com/news-the-global-desalination-market-2013-2023-by-gmr-data-1367313632.html.