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Opportunities for process intensification in the UK water industry: a review

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Abstract:

Process Intensification (PI) refers to the use of novel process technologies to achieve significant (order of magnitude) size reduction in individual unit operations, or the complete removal of process steps by performing multiple functions in fewer steps. This should lead to significant reductions in capital and running costs, and improvements in process efficiency and safety. There are numerous examples of PI being successfully implemented in the oil and gas, pharmaceutical, food and drink, and fine chemical industries, but few in the water industry. There are however a range of drivers for process intensification within the water industry. These include ever more stringent environmental standards and more intractable pollutants. The aim of this review was to identify PI technologies that could be used in the future UK water industry, but require further technical development (to increase their TRL), or transfer from other industries. Recommendations for technologies are given, as well as routes to their implementation.

Highlights:

- PI can significantly reduce the size of unit operations, remove process steps and make processes more efficient and safer
- The UK water industry is facing environmental, financial, and land constraints, all of which may be drivers toward more efficient and innovative processing
- There is significant potential for the application of novel PI technologies

Keywords: Process Intensification; Novel technologies; Oscillatory baffled reactors; UV LEDs; Rotating packed bed; Fluidic oscillator devices

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1. Introduction

The water industry has been notoriously slow to implement change, often embracing tradition and conservative treatment technologies (Speight, 2015; Tanner et al., 2016; Thomas, 2012; Thomas & Ford, 2006; Thomas & Ford, 2008). The barriers affecting the water sector's ability to adopt innovative technologies has been explored by a number authors (Speight, 2015; Spiller et al., 2015; Spiller et al., 2012; Tanner et al., 2016; Thomas, 2012; Thomas & Ford, 2006). They found that key barriers to innovation in the UK water industry include the excessive time it takes for innovations to become adopted within the water sector , the industry's risk-averse attitudes, and a lack of knowledge about new and emerging technologies (Spiller et al., 2012; Tanner et al., 2016; Thomas, 2012; Thomas & Ford, 2006). However, the water industry in the UK is under ever-increasing pressure to meet future water demand, alongside facing challenges due to aging infrastructure, and environmental, financial, and land constraints. The consequences of failing to meet these challenges could include environmental degradation, public health risks, and increased operational costs (Speight, 2015).

Process intensification (PI) is a chemical and process design approach that leads to substantially smaller, cleaner, safer and more energy-efficient process technology. PI technologies have successfully been adopted by innovation led industries such as petrochemical, chemical, food, and pharmaceutical (Reay et al., 2013). The aim of this review is to identify new and emerging PI technologies that could be used in the UK water industry, but require further technical development (to increase their TRL), and technologies that could be transferred from other industries. In particular, this review aims to bring a number of process technologies to greater attention within the UK water industry. It should be noted that this work has a strong focus on the UK water industry as it was funded by UKWIR (Grant No. RG10). However, the PI technologies presented in this review may also be relevant to the US, Australia and the Middle East, where traditional approaches are struggling to meet growing need. There may also be some relevance to the developing world, in that PI technologies are often a good solution when industries become distributed;

decentralized PI water systems could therefore be installed based on need, removing the excessive cost of implementing centralized treatment systems (Massoud et al., 2009). The downside may be that some of the technologies are not “simple” to manufacture or maintain. The work Tayalia and Vijaysai (2012) gives insight into how PI techologies can be applied to multiple global water and wastewater scenarios, such as the increased need to process source water of increasing salinity.

The UK water and sewerage industry was privatised in 1989, and now comprises 32 privately-owned companies in England and Wales, while Scotland, and Northern Ireland operate as non-profit, semi-governmental water authorities (Ofwat, 2017; Speight, 2015). The Water Framework Directive (WFD) in the EU is an overarching legislation that came into force in 2000 and is driving technological investment in the water industry (European Communities 2000/60/EC). It is administered by the Drinking Water Inspectorate (DWI) for water and the Environment Agency (EA) for wastewater and natural water sources in England and Wales. It aims to achieve “good ecological status” in inland and coastal waters through river basin management planning. Concentration limits have been defined for 30 substances under the Environmental Quality Standards (EQSs–EC, 2008), and the UK is required to set its own standards for a further group of potential pollutants (Gardner et al., 2013). New and emerging pollutants (EPs) present a new and significant challenge to UK and global water quality. EPs originate from a wide range of man-made chemicals, such as pesticides, cosmetics, personal and household care products, and pharmaceuticals (Geissen et al., 2015). Increasing scientific evidence has demonstrated that EPs, and endocrine-disruptors (ECDs) in particular, are associated with breast cancer in women and prostate cancer in men, feminisation of male fish reducing their reproductive fitness, and can significantly affect plant growth and development (Acerini & Hughes, 2006; Adeel et al., 2017; Gavrilescu et al., 2015; Geissen et al., 2015). Gardner *et al.* (2013) assessed the performance of 16 wastewater treatment plants (WwTP) to provide an overview of trace substance removal. This study highlighted significant variations in the removal rate of trace substances. This was possibly due to variation within catchments or design and operation of individual works. However, it is evident from this work that improvements in the methods used to remove trace chemicals needs to be prioritised as current methods are inconsistent. Gardner *et al.* (2013) concluded that in order for step changes in performance to occur, new treatment methods are required. Heightened public awareness and concern about the impacts of EPs will no doubt encourage ever stricter limits on priority substances in the near future. The WwT industry has responded by developing and implementing processes and technologies to meet these demands, with resultant increases in utility consumption, notably electrical power and treatment chemicals. These increases in treatment sophistication and energy use have led to increased carbon emissions, particularly operational carbon. The Environment Agency (UK) has stated that "without intervention, increased WwT under the WFD is likely to increase CO_2 emissions by over 110,000 tonnes per year from operational energy use and emissions associated with the additional processes required" (Georges et al., 2009). They suggested five key strategies that the water industry and partners could adopt to mitigate the carbon impact of the WFD. They included increasing operational efficiencies to reduce the demand for power, and redeveloping existing treatment processes by switching from conventional processes to lower energy alternatives (Georges et al., 2009).

Regional growth of the UK is also stretching WwT sites' capacities. It is essential that the demand for new wastewater infrastructure is met to ensure water quality for public health. New infrastructure options are limited in densely populated cities where land is at a premium. Some additional capacity can be provided through minor works and expansions of the sites (Defra, 2010), however, a holistic overview is required to identify robust, efficient, cost effective solutions to satisfy the greater demands of the water industry, without taking up more space.

Further to this ever-increasing treatment and legislation demand, the water industry in England and Wales is also subject to economic regulation through Ofwat (The Water Services Regulation Authority), which, is responsible for setting limits on pricing that the water and sewage companies may levy on their customers, which in turn, puts pressure on costs, driving cost efficiencies through the industry. Ofwat has allowed the companies to invest more than £130 billion in maintaining and improving assets and services, however the total spend for R&D for all water and wastewater industries was only £18 million in 2008, which represents just 0.5% of annual turnover (CST, 2009; Ofwat, 2017; Tanner et al., 2016).

Singapore is an example of the significant changes that can occur when a water sector embraces innovation and invests in research. The country has transformed from having little centralized sanitation and reliance on imported water from Malaysia, to a world-leading research and development 'hydrohub' over the past 50 years (Speight, 2015).

2. Applying Process Intensification to the Water Industry

Water treatment systems commonly depend on complex interactions between mass transfer and various physical, biological, and chemical processes (Owabor, 2013). Water treatment systems are currently dependent on relatively low capital intensity technologies, often relying on stirred or contact tanks systems for processes such as chlorination, anaerobic treatment, the addition of flocculants etc. However, a key issue in these systems is effective mixing, which is technically very difficult at large scales. This means that many processes are mixing-limited (Reay et al., 2013). Therefore, the understanding of mass transfer mechanisms enables the proper design and operation of many processes (Zhou & Smith, 2000). Process intensification (PI) is the philosophy that many unit operations, and entire processes, can be substantially improved by novel equipment, processing techniques and operational methods (Stankiewicz & Moulijn, 2000). These new technologies have on the whole been developed by re-examining the assumptions involved in the heat transfer and/or mass transfer/mixing/fluid mechanics in conventional technologies (Górak & Stankiewicz, 2011; Nikačević et al., 2012; Ponce-Ortega et al., 2012; Reay et al., 2013). This can result in significant (order of magnitude) reductions in equipment size, and/or substantial reductions in the number of steps in a process by performing more than one function in one step.

Colin Ramshaw and colleagues at Imperial Chemical Industries (ICI) pioneered the concept of PI during the late 1970s, where the primary goal was to reduce the capital cost of production systems (Dautzenberg & Mukherjee, 2001; Ramshaw, 1983; Reay et al., 2013). They defined PI as the “strategy of making significant reductions in the size of unit operations, while achieving a given production objective” (Dautzenberg & Mukherjee, 2001). Since that time, there are many examples of intensified technologies being successfully applied, in industries such as petrochemical (Harmsen, 2010), chemical (Stankiewicz & Moulijn, 2000), food (Patist & Bates, 2008; Wang et al., 2017a), and pharmaceuticals (Buchholz, 2010). Figure 1 illustrates the broad range of technologies that are considered “intensified” (but this is by no means comprehensive).

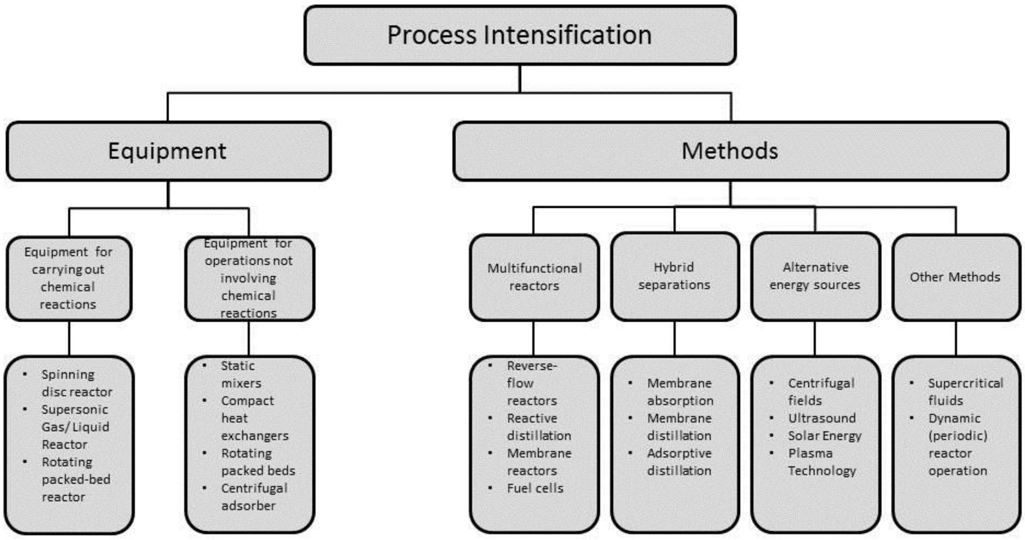

Figure Error! No text of specified style in document.. Examples of the broad uses of Process Intensification equipment and methods. The diagram has been adapted from Process intensification classification by Stankiewicz and Moulijn (2000).

Górak and Stankiewicz (2011) defined four “multi-scale domains” to classify the applications of PI: spatial, thermodynamic, functional, and temporal (Table 1). Utilising one or more of these domains to design new plants, retrofit existing units, or implement new processing methods can lead to the process being more efficient, safer, flexible, smaller, cheaper and more environmentally friendly (Charpentier, 2007; Ponce-Ortega et al., 2012). Development of new chemical routes, even if achieving a dramatic improvement in processing does not qualify as PI, as PI is specifically based upon new process technologies rather than new chemistry (Stankiewicz & Moulijn, 2000).

Table 1: The four fundamental domains, main approaches and their associated motivations of process intensification (PI) (Górak & Stankiewicz, 2011)

Domain	**Main PI approach**	**Motivation**
Spatial	Structured environment	-Well-defined geometry -Creation of maximum specific surface area at minimum energy expenses -Creation of high mass and heat transfer rates -Precise mathematical description

		-Easy understanding, simple scale-up
Thermodynamic	Alternative forms and transfer mechanisms of energy	-Manipulation of molecular orientation -Activating/moving targeted molecules -Selective, gradientless, and local energy supply
Functional	Integration of functions/steps	-Synergistic effects -Better energy management -Increase of overall efficiency -More compact equipment
Temporal	Timing of the events, introducing dynamics (pulsing)	-Controlled energy input -Influencing hydrodynamic behaviour -Increased energy efficiency -Minimization of unwanted phenomena, such as fouling

Many PI technologies can be transferred between industries, when the unit operations are fundamentally similar (Reay et al., 2013). PI technologies and methods could therefore be adopted into the water and wastewater industries where they perform similar duties in other industries.

Figure 2, below, summarises how PI technologies can: reduce energy consumption, reduce foot-prints, potentially generate value from waste, allow for more flexible processing to meet varying feed qualities, improve trace chemical removal, reduce the time to market, reduce life-cycle costs, and a combinations of these objectives (Tayalia & Vijaysai, 2012).

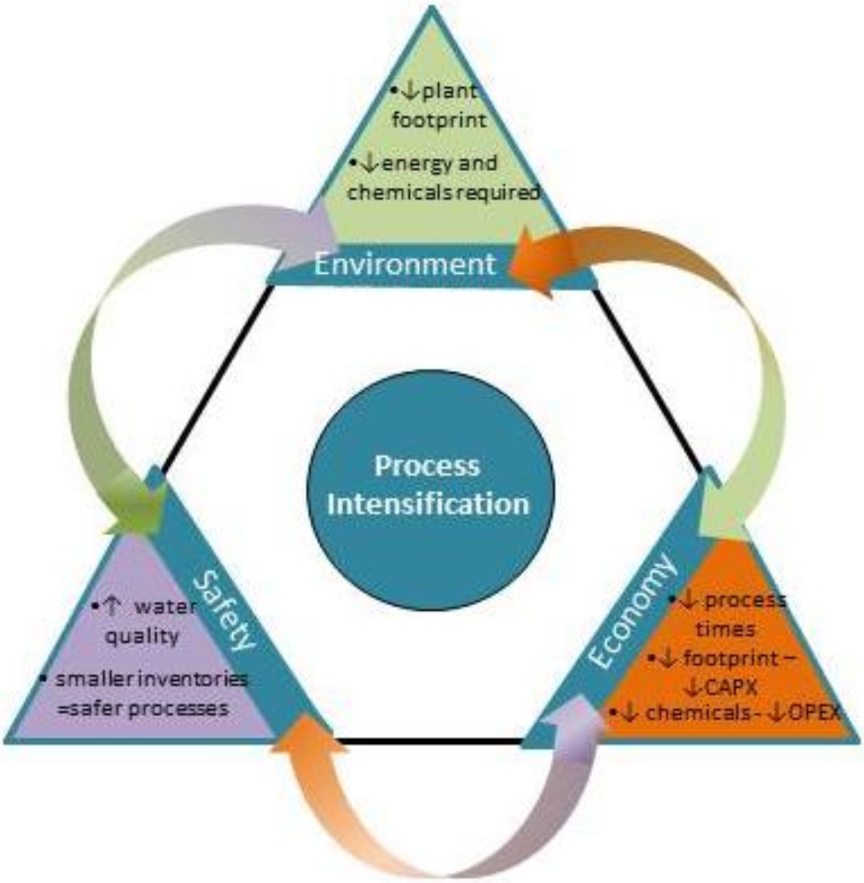

Figure 2: The potential impact of intensified process technologies on key areas in the water industry.

3. Novel PI technologies for the UK water industry

A range of 'scoring criteria' were developed to provide a framework for assessing PI technologies. The evaluation criteria were: capital cost, operating cost, whole life cost, performance, sustainability, foot-print, proximity to market, transferability (when the technology is mature, but is applied in other industries), retrofittability, scalability, novelty. All techniques were scored on a scale of: -1 (worse than), 0 (similar to), or +1 (better than) contemporary water/wastewater technologies. This scoring range allowed for both subjective and objective analysis to be undertaken depending on the volume of information available. Each criterion was given a weighting of 5, apart from the "novelty" criterion, which was given a significantly higher weighting (of 20), to ensure that technologies new to the water industry were highlighted. This was a key aim of the study: to bring technologies to the attention of the water industry that would usually be deemed too far from market/the water industry. An UKWIR project steering group representing seven UK water companies provided regular input and feedback.

A total of 393 technology/application combinations were identified and systematically assessed for application in the water industry by comparing and contrasting recent developments, emerging techniques/technologies, and technologies presently employed within the wider industrial sector, as well as examples in the water/wastewater industry both in the UK and globally for water, wastewater and sludge treatment. The full matrix of technologies and applications is available in the supplementary material.

The 9 technologies described in sections 3.1 to 3.9, following, were selected as the most promising novel technologies for the UK water industry.

3.1 Non-thermal Plasmas (NTPs)

3.1.1. NTP Technology

Plasmas are fully or partially ionised gases, often described as “the fourth state of matter”. They typically contain various reactive species: photons, ions, ozone, and free radicals (Dobrin et al., 2013; Lukes et al., 2005; Magureanu et al., 2015). These species cause a wide range of chemical reactions to take place at or around ambient temperature. They can be created thermally, but this requires thousands of degrees Celsius. “Non-thermal” plasmas (NTPs), on the other hand, are generated by subjecting gas or liquid streams to high voltage electrical pulses. This opens up a range of applications that would be precluded on grounds of cost, were they to be achieved by thermal means (as operating at high temperature tends to incur substantial capital costs).

3.1.2 Opportunities

Most WwTPs are not designed to remove or reduce “micro-pollutants”, such as pharmaceuticals (Feng et al., 2013; Gardner et al., 2013; Magureanu et al., 2015). Removal efficiencies below 20% have been found for compounds including the beta-blockers atenolol, metoprolol and propranolol, the antibiotics erythromycin, sulfamethoxazole and trimethoprim, the anti-inflammatories diclofenac, indomethacin, ketoprofen and mefenamic acid, the antiepileptic carbamazepine and the antiacid omeprazole (Rosal et al., 2010). However, Dobrin *et al* (2013) found that the non-steroidal anti-inflammatory drug (NSAID) diclofenac, a "pseudo-persistent pollutant" (Tixier et al., 2003; Zhang et al., 2008), could be completely removed by 15 minutes of NTP treatment. Gerrity *et al* (2010) (Gerrity et al., 2010)used a pilot-scale pulsed corona discharge plasma to degrade trace organic compounds, including pharmaceuticals and potential EDCs. They found that exactly which compounds were degraded depended upon the power: carbamazepine required relatively little power, whereas more "resistant" compounds such as meprobamate required considerably more. There can therefore be an element of "tuning" to this technology.

NTPs could be a viable alternative to AOPs such as UV/H_2O_2 and ozone/H_2O_2. A key advantage in some scenarios is that NTPs do not require additional feed chemicals. This perhaps lends itself to use in remote areas or developing countries where supply of chemicals is difficult, unreliable or undesirable. The reader is referred to Magureanu *et al* (2015) for a detailed review of NTP use for the degradation of pharmaceutical compounds in water

Decentralised facilities are a common opportunity for PI technologies, as issues such as footprint become more important. Operation at this scale may be a good "first step" for many intensified technologies, as it does not incur the technical/economic risk associated with the substantial scale-up factors of the "full-scale" water industry. Distributed treatment of pharmaceutical-containing effluents could well be viable at the scale of hospitals, care homes etc (Igos et al., 2012). Such facilities are of a scale to have their own water treatment facilities, and will often have significant levels of pharmaceuticals. Lienert *et al* (2011) found that, in Switzerland, hospitals contributed up to 38% of the total pharmaceutical load at WwTPs. Careful targeting of such "hot-spot" areas, by installing compact NTP units, could allow significant percentages of high-risk micro-pollutants to be treated at source.

Odour control can be a significant problem in wastewater processing. NTPs can be used to ionise air that can be merged with waste gas flow, or directly with the main flow containing the odour to convert hydrocarbons to carbon dioxide and water (Schlegelmilch et al., 2005). Ruan *et al* (2005) demonstrated that simulated odours in municipal WwTPs can be treated effectively. They demonstrated that the maximum removal efficiencies achieved for

85 mg.m^{-3} of ethanethiol and 750 mg.m^{-3} of tri-methyl amine, at a gas flow rate of 10.0 m^3.h^{-1}, could be as high as 98% and 91%, respectively.

3.1.3 Summary: NTPs

Current WwT strategies are failing to effectively remove micro-pollutants, such as pharmaceuticals. Non-thermal plasmas (NTPs) offer rapid removal of micro-pollutants. Decentralised NTP units could be installed into "hot-spot" areas such as hospitals to treat micro-pollutants at the source.

3.2 Oscillatory Baffled Reactors

3.2.1 OBR Technology

Oscillatory baffled reactors (OBRs) generally consist of a cylindrical column or tube containing equally spaced orifice baffles. Within the OBRs either the baffles or the fluid is oscillated to produce vortices (Figure 3), which are generated when fluid flow passes through the baffles. These vortices effectively form many continuously stirred tank reactors in each inter-baffle zone (Abbott et al., 2013; Phan & Harvey, 2010).

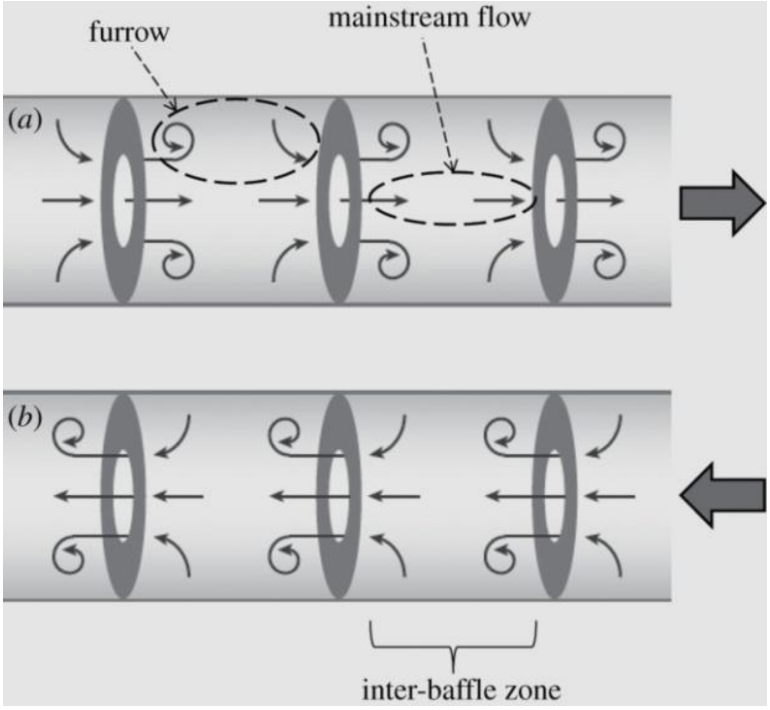

Figure 3: Vortex formation in an OBR created by oscillatory flow (a) Back stroke, (b) Forward stroke (Abbott et al., 2013).

3.2.2 Opportunities

OBRs could be adapted for many uses within the water and wastewater industry. OBR photoreactors, for example, have been shown to be able to oxidise hydrocarbons in water, by uniformly suspending solid photocatalyst particles (TiO_2), whilst exposing them to U.V. and dissolved oxygen (Fabiyi & Skelton, 1999). Enhanced gas-liquid mass transfer in OBRs (Hewgill et al., 1993) may be a particular advantage for applications such as ozonation and chlorination. It has been shown that ozonation is up to three times more efficient in an OBR than in a bubble column (Al-Abduly et al., 2014), which should reduce the size of the ozonation device by the same factor. Similar factors would be expected for other mass transfer-limited applications. Chlorination would be made more effective by the improved uniformity of processing experience in an OBR, which would allow more accurate dosing. Compared to a traditional chlorine contact tank, OBRs would have a significantly smaller footprint due to plug flow, higher mass transfer coefficients and improved mixing. Shorter reaction/contacting times due to the improved mass transfer coefficients would significantly reduce the time of the process, thereby reducing the inventory of hazardous material within the reactor/contactor and the footprint of the contactor (Ni, 2006).

A further advantage is that OBRs exhibit low shear, efficient global mixing. Research at 5-20L scale into oxidation of pollutants in water (Gao et al., 2003), improving the addition of flocculants, such as aluminium sulphate (Ni et al., 2001).

3.2.3 Summary: OBRs

OBRs offer a reduction in footprint, chemical requirements, and processing time for a range of mass transfer-limited applications in the water industry, notably ozonation, hydrocarbon oxidation and chlorination.

3.3 Ultrasound (US)

3.3.1 Ultrasound Technology

Ultrasound (US) refers to sound waves at frequencies above the threshold of human hearing. It can be generated at a broad range of frequencies (20 to 500 kHz) and acoustic intensities. When US is applied in water the liquid medium will absorb the acoustic energy, creating oscillating regions of positive and negative pressure (Chen et al., 2011), leading to the formation, growth and violent collapse (cavitation) of microbubbles. This releases large amounts of energy, which induces extreme localized conditions: temperatures of up to 5000 K and pressures up to 500 atm (Knorr et al., 2013; Wu et al., 2013). US can produce a wide range of physical effects such as microstreaming, microstreamers, microjets, and shock waves (produced by cavitation bubbles) (Chen et al., 2011). Microjets are formed when microbubbles collapse near surfaces, and can be used to clean or scour surfaces.

3.3.2 Opportunities

A number of European countries (Netherlands, Switzerland and Germany) have moved toward potable water delivery systems without residual disinfectants (chlorine, chlorine dioxide, or chloramines). This is partly due to the discovery of disinfection by-products (DBPs), possible human carcinogens in potable water (Rosario-Ortiz et al., 2016). However, use of residual disinfectants is required in the UK due to the estimated average pipe age of 75 to 80 years (DWI, 2010; UKWIR, 2011). Therefore, DBP concentrations are regulated (Rosario-Ortiz et al., 2016). The chemical, mechanical, and biological effects of US can be used for the chemical-free disinfection of water by the direct inactivation of organisms, or by enhancing the effects of other disinfectants (Gibson et al., 2008).

Zou and Wang (2017) recently demonstrated a pilot scale continuous-flow water disinfection system that combined US with chlorine. When a combination of lower frequency US (17 kHz and 33 kHz) was used as pre-treatment with sodium hypochlorite (NaClO), the required dosage was reduced by two thirds. The action was twofold: disaggregation of bacterial clumps and the weakening of cell walls, allowing easier access for the chlorine. US could also be used for chlorine-free disinfection. Vajnhandl *et al* (2015) demonstrated a significant increase in *E. coli* inhibition in 5 minutes, using US alone.

Rosario-Ortiz and Speight (2016) recently recommended that potable water systems should focus on maintaining and replacing their aging delivery systems and consider moving beyond carrying a disinfectant by upgrading their water treatment steps. Ultrasound could be used as a transitional technique to reduce the required disinfectant in the potable water systems and once adequate pipes are in-place could be implanted as a non-chemical treatment method in combination with established Advanced Oxidation Processes (AOP) (Mahamuni & Adewuyi, 2010).

In combination with membrane reactors, ultrasound can be used to reduce membrane fouling and increase the efficiency in the purification process. Borea et al (2017) noted that the performance of membrane ultrafiltration was enhanced when at a lower ultrasound frequency of 35 kHz (USMe 35) when compared to130 kHz due to the stronger vibration and localized turbulence at lower frequency, which act as scrubbers that clean the membrane.

US has also been investigated as a pre-treatment method for sludge treatment processes with a number of reported positive effects, including: improved sludge biodegradability, dewaterability, improving biosolids quality, and shortening the required retention time (Guo et al., 2013; Neumann et al., 2016).

US technology has great promise with a broad range of applications, however the majority of the research remains at the laboratory scale, therefore, the economic feasibility is difficult to predict. Mahamuni and Adewuyi (2010) have calculated that US used in combination with established AOPs was economically more attractive than the use of US alone for WwT. However, the cost of WwT using hybrid ultrasonic processes was estimated to be one to two orders of magnitude *more* than currently established AOPs. However, commercial standard ultrasonic equipment is developing at great pace within the food industry (Patist & Bates, 2008), so it is possible that transferable developments may occur, reducing costs and improving efficiencies.

3.3.3 Summary: US

Ultrasound (US) has a wide variety of potential applications within the water and wastewater industry. It can be used in combination with other chemical treatments to increase chlorination efficacy and reduce dosing requirements. However, scale-up of ultrasound is likely to be challenging, but developments within the food industry may provide transferable knowledge

3.4 Spinning tube in tube (STT) reactor

3.4.1 STT Technology

The spinning tube in tube (STT) reactor consists of two concentric cylindrical surfaces: a rotor and a stationary shell (stator). This creates Couette flow, which mixes the liquids due to the high shear rate. It can be operated continuously or in batch, and could be used for multiple reactions as the changeover of product streams is simple (Jiménez-González & Constable, 2011).

3.4.2 Opportunities

STT reactors have been used in the production of biodiesel by Four Rivers BioEnergy Company, Inc. The STT reactor reportedly reduced reaction time between soybean oil and methanol for biodiesel production to a residence time of 0.5 s (Qiu et al., 2010). This represents a >99% reduction in reaction time, and therefore reactor size. It has also been suggested that it increases selectivity, conversions and yields, and provides real-time control of the quality of chemical processes (Costello, 2006). The STT reactor typically operates at reduced reaction time and mixing power input when compared to conventional reactors, by reducing mixing limitation (Hampton et al., 2008; Qiu et al., 2010). It has been used in: selective oxidation, selective hydrogenation, esterification, transesterification, saponification, hydrosilylation, condensation reactions, and preparation of ionic liquids (Costello, 2006). Note that this selection of applications represents a mixture of liquid-liquid and gas-liquid mixing challenges.

The STT reactor is well suited for the high-volume production of a variety of chemicals and therefore could be utilized in the water/wastewater industry for the enhanced mixing of gas/liquid, liquid/liquid processes, such as chlorination, the addition of flocculants, and potentially the catalysed oxidation of organic pollutants. However, the gap between the rotor and stator could be a significant disadvantage for fluids containing high solids concentrations or larger particles.

STT is an emerging technology and, as yet, has not been applied to the wastewater industry. There is no available data on the operational costs compared to the traditionally used methods. However, it is likely that the STT reactor could reduce residence times, boost reaction rates, minimize side reactions, and reduce energy-intensive downstream processing steps in mixing-limited processes, such as the applications mentioned above (Costello, 2006). Compared to a traditional chlorine contact tank, STT reactors would have a significantly smaller footprint due to the shorter reaction times engendered by the high shear forces developed within. They are also an example, as are OBRs, of technologies that achieve intensification of processes by facilitating conversion of batch technologies to continuous operation.

3.4.3 Summary: STTs

STT reactors are well-suited to high-volume gas/liquid, liquid/liquid processes enhancement. They would reduce footprints, residence time, and downstream process requirements when compared to traditional stirred tanks. However, there has been relatively little research, compared to the other technologies in this study, so for most applications more laboratory-scale investigation would be needed.

3.5 Rotating Packed Beds (RPBs)

3.5.1 RPB Technology

The RPB creates a high-gravity environment (100 to 500 g) via the action of centrifugal force (Wang et al., 2014). A “doughnut” shaped packing material made of foam, mesh, wire, or spheres is used to create a high-specific area (Górak & Stankiewicz, 2011) (Figure 4). When liquid is passed through the packing of the RPB, it is accelerated and split into fine droplets and thin films, resulting in significant intensification of micro-mixing and mass transfer by one to three orders of magnitude (Górak & Stankiewicz, 2011; Wang et al., 2014; Yang et al., 2005; Yang et al., 2011). The RPB also has the advantages of smaller equipment size and negligible scale-up effects compared to conventional reactors and, therefore, the volume and weight of the unit is decreased by two or three orders of magnitude (Zhao et al., 2010).

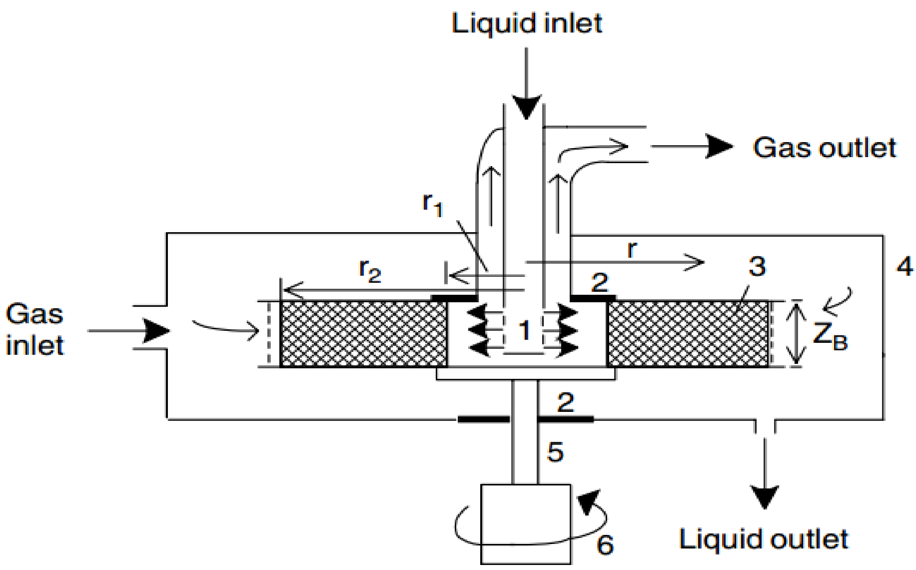

Figure Error! No text of specified style in document. : A typical RPB gas-liquid Contactor. Components: 1, Stationary liquid distributor; 2, Seal; 3, Packed bed rotator; 4, Housing case; 5, Rotor shaft; 6, Motor (Chen et al., 2005)

3.5.2 Opportunities

RPBs have been successfully employed in industry with processes such as reactive crystallization (Chen & Shao, 2003; Guo et al., 2000), distillation (Agarwal et al., 2010), seawater deaeration (Rao et al., 2004), and absorption (Lin & Kuo, 2016).

Yuan *et al* (2016) recently evaluated a pilot-scale continuous-flow RPB for the removal of ammonia from wastewater. The overall volumetric liquid mass transfer coefficient (K_La) and the stripping efficiency (η) for ammonia were significantly enhanced, and required very short liquid hydraulic retention times (t_L) (a few seconds). However, there is the drawback of higher power consumption, due to the energy required to rotate the machinery. It is vital that new research is conducted that considers water/WwTPs holistically, as an increased investment in energy using a RPB could ultimately reduce the overall energy of processing, and reduce the chemical dosing requirements. RPB technology could also remove the majority of the complications related to biological processes used for ammonia from wastewaters such as: sensitivity to shock, toxic loads, and cold weather conditions, relatively longer retention time, and larger spatial requirements (Yuan et al., 2016).

A number of studies have focussed on the combination of RPB and ozone with photolysis and catalysts for the removal of pollutants (Chang et al., 2009; Chen et al., 2005; Chen et al., 2004; Zeng et al., 2012). It was found that total organic carbon mineralization efficiency can be enhanced to 56% for RPB + UV + ozone, 57% for RPB + catalysts + ozone, and 45% for RPB + ozone (Chang et al., 2009).

A significant downside for some applications in the water industry is the narrow interstices through which fluids have to flow in RPBs. These are likely to block and foul, which would severely limit RPB use with fluids containing solids.

The reduction of required volume and footprint means that RPBs could ideally be used in decentralised unit operations, or a number of small units could be used in parallel to remove the need for large contact tanks. RPBs could also be used for odour removal and EP removal, when combined with catalysts.

3.5.3 Summary: RPBs

RPBs intensify micro-mixing, and reduce footprint, operational weight, and chemical dosing requirements when compared to conventional technologies. They have potential applications for chlorination, odour removal, and EP removal (when combined with catalysts). The potential drawbacks of RPBs for the WwT industry include higher power consumption and the narrow interstices through which fluid flows (which would not be compatible with particle-laden flows).

3.6 Ultraviolet light emitting diodes (UV-LEDs)

3.6.1 UV-LED Technology

Ultraviolet light emitting diodes (UV-LEDs) offer a mercury-free source of monochromatic UV radiation. They offer significant advantages when compared to conventional mercury lamps due to their compact form, low power requirements, high efficiency, non-toxicity, and overall robustness (Song et al., 2016; Würtele et al., 2011). UV-LEDs are also capable of emitting light in a narrow wavelength range in the form of electroluminescence (Taniyasu et al., 2006), unlike the currently used low- or medium-pressure mercury lamps that have a wide spectral power distribution (Peters, 2012). Studies using UV-LEDs have shown that the most effective wavelength for disinfection is 275 nm (Bowker et al., 2011; Peters, 2012). UV-LEDs have been shown to deactivate a the diversity of different microorganisms at various wavelengths such as; *E.coli, staphylococcus, Salmonella, and Bacillus subtilis* (Song et al., 2016).

3.6.2 Opportunities

Applications for UV-LEDs include water disinfection (Bak et al., 2010; Song et al., 2016; Würtele et al., 2011) and the degradation of organic compounds and micropollutants (Autin et al., 2013; Jamali et al., 2013; Natarajan et al., 2011). Currently the low output power and current high investment costs are the major limitations to the application of UV-LEDs (Autin et al., 2013; Bak et al., 2010; Würtele et al., 2011). However, LEDs are developing quickly and are projected to overcome these limitations by 2020 (Autin et al., 2013). For example the cost of LEDs has reduced by a factor of 7 within the last 5 years (Autin et al., 2013). Improvements in performance indicators may make UV-LEDs economically competitive in under ten years (Autin et al., 2013; Crook et al., 2015; Ibrahim et al., 2014; Umar et al., 2015). In the near future UV-LEDs have the potential to be combined with microwave technology for water disinfection potentially reducing the footprint, required operational, labour, and maintenance costs, operational safety, and lower cost of labour and maintenance when compared to conventional UV treatment (See section 3.7 *Microwave Processing)*

A further significant advantage of UV-LEDs is that they have a significantly higher functioning lifetime (50,000–100,000 h) than mercury lamps (2,000-10,000 h) (Song et al., 2016). Hence, LEDs could easily be integrated into current systems, gradually replacing mercury lamps, as they come to the end of their lifetimes, i.e. their “retrofittability” is an advantage. Given UV-LEDs compact design and radiation patterns, they will enable greater creative reactor designs for future applications, through the optimization of flow and radiation distribution, as well as reactor geometry and kinetics (Song et al., 2016).

Their small size offers considerable flexibility in their potential areas of application. Point of use sterilisation could be an effective way to remove the need for residual disinfectants and the formation of DBPs, thus improving water safety. However, the design and implementation of the unit could be difficult. The ideal point of use UV-LED sterilisation unit would be retro-fitted into domestic taps.

3.6.3 Summary: UV-LEDs

LEDS are transforming domestic and industrial lighting as they are compact, robust, non-toxic, highly efficient and have low power requirements. These advantages should also be exploited for UV-LEDs in the water and chemicals industry. They are retrofittable, and should be able to replace mercury lamps, as they come to the end of their lifetime. Generally, this suggests applications in water disinfection, degradation of organic compounds and micropollutants, ensuring water at discharge meets present legislations and the potentially stricter future legislations. However, UV-LEDs can, in principle, be used for applications where the use of traditional mercury lamps is impractical or impossible, or wholly new uses. These include:

3.7 Microwave Processing

3.7.1 Microwave Technology

Microwaves are commonly used for drying in the food industry (Ramaswamy & Tang, 2008). Their advantage is often their “volumetric” heating of water, rather than the outside-in heating of conventional convective heat transfer. This often leads to more rapid drying or heating of water-filled solids.

Microwave dryers have been shown to substantially reduce drying times, thereby reducing dryer size. One example from the food industry is illustrative: a microwave dryer was used to reduce the drying time of pasta from 10-20 hours to 15 minutes, thereby allowing for significant increases in production rates (Reay et al., 2013).

3.7.2 Opportunities

Microwaves can also be used in combination with other techniques such as oxidants, catalysts, and advanced oxidation techniques (Remya & Lin, 2011). Microwaves have also been investigated for use as pre-treatments for temperature-phased anaerobic digestion, Coelho *et al* (2011) reported maximum volatile solids (VS) removal of up to 53.1% at a sludge retention time of 15 days, and maximum biogas increase relative to control was 106% after 5 days sludge retention time. When microwaves are combined with oxidants, free radical generation occurs and the pollutant molecule is rapidly polarized (Zhang et al., 2007). High reaction rates can be achieved compared to traditional thermal or catalytic oxidation. This is due to localised heating of solids, particularly metal-containing catalyst particles. The temperature increase can be hundreds of degrees. Jou *et al* (2008) combined microwaves at 700 W for 30 seconds, with Fe^0 acting as a catalyst to remove the pollutant pentachlorophenol (PCP), from contaminated wastewater. A removal of >99% was achieved.

Microwave radiation has been applied at bench-scale for the removal of ammonia from wastewater, achieving 100% removal in 3 min (Lin et al., 2009b). The same technique was then applied at a pilot scale (28 L^{-1}). A removal efficiency of 80% was achieved in a treatment time of 80 min (Lin et al., 2009a).

An exciting development in the disinfection of wastewater, drinking water, and for water reuse application is the coupling of UV disinfection with microwave energy to power the electrodes. The microwave energy is generated by a magnetron, as in domestic microwave ovens, and directed through a waveguide into high-output electrode free quartz lamps. Severn Trent Services has launched the MicroDynamics Series OCS721, which is a microwave-UV system. Four modules have been running at a Leacock (USA) plant since 2010. The four modules are able treat 2.4 million gallons/day. The disinfection system has a total cycle time of 41 minutes, and as the lamps are electrode-free it allows the system to have unlimited starts and stops, which allows for the system to adapt to the flow rate. The system has many advantages over conventional UV treatments: greater operating cost savings; lower whole-life cost; and increased lamp life in a smaller footprint (Shima, 2011).

3.7.3 Summary: Microwave Processing

Microwaves offer a diverse range of applications within the water industry, including: drying, temperature-phased anaerobic digestion, ammonia removal, degradation of pollutants, and disinfection.

A particular technology of interest is the coupling of UV disinfection with microwave energy to power the electrodes. This offers operating cost savings, lower whole-life costs, long lamp life, a smaller footprint, and lower cost of labour and maintenance when compared to conventional UV treatment. UV disinfection with microwave is a mature technology and could be implemented near term.

3.8 Dissolved Ozone Flotation (DOF)

3.8.1 DOF Technology

Dissolved ozone flotation combines a conventional dissolved air flotation (DAF) system with ozone. Using ozone in a DAF unit instead of atmospheric air induces the production of nano/micro-ozone bubbles, where the ozone is supplied through a simple porous diffuser at the bottom of the reactor (Lee et al., 2008). The use of Dissolved Ozone Flotation (DOF) integrates two processes into one unit: (i) the separation of solids and emulsions by gas bubbles (as in conventional flotation) and (ii) oxidation of soluble organic compounds (Wilinski & Naumczyk, 2012), hence the process intensification.

3.8.2 Opportunities

Lee *et al* (2008) compared a conventional mechanical diffuser used for ozone contact with DOF, and showed that the DOF significantly outperformed the conventional diffuser in terms of turbidity, TSS, colour, COD, BOD, nitrogen, phosphorus and aerobic bacteria. DOF can: decrease the dosing requirements of coagulants and flocculants, increase pathogen removal, improve wastewater biodegradability, remove micro-pollutants (antibiotics, hormones, personal care products), and reduce the amount of excess biological sludge (when DOF is used for separation of effluent from excess activated sludge) (Jin et al., 2006; Jin et al., 2015; Lee et al., 2007; Wilinski & Naumczyk, 2012). Furthermore, the off-gas of the DOF system may be used to remove or reduce odour emissions (Jin et al., 2006; Kim et al., 2011; Wilinski & Naumczyk, 2012).

Wilinski and Naumczyk (2012) compared the pre-treatment efficiency of DAF and DOF and estimated the cost reductions of DOF for the biological step of WwT. Taking into consideration the additional costs associated with ozone generation Wilinski and Naumczyk (2012) calculated the total savings incurred by using DOF rather than DAF to be € 32,000 per annum. This was due to the reduction in iron (III) sulphate requirement, lower sludge production, and the lower energy consumption by air blower. Lee *et al* (2008) compared DOF with other relevant technologies for municipal WwT, including the costs of chemicals, ozone generation, and power consumption for DOF processing (Table 2):

Table 2: A comparison of the treatment costs of DOF and other technologies for municipal wastewater treatment (adapted from Lee *et al* (2008))

Process	Cost of treatment (US$/ m^3)	Source
Dissolved ozone flotation	0.031	(Lee et al., 2008)
Granular media filtration and chlorination	0.5	(Hamoda et al., 2004)
Ozone-enhanced electro-flocculation	0.51	(Nielson & Smith, 2005)
Moving bed sand filter, a granular activated carbon adsorption bed and ozone disinfection	0.31	(Petala et al., 2006)
Dual-membrane	0.21	(del Pino & Durham, 1999)

However, Jin *et al* (2015) tested a pilot-scale DOF system and noted the optimal ozone dosage for the DOF process was considerably lower (x ~3), so the economic benefit of DOF could be far greater.

3.8.3 Summary: DOF

DOF induces the production of nano/micro-ozone bubbles, which have a very large surface area, thereby greatly enhancing the mass transfer rate. This can decrease the dosing requirements of coagulants and flocculants, offering considerable economic benefits when compared to DAF. The limited amount of literature available suggests that the integration of ozone into conventional DAFs could have considerable impact on a number of areas of water treatment.

DOF typically leads to improved overall water quality, such as increased pathogen removal, removal of micro-pollutants, and the reduction of odour emissions, compared to

DAF. However, it should be noted that DAF is not widely used in water treatment and so retrofitting, even if the claimed benefits are realised, would be rather limited. The greatest potential for this technology lies in water treatment plants that have a DAF unit, or several DAF units in operation being converted to DOF at very little cost.

3.9 Fluidic Oscillation Devices

3.9.1 Technology Description

Fluidic oscillators convert constant gas flows into oscillatory flows, by creating an instability based on the Coandă effect. Zimmerman et al have developed this technique for the generation of uniform microbubbles (Al-Mashhadani et al., 2012; Hanotu et al., 2013a; Hanotu et al., 2013b; Rehman et al., 2015; Tesař et al., 2006; Zimmerman et al., 2009; Zimmerman et al., 2011; Zimmerman et al., 2008). When an oscillating flow is applied, it creates a "pulse" that provides a lifting force enabling the bubble to break free when significantly smaller (Hanotu et al., 2012; Hanotu et al., 2013b) (Figure 5). Furthermore, the bubbles are released at more similar times, and are similar in size, hence the forces on them are balanced and they rise vertically, meaning that they are less likely to coalesce

3.9.2 Opportunities

The increased surface area to volume ratio available in MBs can significantly increase gas-liquid mass transfer rates (Hanotu et al., 2013a; Temesgen et al., 2017). These characteristics of MBs and NBs have attracted attention in a variety of fields including water and WwT, water purification, fish farming, shellfish culture, and harvesting of microalgae (Coward et al., 2015; Hanotu et al., 2013b; He et al., 2012; Kaushik & Chel, 2014; Khuntia et al., 2012; Rehman et al., 2015).

Aeration is one of the most energy intensive processes in WwT, consuming 45–75% of the total plant energy cost (Rosso et al., 2008). Conventional methods of bubble generation use pore diffusers with a steady flow to produce fine bubbles of 1–3 mm (Rehman et al., 2015). These techniques are unable to produce MBs due to the buoyancy force required for the bubble to break free from the diffuser and inter-bubble forces causing bubble coalescence (Rehman et al., 2015; Zimmerman et al., 2008).

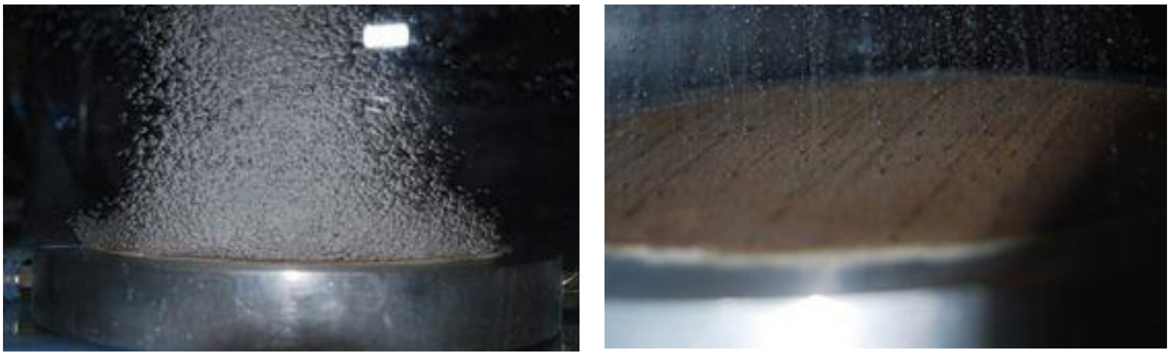

Figure 5: Bubbles created from microporous membrane diffuser, without fluidic oscillation (left). Created from microporous membrane diffuser, with fluidic oscillation (right). (Picture: University of Sheffield)

Aeration is commonly used in activated sludge processes to promote microbial growth. Rehman *et al* (2015) noted that fluidic oscillator-mediated MB generation could provide cost-effective enhancement of mass transfer and mixing efficiency, increasing the bacteria concentration.

A number of methods for the generation of miniaturised bubbles have been developed, such as; dissolved air flotation (DAF), ultrasound techniques (see section 3.3 *Ultrasound*) and induced air flotation (IAF). DAF is the most commonly employed technique for the production of MBs, however supersaturating the water is a highly energy intensive process, with more than 90% of the total operational energy used in DAF being spent on pumping and pressurizing recycled clarified water into the saturator (Hanotu et al., 2013a). It has been suggested that the use of fluidic oscillators could eliminate recycle flow and saturator load required by conventional DAF technologies. Fluidic oscillators could also be combined with ozone to create ozone-rich MBs that could be used to sanitise water (Lozano-Parada & Zimmerman, 2010; Temesgen et al., 2017). Khuntia *et al* (2015) noted that that ozone MBs improved the oxidation of different pollutants by improving the formation of hydroxyl radical for advanced oxidation under acidic and alkaline conditions. Wang *et al* (2017b) found that the reaction rate when using ozone MBs was three times higher than that in normal ozone when used as an advanced treatment method of concentrated leachate.

3.9.3 Summary

Fluidic oscillation devices produce micro or nano scale bubbles by converting constant air flows into oscillating air flow without moving parts, and without the need for energy intensive water supersaturation (DAF). This offers three significant improvements to the WwT process: 1) improved mass transfer rate, 2) reduced energy usage and 3) improved mixing, could bring significant benefits to industry.

MB aeration technology can be retrofitted to existing plants, potentially with little disruption, and can therefore be implemented in the near-term for a number of water and WwT applications. An intriguing possibility is to use the generators with ozone to create ozone-rich microbubbles for water sanitisation.

4 Conclusion

The UK water industry is facing a variety of challenges such as; meeting future legislation on water quality, increasing population densities, and water demand, new and emerging pollutants, and reducing energy use. However, the potential to address these challenges is extremely limited, if not amplified, due to the UK's aging water infrastructure, the industry's risk-averse attitudes, and a lack of knowledge and understanding about new and emerging technologies.

Process intensification (PI) is a chemical and process design approach that leads to substantially smaller, cleaner, safer and more energy-efficient process technology. This review identified 9 new and emerging novel PI technologies that could be applied to the UK water industry to gain a step-change in processing potential. The majority the PI technologies also offer the opportunity for either: 1) small foot-print, decentralised facilities that could be located at "hot-spots", reducing the complexity of waters entering the traditional centralised system, or 2) technologies that could be retrofitted into the current facilities, improving processing potential or reducing energy requirements.

However, this is by no means a comprehensive review of all possible novel intensified technologies that can be used in the UK water industry. The field of intensified process technology is vast, and the set of possible process steps in water processing is substantial. The full matrix (available in supplementary material) demonstrates the extensive range of PI technologies and processes assessed. Technologies that scored relatively highly but were not included in this review include: aerobic granular sludge, membrane-aerated biofilm reactors, magnetite ballasted activated sludge, electro-dewatering, and anti-scale/ FOG technology.

A number of innovation-led industries have demonstrated significant improvements that can occur when PI technologies are adopted, such as: more efficient, safer, flexible, smaller, cheaper and more environmentally friendly processes. It has also been demonstrated that drastic changes can occur when a water sector embraces innovation and invests in research, such as the Singaporean water industry. Therefore, to ensure the continued adoption of PI techniques into the water industry the following three measures are recommended:

1. **Distributed Water Treatment:** A review of PI or other technologies specifically for future distributed water treatment systems may be timely. This should be an area where intensified technologies can make a significant difference to the economics and capabilities of water treatment, with more certainty about the process technology performance at full scale. The greatest technical risk for many of the technologies reported here is scale-up, and the risk increases with the scale-up factor. Furthermore, some technologies are inherently difficult to envisage at the largest scales in the water industry.

2. **Mass Transfer Enhancement:** There are a variety of novel technologies, notably rotating packed beds, but also oscillatory baffled reactors, fluidic oscillators, and spinning tube-in-tube reactors that could be used to enhance gas-liquid mass transfer to intensify process steps such as chlorination or ozonation and oxygen transfer. A more detailed comparative design study and/or techno-economic study is required to determine which technologies would be most economically viable in practice.

3. **Knowledge exchange:** A number of technologies have commercial examples, but are not yet used in large numbers, or could be used at large scale in the near term. There is therefore the need for knowledge exchange by current users for the common good. Knowledge exchange programs or fact-finding missions are recommended.

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Author Contributions

TC, HT and AH designed the methodologies for collecting data on the PI technique; TC and AH analyzed the data; HT contributed materials. TC and AH wrote this manuscript.

Conflicts of Interest

The authors declare no conflict of interest

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