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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.

1. Introduction

The water industry has been notoriously slow to implement change, often embracing tradition and conservative treatment technologies [1–5]. The barriers affecting the water sector's ability to adopt innovative technologies has been explored by a number authors [1,6,7,2–4]. 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 [7,2–4]. 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 [1].

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 [8]. 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 [9]. The downside may be that some of the technologies are not "simple" to manufacture or maintain. The work Tayalia and Vijaysai [10] 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 [11,1]. 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 [12]. 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 [13], and the UK is

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required to set its own standards for a further group of potential pollutants [14]. 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 [15]. 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 [16–18,15]. Gardner et al. [14] 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. [14] 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 t per year from operational energy use and emissions associated with the additional processes required" [19]. 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 [19].

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 [20], 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 [21,11,2].

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 [1].

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 [22]. 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 [8]. Therefore, the understanding of mass transfer mechanisms enables the proper design and operation of many processes [23]. 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 [24]. 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 [25–27,8]. 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 [28,29,8]. They defined PI as the "strategy of making significant reductions in the size of unit operations, while achieving a given production objective" [28]. Since that time, there are many examples of intensified technologies being successfully applied, in industries such as petrochemical [30], chemical [24], food [31,32], and pharmaceuticals [33]. Fig. 1 illustrates the broad range of technologies that are considered "intensified" (but this is by no means comprehensive).

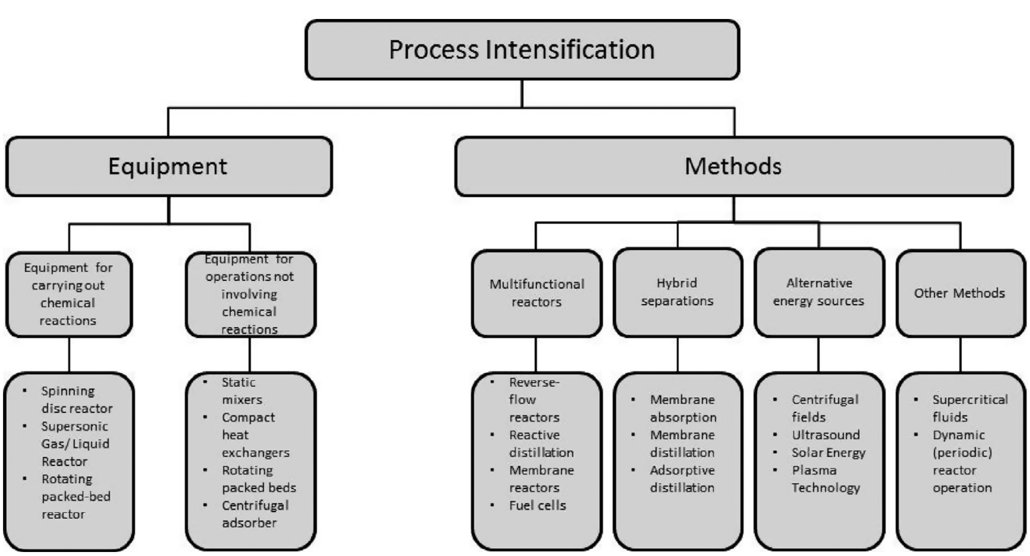

Fig. 1. Examples of the broad uses of Process Intensification equipment and methods. The diagram has been adapted from Process intensification classification by [24].

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