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Review

Reverse osmosis integrity monitoring in water reuse: The challenge to verify virus removal – A review

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ABSTRACT

A reverse osmosis (RO) process is often included in the treatment train to produce high quality reuse water from treated effluent for potable purposes because of its high removal efficiency for salinity and many inorganic and organic contaminants, and importantly, it also provides an excellent barrier for pathogens. In order to ensure the continued protection of public health from pathogen contamination, monitoring RO process integrity is necessary. Due to their small sizes, viruses are the most difficult class of pathogens to be removed in physical separation processes and therefore often considered the most challenging pathogen to monitor. To-date, there is a gap between the current log credit assigned to this process (determined by integrity testing approved by regulators) and its actual log removal capability as proven in a variety of laboratory and pilot studies. Hence, there is a challenge to establish a methodology that more closely links to the theoretical performance. In this review, after introducing the notion of risk management in water reuse, we provide an overview of existing and potentially new RO integrity monitoring techniques, highlight their strengths and drawbacks, and debate their applicability to full-scale treatment plants, which open to future research opportunities.

1. Introduction

With increased shortages of available freshwater in many regions due to global climate change, urbanisation and population growth, alternative sources of water supply will be required to supplement conventional sources (Semiat, 2008). Increasingly, this requires drawing upon “compromised” water sources. Whilst it is technically feasible to produce high quality drinking water from almost any source (including wastewater), the consequence of process failures results in a higher risk than for a more pristine water source. This has led, in many places, to a reluctance of communities to accept effluent sourced recycled water (Hurlimann and Dolnicar, 2010; Dolnicar et al., 2011; Fielding et al., 2015).

The stringent regulatory requirements for recycled water proponents are, in part, driven by the need to instil public confidence. The regulatory requirements are often framed around a multiple barrier concept supported by a strong semi quantitative risk assessment methodology (NRMMC et al., 2008; USEPA, 2012). A risk methodology considers the hazards (e.g. pathogens or chemical contaminants), and the hazardous events that can lead to the hazards being present (e.g. process failure); by then determining the consequence (e.g. pathogens have acute consequences whereas most chemical contaminants have chronic consequences) and likelihood that the hazardous event may occur. With those aspects established, it is then possible to calculate the associated risk. One generally accepted outcome of the risk assessment process is the need to utilise multiple robust treatment barriers to reduce or eliminate the hazards. Once established, there is also a need to continuously demonstrate, through online real-time monitoring, the effectiveness of these barriers.

Reverse osmosis (RO) membranes are commonly used in tertiary treatment for water reuse applications as the last physical removal process and theoretically have the capacity to completely remove viruses (Shannon et al., 2008). RO membranes have been proven to achieve above 5 log removal values (LRV) of viruses in laboratory systems (Lozier et al., 2003; Mi et al., 2004; Pype et al., 2016) and pilot studies (Kitis et al., 2003; Lozier et al., 2003; MWH, 2007). Log removal value is a way to express the removal

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or inactivation efficiency for a specific target such as an organism, particulate or surrogate (1 LRV = 90% reduction in abundance of the target component, 2 LRV = 99% reduction, 3 LRV = 99.9% reduction, etc.). However, due to its modular design, a full-scale membrane installation contains a large number of O-ring seals, interconnectors, glue lines joining membrane sheets and other potential locations, where small leaks may occur. Consequently, it cannot be assumed per se that the actual LRV corresponds to the theoretically achievable value without continuously demonstrating the performance of the system to be at or above the claimed LRV. Therefore, the regulatory requirements often demand operational monitoring of each barrier that continually demonstrate the barrier's effectiveness.

In order to protect public health, validation and monitoring of RO process integrity are necessary to ensure its correct operation. To-date, there is no national or international accepted validation protocol for RO, despite conventional techniques such as conductivity, TOC or sulfate rejection having been used for this purpose. At present, each proposed protocol still requires review and approval by relevant regulators on a case by case basis (AWRCoE, 2014). An agreed validation protocol establishing a correlation between LRV and indirect continuous online monitoring would provide confidence to recycled water treatment plant operators and project developers. In particular the ability to accredit LRV of three and above could reduce the investment costs and simplify treatment process trains by removing potentially unnecessary additional barriers. It has to be noted that the validation of a specific process might be limited by regulation. For example, the state of Victoria (Australia) (VDoH, 2013), limits the validation of a process to 4 LRV in order to force the use of multiple-barrier systems reducing the risk of outbreak in case of a process failure.

The design of a monitoring scheme will have to entail the following five key steps:

1. What is the validation goal, i.e. how many LRVs?
2. What surrogate or indicator could be chosen to allow for the desired LRV accreditation to be granted (real LRV $\geq$ validation goal and established correlation between surrogate and virus removal)?
3. Choice of detection method and, if applicable, pre-concentration and purification steps to achieve the necessary LOD. Is the ratio of natural feed concentration to LOD in permeate high enough to assert the validation aim or is spiking of the surrogate necessary?
4. If surrogate spiking is necessary, does it constitute any secondary risks to the process (e.g. membrane fouling)?
5. Assessment and comparison of different options considered in terms of the criteria chosen (e.g. cost, robustness, etc.).

The current challenge is to identify a methodology that more closely matches the actual performance of the system with the theoretical one.

Antony et al. (2012a) have previously provided an overview of the mechanism of virus rejection by membrane processes, the virus models for membrane studies and the challenge of membrane integrity monitoring for virus-sized particles including the limitation of the current techniques. Some of these notions are briefly introduced in the next sections for completeness. To build on this previous work, the current review focuses on (i) the risk management approach in water reuse; (ii) the introduction of potential new monitoring techniques to validate RO process including their strengths and weaknesses; and (iii) highlighting the needs and potential avenues for additional research in this area.

2. Risk management in water reuse

The use of recycled water poses a risk to public health which obliges authorities to impose strong regulations in order to protect customers (Radcliffe, 2004). The most important water quality risks that must be managed in potable water recycling are related to pathogen contamination by bacteria, viruses and protozoa (WHO, 2011). Recognising and appropriately managing these risks is critical to the successful implementation and acceptance of recycled water schemes. As previously mentioned, risk assessment generally includes the identification of hazards, their potential effect on human health (i.e. consequence) and their likelihood (NRMMC et al., 2006). A risk management strategy will aim at decreasing unacceptable risks of an outbreak due to water recycling using a multiple-barrier treatment system (NRMMC et al., 2008). In the case of one barrier failing, subsequent barriers shall be able to still remove contaminants to a satisfactory level, ensuring the continued delivery of safe recycled water. However, this is not strictly applicable when the effectiveness or even operability of one barrier depends on a previous one.

The transmission of infectious diseases by pathogenic organisms is the most serious concern related to water reuse. Microorganisms associated with waterborne diseases are primarily enteric pathogens, including enteric bacteria, protozoa and viruses. These pathogens can survive in water and infect humans through ingestion of faecal-contaminated water or contact with contaminated surface and food. From a public health perspective, all pathogens are of a concern due to the possibility of infection from exposure to low doses. However, from a process control perspective, enteric viruses are the most critical group of pathogenic organisms due to their small size and their limited consequential removal in physical separation processes based on filtration (Antony et al., 2012b). The detection and quantification of viruses in tertiary effluent is challenging due to their low concentrations. Whilst *E. coli* is often used as an indicator of faecal contamination in drinking water applications, the differences in physical removal between bacterial and viruses mean that it is not useful for determining the presence of virus in water reuse applications (Costán-Longares et al., 2008b). In a “fit for purpose” treatment train, microbial risk can often be managed using performance targets in place of water quality targets (NRMMC et al., 2008; WHO, 2011; USEPA, 2012). Performance targets use reference pathogens (e.g. rotaviruses and enteroviruses) having the same characteristics and behaviour as the represented group of pathogens (e.g. viruses) to identify appropriate combinations of water treatment processes to meet the required water quality. Hence, they aid to prevent pathogens from breaching barriers of source protection, treatment and distribution systems or prevent their growth within the distribution systems by selecting and using control measures (WHO, 2011).

However, there is no universal recycled water policy around the world as legislation is location dependant. To determine the requirement for virus removal for a specific end-use of recycled water, regulatory agencies set benchmarks that must be met. In Australia, the Australian Guidelines for Water Recycling (AGWR) (NRMMC et al., 2008) describe the risk characterisation, which assess the magnitude of risk depending on the concentration and the exposure associated to enteric viruses, and their 95th percentile assumed concentrations in sewage. The minimum LRV for viruses required to be achieved for the production of recycled water for potable purposes from sewage has been set to 9.5 (NRMMC et al., 2006, 2008), with a maximum credit of 4 LRV per barrier. California Department of Public Health (USA) sets the minimum requirement to 12 LRV for using treated wastewater for groundwater replenishment of drinking water aquifers (CalEPA, 2014). California advanced water treatment plant (AWTP) should contain