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Advanced process control for ultrafiltration membrane water treatment system

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ABSTRACT

Dead-end ultrafiltration (UF) has been considered as a more energy efficient operation mode compared to cross-flow filtration for the production of drinking/potable water in large-scale water treatment systems. Conventional control systems utilize pre-determined set-points for filtration and backwash durations of the constant flux dead-end UF process. Commonly known potential membrane fouling parameters such as feed water solids concentrations and specific cake resistance during filtration were not taken into considerations in the conventional control systems. In this research, artificial neural networks (ANN) predictive model and controllers were utilized for the process control of the UF process. An UF experimental system has been developed to conduct experiments and compare efficiencies of both the conventional set-points and ANN control systems. The novelty of this study is to utilize commonly available on-line and simple laboratory analysis data to estimate potential membrane fouling parameters and subsequently utilize the ANN control system to reduce water losses. Reduction of water losses were achieved by prolonging filtration duration for feed water with low turbidity using the ANN control system. This advanced control system would be of interest to operators of industrial-scale UF membrane water treatment plants for the reduction of water losses with existing facilities.

1. Introduction

Proliferation of human population and rapid development on a global scale has pushed towards higher consumption and quality of drinking/potable water particularly in urban cities (Goh et al., 2016). Developed Asian countries such as Singapore, Japan and South Korea have all adopted large-scale ultrafiltration (UF) membrane water treatment systems to partially fulfil their nations need for potable water through public-piped water supply and distribution networks. Membrane technologies have been reported to fulfil multiple sustainability criteria in terms of flexibility, adaptability, minimal foot print and environmental impacts (Le and Nunes, 2016). UF membrane systems have gained immense attention in water treatment industry as it could provide consistent filtrate quality by removing colloids, particles and microorganisms (Monnot et al., 2016). Most of the large-scale UF membrane water treatment plants are operating under constant flux dead-end filtration mode with intermittent backwash sequence to reduce the energy consumption per cubic meter of filtrate (Massé et al., 2011). High energy consumption is directly related to carbon emission which causes environmental issues (Rahim and Raman, 2015). Polymeric membranes particularly Polyethersulfone (PES) and Polyvinylidene fluoride (PVDF) are dominantly utilized at industrial-scale UF membrane water treatment plants (Hög et al., 2015). PES membranes exhibit beneficial properties such as good thermal stability, excellent chemical resistance and wide pH tolerance. This type of membranes have the potential to be blended with additives to reduce membrane fouling tendency (Vatsha et al., 2014).

Membrane fouling remains the most critical issue for commercial systems (Smith et al., 2006; Guo et al., 2012). Many approaches to minimize membrane fouling have been proposed such as membrane surface modification, physical and hydrodynamic cleaning methods to enable better removal of attached solids on membrane surfaces (Shamsuddin et al., 2015). Membrane cleaning

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is defined as procedures applied on the membrane to relieve it of non-integral substances which are known as "foulant" (Porcelli and Judd, 2010). Physical cleaning method such as hydraulic backwash is essential for the sustainable application of UF systems in water treatment processes. The extent of irreversible fouling is highly dependence on the hydraulic cleaning efficiency (Chang et al., 2015). Intermittent backwash after each filtration sequence is commonly conducted as physical cleaning in dead-end membrane filtration systems to recover membrane permeability (Mendret et al., 2009). Membrane fouling could be mitigated by optimization of the operational conditions (Shi et al., 2014).

Natural surface water from rivers are common sources of feed water to industrial-scale water treatment plants to produce potable water (Davies and Mazumder, 2003). It contains matrix of organic matters and particles which are considered to be the main sources of organic foulant on UF membranes (Shang et al., 2015). Feed water characteristics and operational conditions of UF membrane processes are factors which affect the systems performance (Decarolis et al., 2001). Any characteristics or composition changes in the feed water could induce huge changes on membrane fouling (Massé et al., 2015). Most industrial-scale water treatment plants analyse and monitor parameter such as raw water turbidity on hourly basis to detect any possible feed water characteristic changes. Recent literature has suggested that specific cake resistance or α is one of the important parameter for estimation of potential membrane fouling propensity (Sioutopoulos and Karabelas, 2016). It is a commonly used parameter to express the characteristics of the cake layer. Most industrial-scale UF membrane water treatment plants do not have the advanced analysis equipment and skilled-personnel required to determine α experimentally at their own in-house laboratories.

The dominant fouling mechanism in dead-end filtration for physical solid-liquid separation of UF process is known as "cake" formation which could be described by Darcy's equation (Sioutopoulos and Karabelas, 2015). Feed water characteristics such as solids concentrations and specific cake resistance are some essential parameters in Darcy's equation. Constant changes of surface water characteristics due to heavy rainfalls and surface run-off cause these parameters to fluctuate from time to time. Under constant flux dead-end filtration operation mode, the trans-membrane pressure (TMP) readings increase gradually over time due to cake formation on the membrane surface (Iritani et al., 2015). High TMP during operation is considered undesirable as more energy is required for the filtration process.

Conventional set-points control systems for industrial-scale UF membrane water treatment plants utilize a pre-determined filtration duration before an intermittent backwash is initiated (Cogan and Chellam, 2014). Programmable logic controllers (PLC) are often programmed with user's defined set-points to perform the control loop automatically (Alphonsus and Abdullah, 2016). Some of the most common causes of membrane fouling are related to its process control and operation parameters (Damour et al., 2014). Feed water characteristic such as turbidity is one of the major parameter often monitored on hourly basis during operation. The feed water characteristics and the complex interaction of the contaminants with the membrane necessitates formulating and solving highly non-linear equations or theoretical models (Shetty et al., 2003). In accordance to Darcy's equation, the solids contaminants build-up on the membrane surface increases the TMP during constant flux dead-end filtration (Mendret et al., 2009). However, the rate of TMP increase is governed by feed water characteristics which may differ from time to time if the source is from natural rivers.

Artificial neural networks (ANN) provide an alternative method to model these complex systems based on commonly available data (Hussain and Kershenbaum, 2000; Shetty and Chellam, 2003; Chew et al., 2017). Successful applications of ANN in chemical systems as models and estimators have been reported in literature (Mohd Ali et al., 2015a; Mohd Ali et al., 2015b). ANN control system has been utilized in the steel pickling process which involved the release of hazardous wastewater with major environmental impacts (Kittisupakorn et al., 2009). In another research study, ANN based correlation was used to estimate the permeability constant of membrane systems under fouling conditions (Barello et al., 2014).

Fouling mitigation and water losses reduction control methodology for membrane processes are research areas which have generated immense interests. Aluminium coagulation has been reported as an effective control measure to reduce UF membrane fouling from organic matters (Yan et al., 2017). An advanced fouling control method which utilizes pulsed short-wavelength ultraviolet light with pre-coagulation to mitigate membrane fouling by microorganism was also highlighted in literature (Yu et al., 2016). In another different approach, a real-time control system using self-adaptive cycle-to-cycle has been utilized to control the dosing rate of coagulant prior to the UF process (Gao et al., 2017). This control strategy has been found to be very robust to ensure fouling control measured in an UF system. All of the control methods mentioned earlier required the use of coagulant or additional advanced equipment for implementations. Limited and very few research studies have reported using commonly available on-line and simple laboratory analysis data to increase the efficiency of direct feed UF systems by reducing water losses while ensuring acceptable potential membrane fouling propensity.

A typical direct feed industrial-scale UF membrane water treatment system consists of various control valves, pumps, pressure transmitters, storage tanks and flowmeters to implement the conventional set-points control system. Raw water from rivers are usually used as feed water to the UF system. During the filtration sequence, a feed pump is utilized to provide sufficient pressure and flow rate into the UF membrane modules for the solid-liquid separation process. Filtrate from the UF membrane modules are temporary stored in a filtrate tank before transferring to a contact tank for chlorine disinfection. During backwash sequence, water from the filtrate tank is pumped back in reverse flow to the UF membrane modules to dislodge accumulated solids and foulant. Fig. 1 shows the schematic diagram of a direct feed industrial-scale UF membrane water treatment system. Under the conventional set-points control system, both the filtration and backwash sequences operate on alternate basis to produce the desired volume of filtrate while ensuring periodic cleaning of the membrane to reduce fouling.

In this research study, an advanced control system utilizing ANN model and controllers have been implemented on an UF experimental system operating under constant flux dead-end filtration mode. Natural surface water from a river was directly fed to the UF experimental system. It contains significant amount of suspended solids which could cause membrane fouling. Correlation of the feed water turbidity and its solids concentrations were established using simple laboratory analysis procedures. The ANN control system predicts the specific cake resistance using relevant inputs data during the filtration sequence. Potential membrane fouling propensity estimated from these data was utilized by the ANN control system to regulate the filtration durations. Instead of depending on advanced analysis equipment to determine the potential membrane fouling propensity, commonly available on-line and simple laboratory analysis data were utilized in the ANN control system. This approach brings down the capital expenditure required to upgrade available facilities in commercial UF membrane water treatment plants to reduce water losses under fluctuating feed water characteristics. Comparisons between both the conventional