Key issues of ultrafiltration membrane water treatment plant scale-up from laboratory and pilot plant results

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ABSTRACT

Industrial-scale ultrafiltration (UF) membrane systems have gained wide acceptance for producing safe drinking water. Laboratory and pilot plant studies are often carried out prior to the design of full-scale water treatment plants. Emphases are laid on how accurately these laboratory and pilot plant studies represent actual industrial-scale systems and the limitations. A case study which encompasses laboratory experiments, pilot plant and industrial-scale UF systems has been carried out in Malaysia using the same type of modified polyethersulfone hollow fiber UF membrane and surface raw water source. This research elaborates on the practical utilization of laboratory experiments and pilot plant results on the design and scale-up for industrial-scale water treatment plants. The results obtained in filtrate quality, transmembrane pressure and specific electricity requirements elucidate that both laboratory- and pilot-scale studies are essential to determine the detailed design criteria of an industrial-scale UF membrane water treatment plant with limitations that require attention. Design engineers are able to reduce the safety factor allowance and minimize cost by utilizing laboratory- and pilot-scale results for the scale-up of UF membrane water treatment plants.

Key words | industrial-scale, laboratory-scale, pilot plant, ultrafiltration, water treatment

INTRODUCTION

Contaminated water sources cause thousands of human deaths daily due to diseases (Misra & Singh 2012). The water crisis has serious health implications particularly in developing countries (Enders et al. 2015). This has raised an alarm for safe drinking water for public consumption. Membrane systems such as ultrafiltration (UF) have been proven to be effective barriers for segregation of bacteria and viruses to produce safe drinking water (Di Zio et al. 2005). Stringent drinking water requirements are pushing service providers around the world to increasingly turn their attention to membrane filtration technologies (Peiris et al. 2015). Membrane treatment techniques have been proposed for application in green design for urban and municipal implementations due to their cost-effectiveness, user-friendliness and eco-friendliness (Rashidi et al. 2015). Various key design parameters are required prior to the design of industrial-scale membrane water treatment plants. In most cases, laboratory- or pilot-scale experiments are carried out to obtain these design parameters.

Full-scale water treatment plant efficacy in contaminant removal varies with differences in raw water quality and in design and operating conditions (Lohwacharin et al. 2014). Laboratory-scale studies are frequently carried out to determine the feasibility of operational cost for full-scale water treatment plants (Keeley et al. 2012). Preliminary laboratory and pilot plant results are key elements for engineers and plant designers to evaluate the treatment process and subsequently determine the sizing for all the equipment of an industrial-scale treatment system. In UF systems, laboratory-scale experiments provide useful information on the effective membrane configurations and operational parameters (Howe et al. 2007).

The main objective of this study is to highlight the key issues of UF water treatment plant scale-up from laboratory and pilot plant results. A case study of an industrial-scale UF
water treatment plant has been analyzed in detail. This treatment plant is located at Kelantan, Malaysia and began operation in 2013 to supply up to 14,000 m³ a day of potable water to a nearby township (Chew et al. 2013). Detailed discussions are presented in this paper to highlight the limitations of laboratory and pilot plant results. Based on these preliminary laboratory and pilot plant results, engineers were able to use the data for the design of an industrial-scale water treatment plant and scale-up with reduced cost by minimizing the design safety factor allowances.

METHODS

Laboratory-scale and pilot-scale experimental test rigs were set up with the same type of modified polyethersulfone (mPES) hollow fiber UF membrane manufactured by Inge GmbH, Germany. Operational data of an industrial-scale UF membrane water treatment plant located at Kelantan, Malaysia were gathered for analysis and comparison. Figure 1 shows the two experimental test rigs and the industrial-scale water treatment plant.

Figure 1 | (a) Laboratory-scale, (b) pilot-scale and (c) industrial-scale UF membrane water treatment systems.
All the UF systems are operated in dead-end filtration mode with periodical backwash sequences. These two experimental test rigs are fed with the same type of surface river water as the industrial-scale UF water treatment plant. The river water is extracted from the river bank filtration intake near the water treatment plant. Turbidity of the raw water is 10–30 Nephelometric Turbidity Units (NTU) with daily average of about 15 NTU. This low-turbidity raw water is suitable for direct feed to UF systems without the use of coagulant and flocculant. A few types of data were collected for analysis (turbidity, colour, pH, transmembrane pressure (TMP) and electricity consumption). The samples’ turbidity was measured using a HACH 2100Q Turbidimeter and colour was measured using a HACH DR 2800 Spectrophotometer. The samples’ pH was measured using a HACH Sension 1 portable pH meter. TMP was measured using an electronic pressure transmitter. Electricity consumption was measured using the Kyoritsu Kew Snap 2017 digital AC clamp meter. Table 1 shows the operating parameters for this case study.

This case study provides some essential data for analysis as it involves three UF systems which are laboratory-scale, pilot-scale and industrial-scale. The data obtained from the experimental rigs (laboratory-scale and pilot-scale) are then analyzed and compared to determine the accuracy and limitations of these data for the design of an industrial-scale UF system.

RESULTS AND DISCUSSION

All these systems utilized the same UF membrane and feed water to ensure uniformity. Results obtained from all the systems are further analyzed and discussed to determine the accuracy and limitations of the laboratory-scale and pilot-scale systems on the design of an industrial-scale UF membrane water treatment plant.

Quality of filtrate

Table 2 shows the results obtained in the three UF systems in this research. All the UF systems were fed with the same source of river water and the filtration processes were carried out using the same UF membrane. Water turbidity and colour data are used as physico-chemical parameters to indicate the quality of the filtrate (Roig et al. 2014). The filtrates’ turbidity, colour and pH indicated that the quality of the filtrates of all the UF systems is almost the same. This indicates that preliminary laboratory- and pilot-scale experiments to determine the quality of the filtrate are close proximate indications for an industrial-scale system. Other researchers have also carried out pilot-scale studies on the membrane system at Kwai Chung industrial wastewater pumping station at Hong Kong to substantiate future upgrade of existing industrial-scale systems (Guan et al. 2014). These studies were mainly carried out to determine the filtrate quality of the proposed membrane system. Our results in Table 2 indicate that laboratory-scale and pilot-scale experimental results on filtrate quality are in very close agreement with an industrial-scale membrane system.

Pressure drop through membrane modules

The TMP are not very consistent, with the laboratory-scale system giving the highest value among the three UF systems.
as shown in Figure 2. This can be explained by analyzing the UF membrane module design of each system. Both the laboratory-scale and pilot-scale UF membrane modules utilize a traditional central core system. The industrial-scale system uses an annular gap UF module which has been hydro-dynamically optimized to reduce pressure losses. Figure 3 shows the difference of the hollow fiber UF membrane arrangement in both the annular gap and central core membrane modules. Three types of UF membrane module geometry have been studied by researchers to identify the performance (Cano et al. 2015). This study has shown that different geometries of the membrane modules incurred various pressure and velocity fields. The design of the membrane module would cause an additional pressure drop in the system beside the membrane resistance of the hollow fiber UF membrane. In this case study, the annular gap being the more hydro-dynamically optimized resulted in a lower TMP than the central core modules used for the laboratory-scale and pilot-scale experiments. It is worth noting that when many hollow fibers are packed into a membrane module, the interaction between the hollow fibers in the network would yield additional pressure losses compared with a single hollow fiber (Kostoglou & Karabelas 2008). In this study, the backwash rate of 230 L/m² hr was applied in all the UF systems for 60 seconds after each filtration sequence. This backwash rate is recommended by the membrane manufacturer and could hydraulically clean the membrane. Membrane fouling analysis is beyond the scope of this study as it involves continuous operation and monitoring for more than a few months to justify the findings.

Specific electricity requirements

The specific electricity required to produce a unit of filtrate is much lower for the industrial-scale system as shown in Table 2, for a few reasons. As mentioned earlier, the annular gap module is much better optimized to reduce pressure loss and thus reduce energy to overcome these losses. The TMP for the industrial-scale system (0.18 bar) is the lowest compared to the laboratory-scale (0.31 bar) and pilot-scale (0.28 bar) systems. In addition, most high-capacity pumps (motor power rating above 0.75 kW) have higher efficiency compared to smaller pumps (motor power rating below 0.75 kW) due to regulation requirements (Sauer et al. 2015). These small pumps have low energy efficiencies which normally do not exceed 40% (Skrzypacz 2014). The feed pumps used in the laboratory-scale and pilot-scale systems have motor ratings of 0.38 kW (pump efficiency of 14%) and 0.70 kW (pump efficiency of 27%), respectively, whereas the
industrial-scale system feed pump is rated at 65 kW (pump efficiency of 87%). Pump efficiency is determined through Equation (1) in which P is the power required in kW, Q is the flowrate in m³/hr and H is the pump operating pressure in m. In this study, the pump efficiency in Table 2 is considered to be the overall efficiency of the motor and pump. Higher energy efficiency of pumps will translate into lower energy losses which mean less energy is used to overcome the TMP of the UF systems.

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\text{Pump efficiency} = \frac{(Q \times H)}{(270 \times 1.36 \times P)}
\]  

(1)

**Construction/set-up cost against data accuracy**

The results obtained in this case study are in very close agreement with the study carried out by other researchers (Blondeel et al. 2014), which states that more realistic simulations are in the order of industrial-scale > pilot-scale > laboratory-scale. Even though the results indicate a similar order, this case study has elucidated the limitations of laboratory-scale and pilot-scale studies which are of interest to industrial-scale UF plant design engineers. The cost-analysis perspective indicates the most economical systems to set up are in the order of laboratory-scale > pilot-scale > industrial-scale. A similar trend has also been observed by other researchers (De Groot & Traoré 2005), which emphasized that the higher expenditure cost for sampling would yield a more accurate prediction of the actual process.

Variation in feed water characteristics is the biggest challenge for UF membrane filtration systems as the flux rate would need to be adjusted accordingly to reduce the fouling of the membrane. Pilot-scale experimental rigs provide a cost-effective method to collect these fluctuating inputs for plant designers and engineers to determine the optimum size for an industrial-scale system on a specific type of feed water. Laboratory-scale experiments, even though they are less costly to carry out, are much more limited and less accurate for the design of an industrial-scale system.

If the intention of the experiments is to determine the filtrate quality based on the feed water characteristics and the compatibility of the UF membrane, the laboratory-scale data are a good indication. As for the detail that sizing of equipment such as feed pumps, backwash pumps and membrane surface area require, the pilot-scale study should be carried out to yield a much more accurate estimation for the design engineers.

**Utilizing results for the design of industrial-scale UF water treatment plants**

Based on the laboratory-scale and pilot-scale results, proper judgement is required to design an industrial or full-scale UF membrane water treatment plant. Previous studies (Kamp et al. 2000) carried out on pilot test and full-scale UF membrane systems in the Netherlands by other researchers indicated a significant difference in the TMP for both systems. The TMP for the pilot test is much higher than in
the full-scale systems under the same operating condition. Under such circumstances, it is recommended to install variable frequency drive (VFD) on the feed pump of industrial-scale systems to regulate the speed of the motor. Installation of VFD for the induction motor on pumps in shown to be capable of saving electricity consumption to cater for different loads (Al-Bassam & Allasseri 2013). It has been found that the TMP from industrial-scale UF systems are much lower than the laboratory-scale and pilot-scale systems from Table 2. Using VFD to regulate the UF feed pump speed to ensure the specific flow rate is reached with a low TMP would reduce the energy consumption making the industrial-scale system much more efficient.

Another piece of useful information that can be fully utilized from the laboratory-scale and pilot-scale results is the turbidity of the filtrate. Both the laboratory-scale and pilot-scale systems indicate very close proximity of the filtrate quality of industrial-scale systems in terms of turbidity. This allows industrial-scale water treatment plant owners to easily determine the membrane integrity or membrane fiber breakages just by conducting laboratory experiments. These laboratory experiments on the filtrate quality are then compared with the filtrate from the water treatment plant to determine possible UF membrane fiber breakages. If the filtrate from the treatment plant shows relatively high turbidity compared to the laboratory results, there are possible fiber breakages in the UF modules which require attention.

Preliminary laboratory-scale and pilot-scale systems on specific feed water and membrane type also serve as indicators of the operating cost per unit of the filtrate. Based on Table 2, the specific electricity requirement of industrial-scale systems (0.10 kWh/m³) is much lower than the laboratory-scale (0.57 kWh/m³) and pilot-scale (0.41 kWh/m³) systems. It has been reported in the literature that the electricity requirement of a full-scale UF membrane water treatment plant is about 0.20 kWh/m³ (Pearce 2008). A safe assumption can be made that the specific electricity requirements of industrial-scale UF systems are much lower than laboratory-scale and pilot-scale systems. If both the laboratory-scale and pilot-scale systems indicate good quality of filtrate and reasonable TMP with specific electricity requirements acceptable to the design engineers, it is very likely the industrial-scale system would have much better performance. The engineers are able to minimize the design safety factor allowance, reduce cost on feed pumps and having lower specific electricity requirements based on the laboratory- and pilot-scale results to scale up the UF system.

CONCLUSIONS

The utilization of laboratory-scale and pilot-scale UF systems results for the design of industrial-scale systems is highlighted in this work with a case study. Filtrate quality from laboratory-scale and pilot-scale experimental rigs results is in close proximity with the industrial-scale system. Pressure drops through membrane modules or TMP are higher for the two experimental rigs due to the central core membrane module design which incurred higher pressure losses compared to the more hydro-dynamically optimized annular gap design for the industrial-scale membrane module. Specific electricity requirements from the experimental rig results are higher than the industrial-scale system due to the higher TMP and less energy-efficient feed pumps. The limitations of the laboratory-scale and pilot-scale system results are elucidated with comparison to the industrial-scale system in this case study. Design engineers of industrial-scale UF membrane water treatment plants could utilize these experimental rig data to minimize the design safety factor allowance and reduce the cost on equipment such as feed pumps. Future works on effective membrane cleaning procedures in laboratory-scale and pilot-scale systems are recommended to enhance understanding of the results obtained for utilization on industrial-scale systems.

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