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SURFACE WATER TREATMENT BY CUSTOM-MADE MOBILE WATER TREATMENT SYSTEM

Rosdianah Ramli, Nurmin Bolong*

Faculty of Engineering, Universiti Malaysia Sabah, 88400, Jalan UMS, Kota Kinabalu, Sabah, Malaysia

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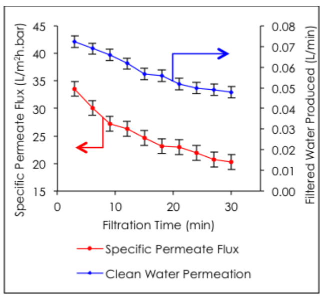
*Corresponding author
nurmin@ums.edu.my

Graphical abstract



Abstract

Advances in membrane technology have stimulated a growing interest in the development of mobile water treatment systems for rural areas lacking clean water access. This study explored the use of ultrafiltration hollow fibre (UF-HF) membranes as a filter medium in a mobile water system for surface water treatment. Prior to the surface water treatment operation, two types of UF-HF modules were prepared using different numbers of fibres (i.e. 15 and 30 fibres). By considering the effect of turbidity on the membrane permeate flux, it was found that the 30-fibre module performed with higher consistency than the module with 15 fibres within the same range of turbidity. It was observed that the specific permeate flux decreased gradually with operation time and that, simultaneously, specific permeate flux was governed by transmembrane pressure and feed water temperature. Consequently, the filtered water production was found to decrease with time. The UF-HF membrane module demonstrated good surface water treatment efficiency for a smaller-scale filter module and was able to improve surface water from water quality index (WQI) Class III to Class II.

Keywords: Surface water, Hollow Fibre, mobile water treatment, ultrafiltration

Abstrak

Kemajuan teknologi membran telah merangsang peningkatan dalam pembangunan sistem rawatan air mudah alih untuk kawasan yang sukar mendapatkan air bersih seperti kawasan pedalaman. Oleh kerana itu, penyelidikan ini meneroka keupayaan membran ultra gentian geronggang (UF-HF) sebagai medium penapis untuk sistem rawatan air mudah alih. Untuk operasi rawatan air permukaan tersebut, dua jenis modul UF-HF telah disediakan berdasarkan bilangan serat membran iaitu 15 dan 30. Kesan kekeruhan air permukaan terhadap flu pengeluaran menunjukkan modul dengan 30 serat membran mempunyai konsistensi yang lebih baik berbanding modul dengan 15 serat. Seterusnya, dalam operasi merawat air permukaan, flux pengeluaran spesifik telah menurun dengan peningkatan masa dan didapati bahawa tekanan antara membran dan suhu air mempengaruhi flux pengeluaran spesifik. Pengeluaran air bersih juga mencatatkan penurunan dengan peningkatan masa operasi. Walaupun dalam skala kecil berbanding modul komersil lain, modul UF-HF tetap menunjukkan prestasi merawat air permukaan yang baik yang mana kualiti air permukaan yang telah dirawat menunjukkan peningkatan kualiti dari Index Kualiti Air Kelas 3 kepada Kelas 2.

Kata kunci: Air permukaan, membran gentian geronggang, sistem rawatan air mudah alih, ultrafiltraso

1.0 INTRODUCTION

People in rural areas frequently have inadequate access to clean water due to limited or non-existent supply to their area from a centralised water treatment plant. Often, rural people are forced to obtain their water supply from natural sources such as rivers and lakes [1] and it has been reported that approximately 50% of this population have suffered health problems due to the consumption of untreated surface water [2]. Resolving this problem by building centralised water systems in rural areas is economically infeasible due to inadequate clean water resources, and attempting to harvest rainwater is also unlikely to succeed in a monsoon climate known for long droughts.

However, it has been recently demonstrated that decentralised water treatment systems can be used to treat existing surface water in rural areas [3], [4]. Decentralised water treatment systems, also known as mobile water treatment systems, are smaller and more compact than their centralised counterparts [5] and can therefore be transported to rural or remote areas. In addition, mobile water treatment systems are a stand-alone filter system which can be operated by gravity, with renewable energy, or by battery [1], [6]–[9].

Membrane technology has emerged as a reliable water treatment tool and has been applied in numerous mobile water treatment systems. Among membrane types, ultrafiltration (UF) membranes are used widely as an alternative water treatment process [10] due to their remarkable effectiveness in reducing the turbidity of surface water for non-potable purposes [11]–[13]. Moreover, UF is an absolute particle removal barrier to contaminants such as pathogenic microorganisms and even viruses [12], [13]. Specifically, ultrafiltration hollow fibre (UF-HF) membranes have shown good performance in both centralised and decentralised water treatment systems [14]–[20]. Furthermore, UF membrane systems generally require less floor space than conventional media filtration systems and can be used as an independent filtration unit [21]. Hence, they can be considered appropriate for use in a small-scale water treatment system intended to be mobile.

With the preceding as motivation, the current study aims to investigate the operational performance of a custom-made mobile water treatment system unit utilising a UF-HF membrane in surface water treatment for non-potable purposes.

2.0 METHODOLOGY

In this study, a mobile water treatment system is defined as a water treatment system that is easy to transport, deploy, and to operate. Such a unit is intended to be user-friendly, stand-alone, and of low cost. To accommodate these requirements here, the UF-HF membrane module has been designed to be small-scale, comprising a maximum of 30 fibres per bundle and with dimensions of 1.5 cm in diameter and 30 cm in length. The module designed is shown in Figure 1.

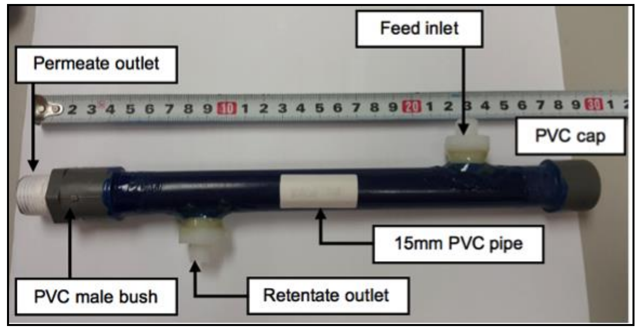


Figure 1 Schematic diagram of the UF-HF membrane module developed in our previous work [22]

In our preliminary study, two UF-HF membrane modules were developed due to the restricted space available in the module shell: a 15 fibre-bundle module and a 30 fibre-bundle module. According to [23], HF membrane modules require empty space around fibres in the bundle for permeate flow and to facilitate mass transfer between the fibres at the middle of the bundle to the periphery. Furthermore, increasing the packing density for the small shell used in this study (Figure 1) would increase the compactness of the membrane module and thus its resistance to mass transfer [19].

The UF hollow fibre membranes used here were obtained commercially as in our previous work [22]. Their effective areas were calculated to be 0.0153 m^2 and 0.0305 m^2 for the 15-fibre and 30-fibre modules respectively.

A custom-made membrane-testing rig (also a laboratory scale mobile water treatment system) was developed and used in this study to test the UF-HF membrane modules. A schematic drawing of the membrane-testing rig is given in Figure 2.

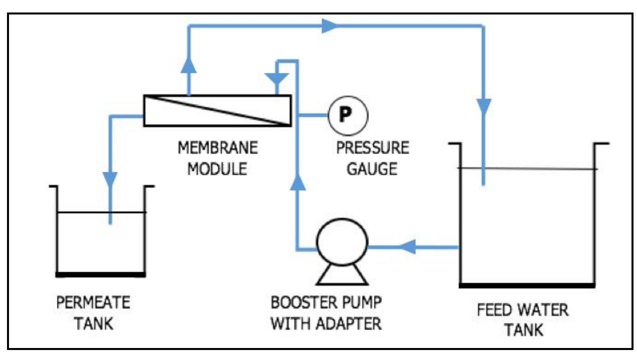


Figure 2 Schematic drawing of custom-made membrane testing rig used in this study

Our system uses no chemical treatment and works solely on physical filtration by the UF membrane module.

Surface water sample was obtained from a lake adjacent to the Faculty of Science and Natural Resources at Universiti Malaysia Sabah (GPS coordinates 6.031232, 116.121209, see Figure 3). The surface water samples were taken from three points located along the lakeside.

Figure 3 Surface water sampling location (circled red) near the Faculty of Science and Natural Resources, Universiti Malaysia Sabah

Before the experiments with synthetic feed water were started, a pure water permeation (PWP) procedure was conducted on both of the modules to determine their initial membrane resistance, R_m.

Raw water was pumped from a feed water tank using a booster pump (KEMFLO Booster Pump) at a constant feed flow rate of 1 L/min. Permeate water was collected at the permeate tank and measured on a mass balance (Mettler Toledo PB3002-S) over a constant filtration run time. Throughout the filtration run, transmembrane pressure (TMP) was monitored using a pressure gauge (YN-40ZT).

The surface water samples were analysed and characterised for biochemical oxygen demand (BOD), dissolved oxygen (DO), chemical oxygen demand (COD), ammoniacal nitrogen (AN), total suspended solids (TSS), and pH, as required for the Water Quality Index (WQI) based on the Malaysian Interim National Water Quality Standard (INWQS). The samples were analysed using APHA Standard Methods for the Examination of Water and Wastewater [24].

In addition to these parameters, the turbidity of the surface water samples was also measured. For the purpose of investigating its effect on membrane permeate flux, synthetic feed water was prepared by diluting 16L of surface water. The feed water turbidity was measured with a HACH 2100AN Turbidimeter. A portable measuring device (HANNA HI 9811-5) was employed to monitor the feed water temperature throughout the experiments.

The operational performance of the UF-HF membrane was determined based on its permeate flux. The measurement of permeate flux throughout the filtration run in this study was based on that of Darcy-Weisbach and Hagen-Poiseuille [22]. Then, during the surface water treatment, the specific permeate flux was used, based on the change of transmembrane pressure and feed water temperature throughout the operation.

3.0 RESULTS AND DISCUSSION

i) Effects of turbidity on membrane permeate flux

The first part of this work was to determine the effect of surface water turbidity on permeate flux, based on different membrane packing densities.

Surface water turbidity was divided into three ranges: low (0 NTU to 4 NTU), intermediate (4 NTU to 8 NTU), and high (8 NTU to 10 NTU). Both UF-HF membrane modules demonstrated reduced permeate flux as feed water turbidity increased, as shown in Figure 4. This reduction in operational performance attributed to membrane fouling caused by substances or particulate matter in the feed water [25], [26]. This fouling produced an additional resistance to mass transfer [27] that augmented the existing membrane resistance [28]. The reduction of permeate flux at such low ranges of feed water turbidity was similarly reported by other study [29], who stated that an additional layer on membranes formed by turbidity occur at turbidity levels of 12 NTU and below.

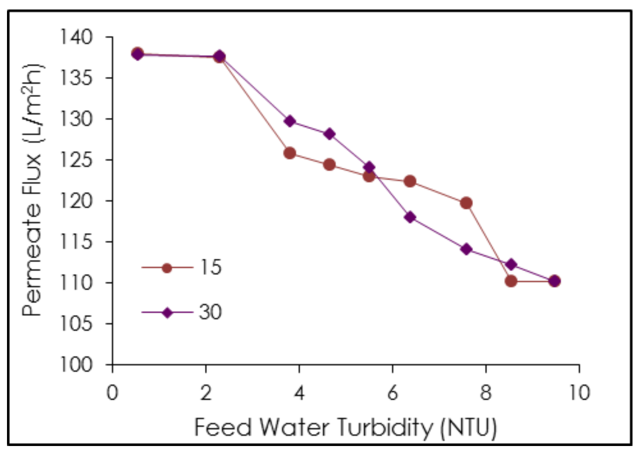


Figure 4 Effect of surface water turbidity on membrane permeate flux for UF-HF membrane modules with different membrane packing densities

As demonstrated by Figure 4, permeate flux for both membrane modules was almost constant at the lowest turbidity level but dramatically decreased beyond a turbidity level of 2 NTU.

At an intermediate level of feed water turbidity, the permeate flux in the 15-fibre module decreased more gradually (2.91%) than the 30-fibre module, which dropped significantly (7.83%). The 30-fibre module's high packing density may have contributed to this significant drop of permeate flux [13] by facilitating the mass transfer in the module. As a result, the permeate flux recorded for the 15-fibre module was higher than that of the module with 30 fibres at feed water turbidity level 5.5 to 8 NTU eventhough its surface area is 2 times lower than 30-fibers.

At higher levels of feed water turbidity, the reduction of permeate flux for the 30-fibre module became steady while the permeate flux for the module with 15 fibres decreased abruptly, becoming almost constant at the end.

Comparing both modules, the 30-fibre module had better operational performance than the 15-fibre module since its permeate flux drop was not as abrupt at the low and high ranges of turbidity. The 15-fibre module demonstrated a more stable reduction in permeate flux only at the intermediate level of feed water turbidity.

For these reasons, the UF-HF membrane module with 30 fibres was selected for use in the actual surface water treatment operation.

ii) Surface water treatment operation

The specific flux throughout the short-term treatment operation and the amount of filtered water produced are summarised in Figure 5. A recurring pattern in the specific permeate flux was observed throughout the short-term operation. During the 9th and 12th, 18th and 21st, and 24th and 30th minutes of the operation, specific permeate flux became almost constant. Even though the transmembrane pressure (TMP) was changed, there was no obvious variation in the feed water temperature (where the maximum difference was 0.1˚C). At these points, unlike the first 10 minutes, the specific permeate flux was influenced more by the temperature (i.e. the water viscosity) [14]. This shows that TMP and feed water temperature were crucial to the permeate flux individually, but not simultaneously which had been discussed in the previous work [19].

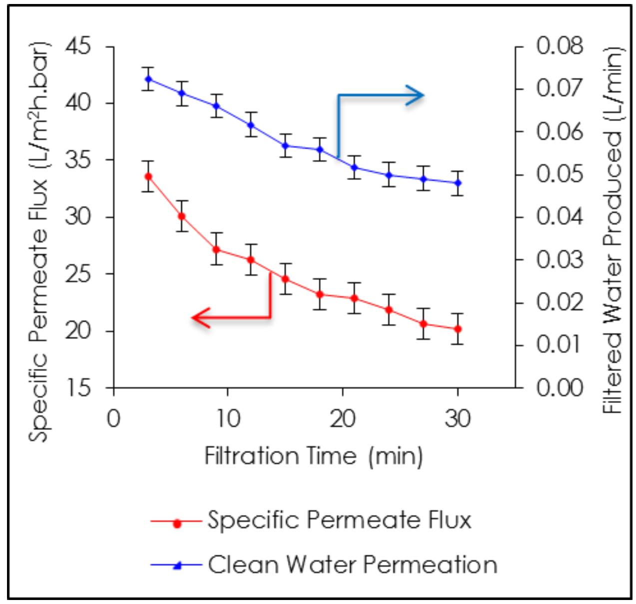


Figure 5 Specific Flux and Filtered Water Production of Developed UF-HF membrane in Surface Water Treatment

Aside from the three periods of near-constancy, the specific permeate flux observed throughout the operation decreased gradually, albeit not as much as within the first 10 minutes. Consequently, the corresponding filtered water production reduced steadily with operation time.

The highest filtered water production recorded was 0.073 L/min – a value higher than the requirement suggested by [4]. It has been reported that commercial household water treatment systems are able to provide 0.007 to 0.028 L/min of filtered water for a five-member family so the value obtained here is an attractive feature of our UF-HF membrane module.

Throughout the filtration run, the recorded feed water temperature decreased as retained water was recirculated into the feed tank. This is because the heat energy from the feed water transferred to the water particles, assisting permeation at higher TMPs of 3.0 bar and above.

Table 1 Surface water samples characterisation

Samples	TSS (mg/L)	BOD_5 (mg/L)	COD (mg/L)	AN (mg/L)	pH	DO (mg/L)
SWS1	38.00	0.60	55.00	0.15	7.90	5.00
SWS2	44.50	0.57	56.70	0.19	7.20	4.30
SWS3	35.30	0.91	56.50	0.13	8.10	4.90
Average	39.27	0.69	56.07	0.16	7.73	4.73
Class (Index)	I	I	IV	II	I	III

iii) Surface water treatment efficiency

Before the treatment operation was conducted, the surface water obtained from the sampling points at the source location was characterised. The characteristics of the surface water based on WQI parameters are shown in Table 1.

From Table 1, it may be seen that the quality of surface water in terms of total suspended solids (TSS), biochemical oxygen demand (BOD), and pH were of Class I quality. The quality for ammoniacal nitrogen (AN) and turbidity was found to be lower and these parameters were classified as Class II. The worst parameters were dissolved oxygen (DO) and chemical oxygen demand (COD), which were classified as Classes III and IV, respectively. By calculating the sub-indices of the average values for the six water quality parameters, the water quality index (WQI) of the surface water samples was obtained as 66.27, making the samples Class III overall. This indicated that the surface water at the sampling site would require extensive treatment before it could be supplied to the public.

Two permeate samples were taken after the surface water was treated in the short-period operation. The water quality of the permeate water samples in comparison to its initial quality is tabulated in Table 2 and the treatment efficiency for each water quality parameter is illustrated in Figure 6.

Table 2 Water quality of surface water before and after treatment using UF-HF membrane module

Water Quality	Raw (Ave)	Permeate 1	Permeate 2	Treatment Efficiency (%)
BOD	*0.69*	0.38	0.41	*43.57*
COD	*51.07*	16.18	16.15	*68.30*
AN	*0.16*	0.11	0.10	*34.38*
DO	*4.73*	4.50	4.20	*5.75*
TSS	*19.27*	0.00	0.00	*100.00*
pH	*7.73*	8.00	8.30	*5.52*

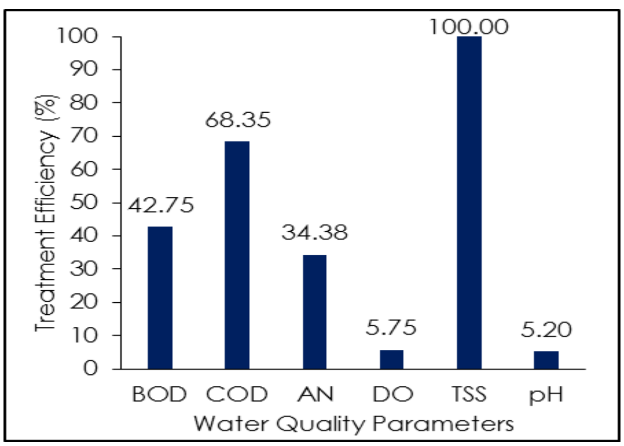


Figure 6 Surface water treatment efficiency using UF HF membrane module

It can be seen that the quality of surface water samples improved after treatment using the mobile UF-HF membrane. The UF-HF membrane demonstrated its effectiveness in physical filtration by removing 100% of TSS. However, only 30% to 70% of the organic parameters (AN, BOD and COD) were removed. This is because most of the organic component in the raw water was not in suspended form [30] - a fact shown by the value of TSS in the raw water (19.27 mg/L). This could also contribute to the very low removal of DO and pH, since it was found by other study [16] that UF membranes do not remove DO well on their own. However, adding coagulation to the treatment system could improve treatment efficiency as organic matter could be aggregated and thus filtered by the UF membrane effectively [10].

Overall, the WQI values obtained for both permeate water samples were 85.53 and 83.16 for Permeates 1 and 2, respectively. With no pre-treatment prior to the filtration, the permeate water samples were now in Class II, which can be used for recreational purpose with body contact.

4.0 CONCLUSION

In this study, surface water was treated with a custom-made UF-HF membrane module and membrane testing rig. Overall, the custom-made membrane module was capable of good operational performance in treating surface water. It was found that TMP governed the specific permeate flux at an early stage of operation while feed water temperature influenced the operational performance. In terms of filtered water production, the system developed in this study demonstrated a higher rate of clean water production than a previous study.

The UF-HF membrane module showed good surface water treatment efficiency, improving the treated surface water from water quality index (WQI) Class III to Class II. Thus, the permeate water produced can be used for non-potable purposes.

From this study on surface water treatment in a short-term operation, it can be concluded that the the UF-HF membrane module is suitable for use in a mobile water treatment system which may be used in rural areas.

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