

# Numerical Estimation of Hollow Fiber Membrane for Mobile Water Treatment

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## Article history

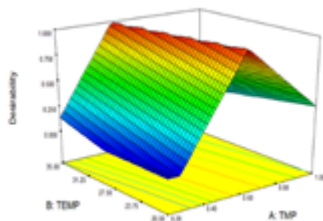
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## Graphical abstract



## Abstract

In the application of water treatment system, membrane has gained favour in the industry as well as in the research field. In pressure-driven category, ultrafiltration membrane with pore size of 3 to 10 nm is one of the choices for water treatment application. With the advantages of being compacted and self-supporting, hollow fiber membrane configuration has been widely used as ultrafiltration membrane. This is an important feature for a mobile water treatment system developed in this work. The mobile water treatment system is investigated in terms of its operational performance focusing for simple setup configuration. Mobility of the membrane treatment system in this work is aim to develop a stand-alone membrane water treatment system that can operates without electricity. Therefore, the system targeted to be a self-sufficient in rural areas where electricity and delivery of spare parts are difficult. A membrane filtration system with outside-in hollow fiber membrane is developed. The numerical approach of Response Surface Method (RSM) is used to estimate and optimize the flux performance in this work. The operating conditions i.e transmembrane pressure (TMP) as well as the local condition (water temperature) were considered in the numerical estimation. The initial numerical estimation found that the developed mobile system has permeate flux range from 0.422 L/m<sup>2</sup>h up to 3.035 L/m<sup>2</sup>h for local temperature of 20°C to 35°C and further optimization were discussed in this study.

**Keywords:** Hollow fiber; ultrafiltration; mobile water treatment operation; numerical estimation and optimization; response surface method

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## 1.0 INTRODUCTION

With the increasingly stringent standards of water and wastewater treatment, membrane filtration as emerged as strong contender compared to the conventional methods<sup>1,2</sup>. Not only that, membrane filtration becomes an attractive alternative to the conventional methods because it is not destructive separation process with low energy consumption, low capital cost and compacted design<sup>3</sup>. Amongst the membrane technology offered, pressure-driven membrane process is one of the best choice for water treatment. This is because, pressure-driven membrane is health hazard free and its permeation product is generally high<sup>4</sup>. Pressure-driven membrane process are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). In 1996, Japanese researchers<sup>5</sup> developed a new system featuring UF membrane filtration for water treatment plant which needed a smaller and little attention in Japan. The system has been proven to be successful in filtration as well as saving area and economical cost. Decades later, there are more

technology utilizing membrane in the water treatment application.

There are four membrane configurations regardless of the driving force which are flat-sheet, spiral-wound, hollow fiber and tubular<sup>6</sup>. Hollow fiber is stated as one of the common UF design<sup>7</sup>. This arrangement has advantages of low cost of investment and operation, easy flow control and cleaning and high specific surface area per unit volume<sup>7</sup>. Hollow fiber membrane itself has advantages over other configurations; highest packing density, ease of backwashing, compact and self-supporting<sup>8,9</sup>.

Lack of water sources is not the only reason for the high demand of water treatment nowadays. There are additional reasons such as non-uniform distribution of water resource and natural disasters<sup>10</sup>. These reasons required the water treatment not only be available in urban areas but as well as rural areas and disaster sites. For such area, a mobile or transportable membrane system will be a great asset.

In this study to design and develop a mobile water treatment (MoWT) system with the application of UF hollow fiber membrane technology. The mobile feature for the water treatment system refers to a small, stand-alone, transportable and independently-powered system. This term is different from the commercial term that usually refers water treatment system units in a big container lorry. Numerical approach was used in this paper to estimate and optimise the operational performance of the MoWT system. With the numerical estimation and optimisation of its operational performance, it would ease the further development of the MoWT system

## 2.0 EXPERIMENTAL

### 2.1 System Design

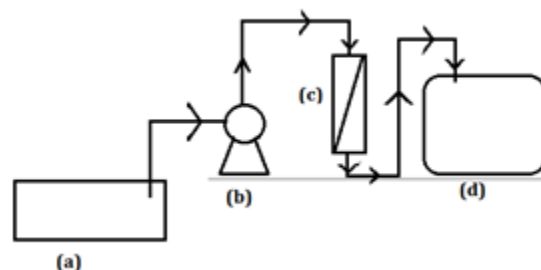
The utmost aim for the design of the mobile water treatment (MoWT) system is its mobility and water filtration efficiency. To ease the mobility and application of the system designed in targeted area i.e. rural area, the items and materials integrated into the system are kept simple and light-weight. Table 1 shows the list of items used to build and incorporated into the MoWT system. These parts were assembled in the arrangement as shown in Fig. 1. This arrangement was made for the ease of mobility of the unit when used. The focus of this study is on the effect of operating conditions (transmembrane pressure and cross-flow velocity)<sup>8,11,12</sup> and also the local conditions (feed water temperature)<sup>2</sup>.

**Table 1** List of parts used in the mobile water treatment system

Parts	Materials	Specifications	Other remarks
Body	Plywood	Size: 600 × 600 × 600 mm Thickness: 25 mm	
Body surface	Formica	ICA S 139 MF Size: 101.6 × 203.2 mm Thickness: 2 mm	Water proof and durable
Pump	Fujiyama DB125 Water Pump	Size: 25 × 25 mm Horsepower: 0.5HP Qmax : 2100 L/h Voltage: 240V (50 Hz)	Max. height: 24 m Max. suction: 9 m
Filter media	Hollow fiber membrane	Dimensions: 73 mm (dia.) × 254 mm (length) Average cut off: 0.01 – 0.1 μm Flow rate: 180 L/h Temperature: 4 – 40 °C	Hollow fiber membranes are assembled in U-shaped. Recommended TMP: ≤0.25 MPa
Permeate Storage	Gallon bottle	Material: Polyvinyl chloride (PVC) Volume: 20 L	
Mobility	Trolley wheels	Stainless steel	Fixed
Water flow control	Control valve	½ Galv. Valve	
Feed Water flow	PVC Check Hose	Diameter: 25mm Length: 30 mm	
Water flow	PVC pipe	Diameter: 25 mm Length: 125 cm	
Pipe connectors	V- socket	20 mm	Quantity: 4
		15 mm	Quantity: 2
	Nipple	1" × ¾"	Quantity: 2
		¾" × ¾"	Quantity: 2
	Tee	20 mm	Quantity: 2
L-elbow	20 mm	Quantity: 5	

### 2.2 Hollow Fiber Membrane

The hollow fiber membrane integrated into the MoWT system in this study is a commercially sold hollow fiber membrane cartridge. The cartridge was modified and put into a casing to make it as a membrane module. With the modification made, the inlet and outlet of the hollow fiber module now has connectors at both end. These connectors ease the installation of the module into the MoWT system as well as uninstallation. As mentioned in Table 1, the hollow fiber membrane bundle in the cartridge is potted in the U-shaped. It is basically cross-flow with double surface because it is 'folded'. The membrane operated with the outside-in mode of operation, where only permeate (clean water) is allowed to penetrate the membrane wall and exited at the outlet of the module.



**Figure 1** Schematic drawing for Mobile Water Treatment (MoWT) System where (a) reservoir or raw water feed, (b) water pump, (c) hollow fiber membrane module and (d) storage gallon

### 2.3 Mobile Water Treatment (MoWT) System Testing

A simple ultrafiltration test was conducted using the MoWT system unit to determine the permeate flux. The unit was assembled as shown in Figure 1 earlier. The flux, in L/m<sup>2</sup>h, was calculated using the equation below<sup>13</sup>:

$$J = \frac{Q_p}{A_m} \quad (1)$$

where  $Q_p$  is the permeate flow rate and  $A_m$  is the membrane area. When transmembrane pressure and membrane resistance are taken into account, the flux then can be calculated using the Hagen – Poiseuille equation<sup>7,13,14,15</sup>:

$$J = \frac{\Delta P}{\mu R_t} \quad (2)$$

where  $\Delta P$  is the transmembrane pressure,  $\mu$  is the water dynamic viscosity (dependent to temperature) and  $R_t$  is the membrane resistance coefficient. This equation has been used by many researchers especially in the study of fouling effect.

The unit was tested by filling up the storage gallon, first without the membrane to ensure all connections were in good condition and no leakage. For this study, three parameters (or variables in the software) were taken into account which are the transmembrane pressure (TMP), cross flow velocity and water temperature.

### 2.4 Estimations and Optimisation

Response surface method (RSM) collected the mathematical and statistical techniques that are useful for optimization<sup>16,17</sup>. This

method helps in understanding the interaction effects between factors and thus, number of total experiment runs can be reduced. In this study, RSM is applied by using Stat-Ease Design Expert 7.0 software to analyse and estimate the optimization for the MoWT unit. Particularly, RSM in this study is conducted based on central composite design (CCD).

As mentioned previously, only three factors were considered in this study: TMP, cross flow velocity and feed water temperature. Since ultrafiltration (pressure driven) hollow fiber membrane was used, TMP was set to be at low pressure range i.e. 0.2 to 1.0 kPa. For the feed water treatment, the range values taken were 20 to 35 °C based on the local temperature in Kota Kinabalu, Sabah area. While the cross-flow velocities were generated numerically from the permeate flow rate using both Equation (1) and (2) above. Table 2 lists the variables ranges used in RSM with actual and coded values.

## 3.0 RESULTS AND DISCUSSION

### 3.1 RSM and ANOVA

In RSM, the experimental data were analysed using ANOVA (analysis of variance). The experimental response model was achieved. It was found that Two-Factor Interaction (2FI) is the most suitable model for the experimental design of MoWT operational performance after the fit testing by the software was summarised. Analysing with ANOVA shown any significant and non-significant factors that may or may not influence the model. Table 3 shows the results from the ANOVA analysis where the Model F-Value is significant and there's only slight (about 0.01%) chance of large Model F-Value would occur.

**Table 2** Parameters ranges used in RSM with actual and coded values

Variables	Symbol		Coded Level			
	Actual	Coded	– $\alpha^a$	–1	+1	+ $\alpha^a$
Transmembrane Pressure	TMP	A	– 0.0727171	0.2	1.0	1.27272
Temperature	TEMP	B	13.1821	20	35	40.1134
Cross Flow Velocity	CFV	C	–0.00101137	0.000908723	0.006541238	0.00846134

<sup>a</sup>  $\alpha = 1.682$  (star or axial point for orthogonal CCD in the case of 3 independent variables)

**Table 3** Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value (Prob > F)
Model	9.761736	6	1.626956	15797119	< 0.0001
A-TMP	1.388893	1	1.388893	13485621	< 0.0001
B-TEMP	0.232955	1	0.232955	2261905	< 0.0001
C-CFV	0.003783	1	0.003783	36730.22	< 0.0001
AB	3.56E-08	1	3.56E-08	0.345276	0.5669*
AC	1.35E-08	1	1.35E-08	0.130745	0.7235*
BC	0.009139	1	0.009139	88737.37	< 0.0001
Residual	1.34E-06	13	1.03E-07	No data	No data

\* not significant

With ANOVA, the final equation for the model was determined and therefore, the model was developed. The response model of the MoWT operational performance analysis in terms coded and actual factors of permeate flux are:

$$Y = + 1.48 + 1.06*A + 0.33*B - 0.083*C + 3.724 \times 10^{-4}*A*B - 7.505 \times 10^{-5}*A*C + 0.25*B*C \quad (3)$$

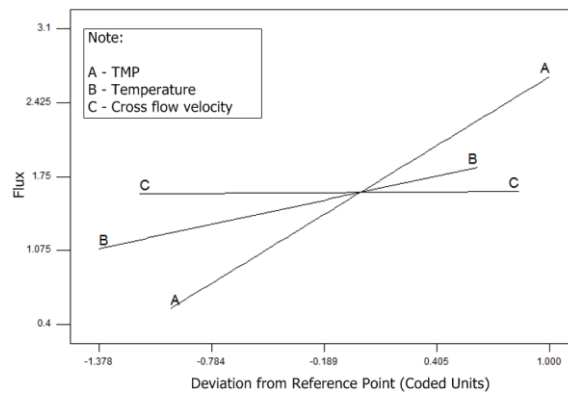
$$\text{Flux} = +9.29085 \times 10^{-4} + 2.64354 * \text{TMP} - 3.98111 \text{E-}005 * \text{TEMP} - 355.22196 * \text{CFV} + 1.24130 \times 10^{-4} * \text{TMP} * \text{TEMP} - 0.066625 * \text{TMP} * \text{CFV} + 11.84329 * \text{TEMP} * \text{CFV} \quad (4)$$

**3.3 Relationship of Operating Parameter to the Permeate Flux**

The relationship of the operating parameter to the permeate flux in the MoWT operational performance was shown in the Figure 2 below. From the figure, it is obvious that TMP has linear correlation with permeate flux. This has been proven by other researchers<sup>2,18</sup> where as long as the TMP does not exceeded 0.12MPa, it relationship between TMP and the permeate flux will maintain to be linear in the Darcy’s Law region. It must be noted that increasing TMP would increase the occurrence of membrane fouling<sup>2,11</sup>.

The temperature also shown linear relationship with the permeate flux. Such increment has been observed where the

permeate flux increased by 1.18 times when the temperature was increased by 5°C<sup>2</sup>. However, in the case of MoWT system in this study, there were no significant increment observed due to temperature changes. As for the cross-flow velocity, it is shown that only relatively small effect (approximately - 0.085) was produced to the permeate flux. Therefore, for contouring purpose (shown in Figure 3a), only TMP and temperature were taken into consideration and cross-flow velocity was considered as constant. This interaction was further analysed using 3D surface as shown in Figure 3b. Though the permeate flux gradually increases with increase of TMP and temperature, it can be seen that TMP and temperature has inversely proportional relationship. It can be said that for any given temperature, higher TMP gives higher yield. However, that is simply not the case because other factors such as fouling and concentration polarization of membrane have not been taken into account yet.



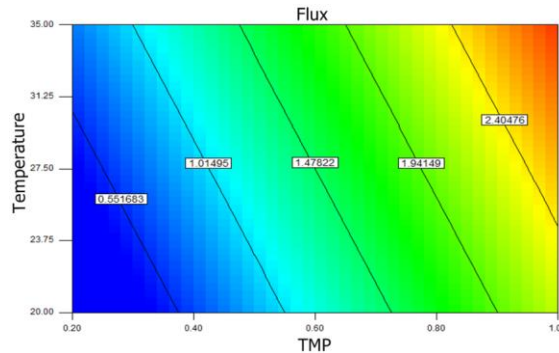
**Figure 2** Relationships between every operating parameters (taken into account in this study) to permeate flux

**3.4 Estimation and Optimisation of MoWT Operation Performance**

After the data had been analysed, future operational performance of the mobile water treatment (MoWT) system can be estimated and thus optimized. As mentioned earlier, the cross-flow velocity in the MoWT operational performance has relatively small effect. Therefore, it is kept constant. In Figure 4, it is shown for temperature of 30.03°C (normal local

temperature) and TMP of 0.6 kPa, the flux produced is estimated to be 1.59 L/m<sup>2</sup>h. For any operating conditions set as well as the influence of local conditions (such as temperature), RSM can estimate the response such as permeate flux.

Optimisation was determined by the software through regression analysis. For this study, the permeate flux was targeted to achieve maximum permeate flux i.e. 3.035 L/m<sup>2</sup>h. This value is based on initial estimation using the both equations above.



**Figure 3a** Interaction between TMP and feed water temperature in the MoWT system. The cross flow velocity was kept constant at 0.00372498 m/s

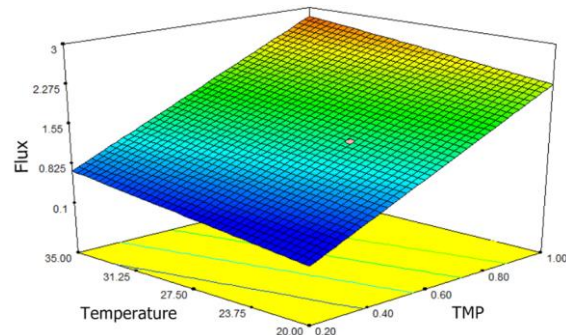


Figure 3b 3D graph response surface plotted on TMP and temperature on permeate flux

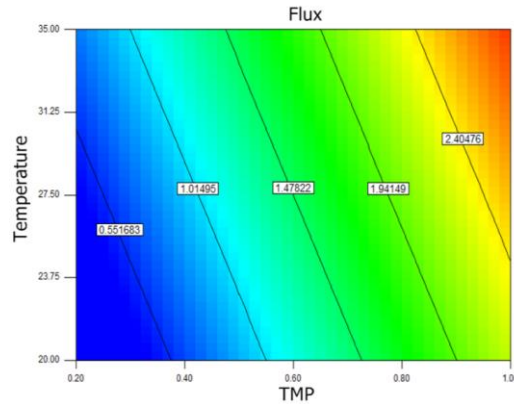


Figure 4 Estimation of MoWT system permeate flux with design expert software

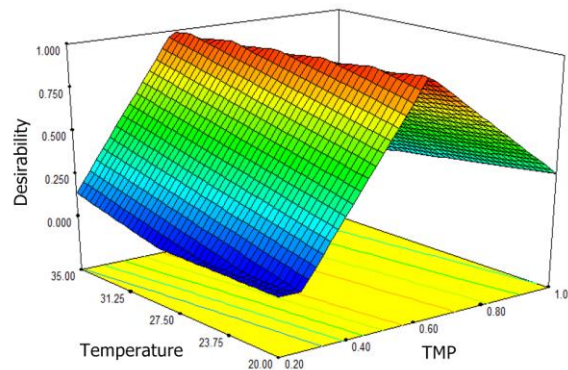


Figure 5 Optimisation of the MoWT system operational performance

The RSM optimisation in this software is presented by desirability. Since the maximum permeate flux of  $3.035 \text{ L/m}^2\text{h}$  was the target to be achieved in this optimisation, desirability of 1.00 (full scale) represented the maximum permeate flux. As can be observed in Figure 5, the red region at the peak is the highest desirability of 1.00. Therefore, this has shown that it is possible to obtain maximum permeate flux for the MoWT system. In order to get the highest yield, the estimated optimised region for the MoWT operation where the TMP was shown to be ranging between 0.45 and 0.63 kPa. This range of value was good enough since it was proven during the experimental work, too high of TMP could caused leakage to the system and even to the in-house fabricated membrane module. Lower TMP values however, would have low permeate flow rate therefore the time taken to obtain desired volume of clean water may be dragged longer.

#### 4.0 CONCLUSION

With numerical approach of Response Surface Method (RSM), estimation and optimisation of mobile water treatment (MoWT) system operational performance were able to be achieved. Initially, it was estimated that the permeate flux ranges from  $0.422$  to  $3.035 \text{ L/m}^2\text{h}$  with varying transmembrane pressure (TMP), feed water temperature and cross-flow velocity. From three parameters considered, two were shown to be significant which were transmembrane pressure and feed water temperature. Further optimisation was conducted and optimum TMP range was found to be 0.45 to 0.63 for feed water temperature of 20 to  $35^\circ\text{C}$ .

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