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Impact of Process Control Devices on the Performance of Ultrafilter Membrane in Clean Water Production

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ABSTRACT

This paper aims to publish an experimental finding addressing ultrafilter membranes' higher energy consumption rate (UFM) in producing clean water. The novelty of the research published in this paper is to establish the contribution capability of process control devices (PCD) in reducing the energy consumption rate of UFM and the effect of PCD on the overall performance of UFM in producing clean water (SDG6). The novelty of the research published in this paper is to establish the contribution capability of PCD in reducing the energy consumption rate of UFM and the effect of PCD on the overall performance of UFM in producing clean water (SDG6). An experiment has been conducted with a UFM to answer the question. The UFM plant operated with and without process control devices to evaluate the impact of the process control devices on energy consumption rate [kW/m^3] in producing clean water. Experiments revealed that process control devices are positively associated with energy consumption rate and contributed to reducing 44% of energy consumption in clean water production. This research disclosed that process control devices have contributed to an increase of 38% in the efficiency of the UFM in clean water production. Research outcomes have several implications in the water industry, engineering, and policy implementation domains relating to process control devices in water treatment. From our findings, further research should continue using process control devices for the water treatment plants to increase overall performance and contribute to achieving sustainable development goals (SDG).

1. Introduction

This paper presents experimental research outcomes that unlock the effect of a few plant operating factors on the overall performance of Ultra-filtration membrane (UFM) in producing clean water [1,2]. Membrane filtration is an advanced water treatment process that attracted attention because of its economic benefits [2,3]. Among the membrane family, the UFM has potential due to its simple design, less energy consumption, and minimum capital investment. A myriad of research studies in this field have disclosed the factors responsible for the performance of UFM [4-6]. The

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mode of UFM plant operations has also appeared as a factor in achieving performance. The potential factors are the quality of feed water, plant operating time, and plant cleaning efficiency. All these factors are associated with energy consumption, plant maintenance frequency, the life cycle of UFM modules, and water production cost. Indeed, optimizing factors could be vital in achieving the required performance [3,7]. With this background, this study revealed the optimum operating conditions of UFM to achieve sustainable performance by reducing energy consumption and the cost of plant operation for producing clean water at an affordable price.

1.1 Problem Statement and Research Objectives

Climate change and geopolitical instabilities present a formidable challenge to the fulfillment of clean water demand across the globe. This reality forces researchers and engineers to scale the problem from various perspectives across many disciplines. Some groups look towards diversifying the source of raw water for treatment. An example of this is the work done by Mirmanto *et al.,* [8], which attempts to improve the quantity of water produced by the evaporation coil of a device operating on a refrigeration cycle. Some, on the other hand, are working on improving desalination technology within the context of reducing its reliance on fossil fuels to power the boilers [9]. Others focus their efforts on improving individual subprocesses of the water treatment system, such as evaluating the feasibility of banana peels as a flocculating agent [10].

Studies on clean water production using UFM have established a relationship between energy consumption rate and productivity in water production. Research findings demonstrate that the energy consumption rate in clean water production by UFM has played a vital role in managing the water crisis. Various studies reveal that the clean water crisis partially relates to the poor productivity of plant machinery due to the lack of process control devices in the production process. A few researchers have confirmed that UFM plants operate continuously, and a certain amount of product water is discharged through the overflow pipe due to a lack of water level sensors in the water tank and speed controller for the pump. This statement has raised the question of 'What is the effect of water level sensors on the energy consumption rate [kW/m^3] of a UFM system when operating to produce clean water?' This research project has been undertaken to answer the question stated.

The broad objective of this research is to determine the optimum operating conduction of the UFM system. The experiment is divided into two specific objectives to achieve the research goal. First, to determine the energy consumption rate of UFM's feedwater pump when the plant operates without process control devices. Second, to estimate the energy consumption rate of UFM's feedwater pump when the plant works with process control devices. Third, to evaluate the impact of process control devices on the UFM's energy consumption rate and overall performance.

1.2 Novelty of Research

The novelty of the research published in this paper is to establish the contribution capability of process control devices (PCD) in reducing the energy consumption rate of UFM and the effect of PCD on the overall performance of UFM in producing clean water (SDG).

2. Literature Review on Performance of Ultrafilter Membrane

The UFM is a low-pressure driven system widely used in water treatment for producing potable water, cooling water for power plants, and processing water for food and chemical industries. UFM membrane has been installed at the secondary and tertiary levels in the water treatment system

[11,12]. A few indicators have been used for measuring the UFM's performance in producing clean water; the indicators are permeate flux rate, efficiency in separating TSS and pollutants from feed water, energy consumption rate [kW/m^3], and productivity in clean water production [13,14]. Chemical oxygen demand (COD), Biological oxygen demand (BOD), and water-born bacteria separation capability have also been used to measure the performance of UFM [15-17].

2.1 Measuring the UFM's Performance in Permeate Flux Yield

A few researchers have used the input-output water production model to measure UFM's performance. The standard model is present in Eq. (1) [15,16,18,19].

$$J = K\frac{\Delta P}{t} \quad (1)$$

Here, J is the permeate flux, ΔP is the feed pressure difference across the membrane, t is the membrane thicknesses and K is the efficiency factor of UFM. Singh & Hankins [18], and Ghidossi & Daorelle [20] also used a similar model for measuring the UFM's performance. The performance of the UFM membrane in clean water production also depends on the cake layer formation on the membrane. The cake layer increases transmembrane pressure (TMP) and contributes to a decrease in the permeate flux [1,21].

Anis *et al.,* [22], Giakoumis *et al.,* [23], Weber *et al.,* [24], Singh & Hankins [18], and Ramli & Bolong [16] demonstrate that pore size, the thickness of the membrane, and transmembrane pressure (TMP) have a significant role that affects the performance of UFM. A similar argument has been made by Karabelas & Sioutopoulos [25]. The permeate flux for the transmembrane pressure is present in Eq. (2).

$$J_w = \frac{1}{A}\frac{dV}{dt} = \frac{[\Delta P]}{\mu[R_m + R_c]} \quad (2)$$

Here, J_w is the permeate flux $(L\, m^{-2}h^{-1})$ or m/s. R_m is the membrane resistance and R_c the cake resistance. Δp presents effective transmembrane pressure (TMP) (Pa). μ is the viscosity $(Pa \cdot s)$ of the feed stream. In this regard, Zirehpour & Rahimpour [15], Ramli & Bolong [16], and Yangang *et al.,* [26] suggested that lower cake layer resistance can be achieved by keeping a high crossflow rate of backwash water through the membrane, which would shear the cake layer formed on the membrane surface. Hong Tek [27] disclosed that the filtration efficiency increases with the operating pressure up to the optimum pressure level, and when the operating pressure goes higher than that level, the performance could start to decrease [28]. In this regard, Zirehpour & Rahimpour [15], Ramli & Bolong [16], and Yangang *et al.,* [26] suggested that lower cake layer resistance can be achieved by keeping a high crossflow rate of backwash water through the membrane, which shears the cake layers formed on the membrane surface.

2.2 Measuring the UFM's Performance by Efficiency in Permeate Flux Production

Zirehpour & Rahimpour [15], Ramli & Bolong [16], and Yangang *et al.,* [26] have used efficiency (η-water recovery in percentage) to measure the performance of UFM as expressed in Eq. (3).

$$\text{Efficiency}, \eta\ (\%) = \frac{\text{Permeate flow } (Q_P)}{\text{Feed flow } (Q_f)}\, x\ 100\% \quad (3)$$

2.3 Measuring the UFM's Performance by Productivity in Permeate Flux Production

Yangang *et al.,* [26] and Wang *et al.,* [17] have used productivity to measure the performance of the membrane. The productivity is present in Eq. (4) [29].

$$\text{Productivity } \left(J_p\right) = \frac{Q\left(\frac{L}{h}\right)}{A_m} \tag{4}$$

Here, J_p is a productivity indicator. Q_p stands for clean water output (litre per hour). A_m - the surface area of the membrane in square meters (A^2). Productivity is the rate of mass flow concerning the permeate flux through the cross-sectional area of UFM [17,26]. Lawrence *et al.,* [30], and Ramli & Bolong [16] have also used productivity to evaluate the performance of the membrane.

2.4 Measuring the UFM's Performance by Energy Consumption Rate

Energy consumption rate in clean water [kW/m^3] production was used for measuring the performance of UFM. Li *et al.,* [31] and Ana *et al.,* [32] also undertook a pilot study to evaluate the performance of UFM with energy consumption concerning the permeate flux [kW/m^3]. Eq. (5) presents a model for measuring the energy consumption of a membrane in water production.

$$P\left(\frac{\mathrm{kW}}{\mathrm{m}^3}\right) = \frac{QP}{\eta_{\mathrm{pump}}} \tag{5}$$

Here P is the power consumed by pumps. Q (m^{3}h^{-1}) is the feed water flow passing through the membrane at a pressure P. A series of R&D was performed to optimize the energy consumption [kW/m^3] by reducing TMP. The findings of this R&D demonstrate that the energy consumption rate in UFM could decrease by installing efficient pre-treatment [33-36]. Also, it has been discovered that the UFM system is an economical, sustainable, and environmentally friendly water treatment process due to a lower energy consumption rate [20,31,37,38]. The conclusion is that efficiency, productivity, and energy consumption rate per unit of water production are the indicators used to measure the performance of UFM.

2.5 Measuring the UFM's Performance by the Effect of Feed Water Pressure on Permeate Flux Production Yield

A few reports demonstrated that feed pressure is a factor that affects the performance of UFM. Vishali & Kavitha [39] observed that feed water pressure has a positive impact on the water production performance of UFM [39,40]. Figure 1 presents the effect of feed pressure on the permeate flux of this membrane.

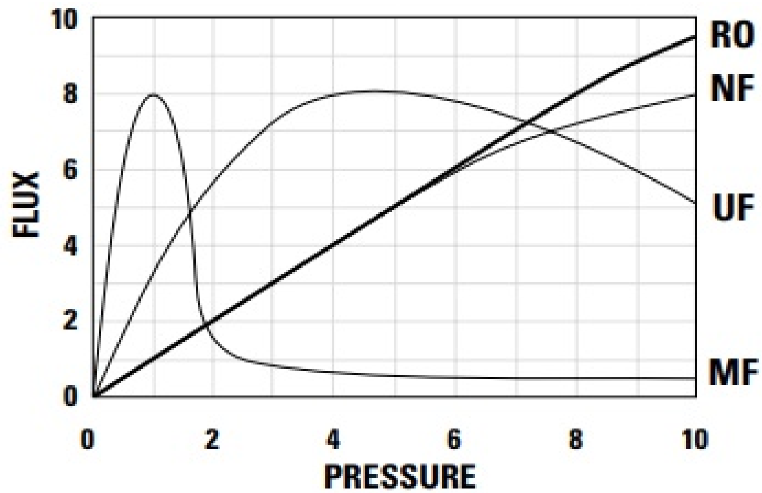

Fig. 1. The effect of feed pressure on permeate flux of UFM [19]

According to Figure 1, permeate flux increases with feed water pressure, and after attaining optimum value, flux starts to reduce. In similar studies, Lise *et al.,* [41]; Azmi *et al.,* [42] and Tansel *et al.,* [43] it was revealed that permeate flux increases with feed pressure up to the optimum level. Furthermore, it also discovered that the effect of feed water pressure on TDS separation by UFM is insignificant (p-value > 0.05). On the other hand, the TSS separation appeared to be significantly higher (p-value ≤ 0.05) [44,45]. Moreover, Yunos *et al.,* [46] and Wu *et al.,* [47] disclosed that the permeate flux of UFM increased to an optimum level with an identified feed pressure [46,47]. These findings suggested that feed pressure affects the performance of UFM.

2.6 Measuring the UFM's Performance by the Effect of Using Process Control Device on Permeate Flux Yield

Paulen & Fikar [48], Bernhard & Uwe [49], and Huang *et al.,* [50] discovered the impact of the process control device on the performance of UFM. Appels *et al.,* [51] installed a process control device in the UFM plant to optimize permeate flux and energy consumption rate by controlling the factors that affect performance.

A few researchers also used process control devices to optimize the permeate flux, energy consumption, and operating cost [32,52,53]. Research findings concluded that a real-time monitoring technology with a process control device could effectively contribute to removing colloidal and nanoparticles from the feed water. Thus, a real-time monitoring-based process control device contributes to optimizing permeate flux, energy consumption, and operating cost.

Ghidossi *et al.,* [20] experimented with the UFM plant to develop a model for measuring energy consumption. Findings revealed that pumps installed for feed water and membrane backwash were potential energy-consuming components. Li *et al.,* [31] revealed that pumps installed for membrane cleaning consumed a significant part of total energy. Optimizing energy consumption, Aditya *et al.*, [54], Chang *et al.,* [55], and Chon *et al.,* [2] installed an efficient pre-treatment system for UFM and discovered that macro and microfiltration was effective in removing foul elements from feed water, which contributed to reducing energy consumption.

Zambujo conducted a similar experiment and discovered that pumps used for feed water and backwash consumed the maximum energy, which could be 1 kW/m^3, due to an inefficient pre-treatment [56].

2.7 Measuring the UFM's Performance by Operating Cost in Clean Water Production

Samaco [1] and Nguyen *et al.,* [57] revealed that the operating cost of UFM in producing clean water potentially depends on energy costs. According to their research findings, the operating cost for UFM depends on a few primary factors. Energy expenditure, chemicals used for membrane cleaning, and plant maintenance are the main costs. Nguyen *et al.,* [57], Yoo *et al.,* [3], and Jamalinezhad *et al.,* [14] concluded that at an optimum plant operating condition, operating costs would be within 11.2% of the total water production cost.

The literature review findings conclude that permeate flux rate [m^3/hour], energy consumption rate [kW/m^3], efficiency, and productivity in permeate flux production are the indicators of measuring the performance of the UFM plant. This study also revealed that efficient pre-treatment for feedwater would improve the performance of UFM to achieve a sustainable clean water supply (SDG6).

3. Methodology

3.1 Research Methodology and Experimental Setup

The experiment setup aims to measure the effect of process control devices on the energy rate in clean water production. The experiment was conducted in two phases. The first phase of the experimental setup is present in Figure 2.

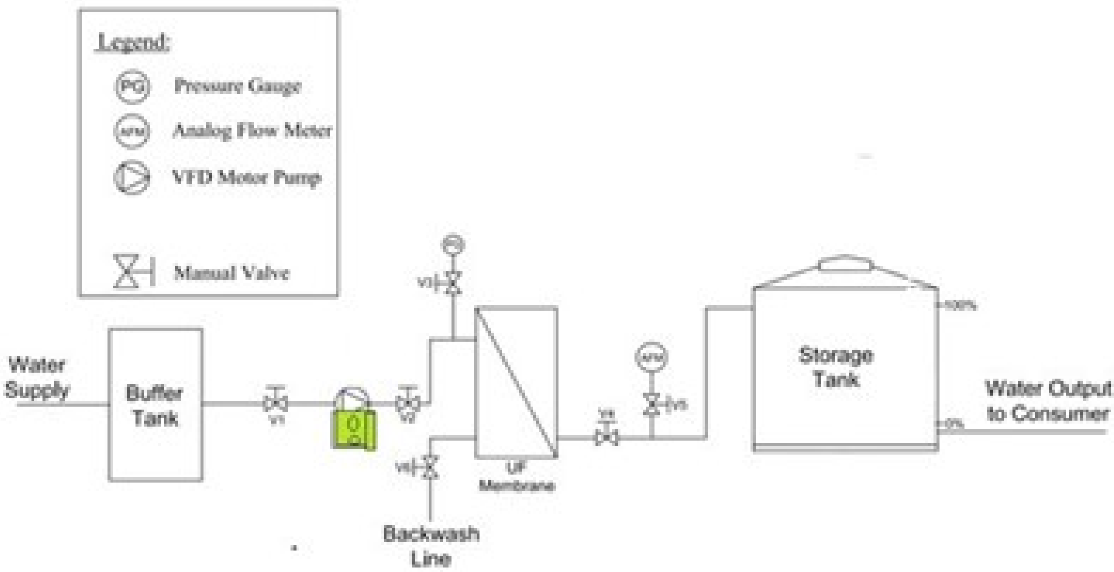

Fig. 2. Experiment with level sensors in the water tank

The equipment used in the first phase experiment was a feed water pump, UFM, product water storage tank, and pressure indicators. The second phase experimental setup is present in Figure 3.

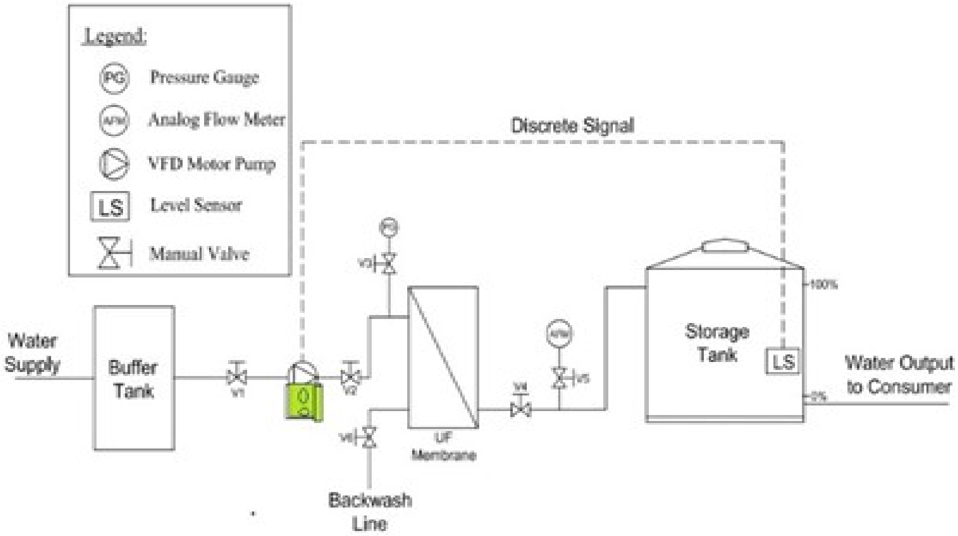

Fig. 3. Experiment with level sensors in the water tank

The equipment used in the second phase experiment was a feed water pump, UFM, product water storage tank, level sensor, level controller with feedback system, variable-frequency drive (VFD), and pressure indicators. The experimental runs were 14.

The data collection sequence for each run was 1/2 hour for 14 experimental runs. The total time for 14 experimental runs was 7 hours. Every experiment was repeated 8 times. In data analysis, statistical techniques SPSS and Excel software were used to eliminate the outlier data.

3.2 Theoretical Framework

The energy consumption rate [kW/m^3] of UFM depends on the volume of water produced (m^3) and the duration (time) of water production. The average energy consumption rate (E_{avr}) over time can be estimated from Eq. (6).

$$E_{avr} = \frac{\sum_j^n E_j}{n}\ (\mathrm{kW/m^3}) \tag{6}$$

Here, E_j -energy consumption rate of UFM's feed water pump. 'n' is the number of repeats of the same amount of water production from a UFM plant (n>1). Variable j= 1, 2, 3,…, n. Average energy consumption (E_{ave}) over the entire production period or experimental runs (Ø) can be estimated from Eq. (7).

$$E_{ave} = \frac{\sum_i^{Ø} \mathrm{E_{ave}}}{Ø}\ (\mathrm{kW/m^3}) \tag{7}$$

Here, Ø is the number of the total experimental runs, and its value is more than one (Ø > 1). The range of variable i is, i = 1, 2, 3,…, Ø. The total water outputs (Q_t) of UFM's pump can be estimated from Eq. (8).

$$Q_t = Q_{\mathrm{out}} \times Ø\ (\mathrm{m^3}) \tag{8}$$

Total energy consumption (E_t) during an identified quantity of water production (Q_m^3) can be estimated from Eq. (9).

$$E_t = E_{ave}\ (\mathrm{kW/m^3}) \times Q_{t1}\ (\mathrm{m^3}) = E_{ave} \times Q_{t1}\ (\mathrm{kW}) \tag{9}$$

Here, Q_{t1} is the total water output from an identified experimental run during UFM's plant operation. The required water production and supply rate Q_{t2} (m^3/hour), can be estimated from Eq. (10).

$$Q_{t2} = \frac{\beta \times \text{Water demand}}{\text{No of the experiment runs}} \tag{10}$$

Here, β is the safety factor of water demand (β = 1.1). Pump speed (RPM) and pump output (Q_{t2}) can be estimated from Eq. (11) [52].

$$\frac{Q_{t2}}{Q_{t1}} = \frac{N_2}{N_1} \tag{11}$$

The impact of process control devices on energy consumption (ΔE) can be estimated from Eq. (12).

$$\Delta E = E_{t(\mathrm{oc})} - E_{t(\mathrm{wc})} \tag{12}$$

Here, $E_{t(\mathrm{wc})}$ – energy consumption of UFM's pump when operating with the process control devices, while $E_{t(\mathrm{oc})}$ – energy consumption of UFM's pump when operating without the process control devices. The impact, in percentage, can be computed using Eq. (13).

$$\Delta E\ (\%) = \frac{E_{t(\mathrm{oc})} - E_{t(\mathrm{wc})}}{E_{t(\mathrm{oc})}} \times 100\% \tag{13}$$

The efficiency of UFM can be estimated from Eq. (14),

$$\eta = \frac{\text{Water used by end users}}{\text{Clean water produced by UFM}} \times 100\% \tag{14}$$

Here, η is the efficiency of UFM in producing clean water. The impact can be measured by estimating Eq. (15).

$$\Delta\eta = \eta_{\mathrm{oc}} - \eta_{\mathrm{wc}} \tag{15}$$

Here, η_{oc} – efficiency of UFM in producing clean water when operating without process control devices. η_{wc} – efficiency of UFM in producing clean water when operating with the process control devices. Eq. (6) - (15) can be used to analyse the experimental data to achieve the research objective.

4. Results and Discussion

4.1 Measuring Energy Consumption of UFM when Operate without Process Control Devices

This is conducted to characterize the energy consumption pattern of UFM's feedwater pump when operating without process control devices. The experimental set-up of phase 1 is presented in Figure 1. UFM, a feed water pump, and a product water storage tank are the equipment used for experiments. The water storage tank size was 2.0 m^3 and connected with water end users. The pump capacity was 2.0 m^3 at 1500 RPM. The water consumption rate by the end users was 10.0 m^3 for 7 hours from 8:00 am to 3:00 pm. The experimental run was 14, and the data collection rate was 0.5 hours per experimental run. Experimental runs (Ø) and time spent to experiment are presented in Table 1.

Table 1
Distribution of experimental runs and duration of the experiment

ϕ	Duration of experiment	No. of experimental repeats (*n*)	The total duration of the experiment
1	08:00-08:30	8	
2	08:30-09:00	8	
3	09:00-09:30	8	
4	09:30-10:00	8	
5	10:00-10:30	8	
6	10:30-11:00	8	
7	11:00-11:30	8	7 hours daily
8	11:30-12:00	8	
9	12:00-12:30	8	
10	12:30-13:00	8	
11	13:00-13:30	8	
12	13:30-14:00	8	
13	14:00-14:30	8	
14	14:30-15:00	8	

In data analysis, statistical techniques SPSS and Excel software were used to eliminate the outlier data. The experimental data were used to estimate Eq. (6) and (7), which are listed in Table 2. Table 2 shows that the average water production Q_{out} is 1 m^3. The total permeate flux over 14 experimental runs is 14 m^3, according to Eq. (8).

Table 2
Data when the plant operates without process control devices

ϕ	Q_{in} (m^3)	Q_{out} (m^3)	$E_{\mathrm{avr(oc)}}$ $(\mathrm{kW/m}^3)$	$E_{\mathrm{ave(oc)}}$ $(\mathrm{kW/m}^3)$
1			0.54	
2			0.56	
3			0.55	
4			0.56	
5			0.55	
6			0.56	
7			0.54	
8	1	1	0.55	0.55
9			0.57	
10			0.54	
11			0.53	
12			0.56	
13			0.56	
14			0.55	

The experimental run and energy consumption rate are present in Figure 4.

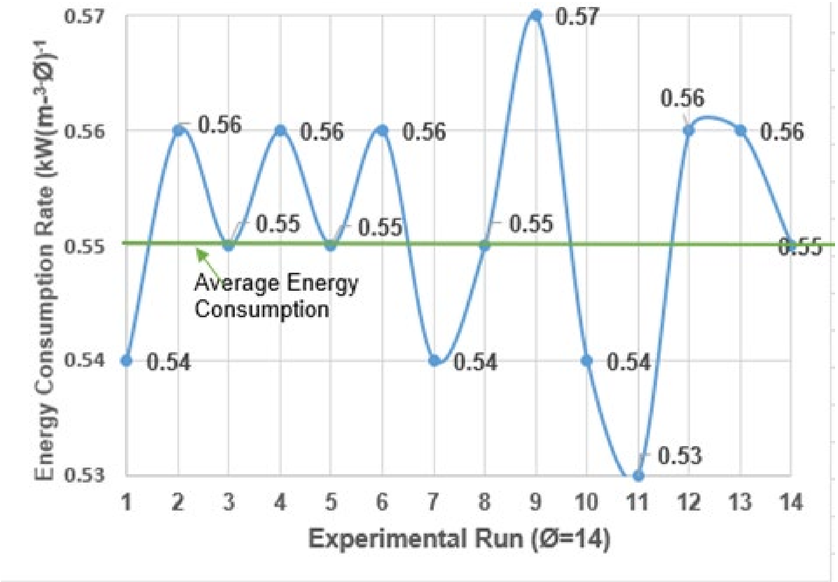

Fig. 4. Energy consumption pattern of UFM's pump when operating without process control devices

Figure 4 and Table 3 demonstrate the average energy consumption pattern of UFM's pump. The total energy consumption of the UFM is listed in Table 3. Using Eq. (9), the energy consumption is estimated to be 7.7 kW.

Table 3
Average energy consumption and efficiency by the UFM without PCD

Equation	Data source	Result
Required water output from UFM, i.e., Eq. (8)	Table 2	$Q_t = 14\ \text{m}^3$
Total energy consumed by UFM, i.e., Eq. (9)	Table 2, Table 3	$E_t = 7.7\ \text{kW}$
The efficiency of UFM, i.e., Eq. (14)	Table 3	$\eta_{oc} = 71.4\%$

This finding demonstrates that the UFM produces 14.0 m^3 of water in 7.0 hours, and the end users consumed only 10.0 m^3 at the 7.7 kW energy consumption. The wastewater amount is 4 m^3 or 40% of the total production at an efficiency of 71.4%. Water wastage was as the pump operated for 7 hours at full capacity due to the lack of a pump speed (RPM) control device.

4.2 Energy Consumption of UFM's Pump when Operated with Process Control Devices

The result of the experiment stated in section 4.1 demonstrates that the wastage of product water is about 40%. The experiment was designed with a variable frequency drive (VFD) for speed control of the pump and water level sensors in the water tank. Then, the required water production rate to meet the water demand (Q_{t2}) at zero waste (only 10.0 m^3 for 7 hours at $\beta = 1.1$), Eq. (10) was estimated to be 0.78 m^3. Next, solving Eq. (11) for N_2 lets us know the required pump speed to produce the 0.78 m^3 of water, which is $N_2 = 1170$ RPM.

The schematic diagram Figure 3 presents the experimental setup with process control devices. The experimental setup is equipped with one set UFM, feed water pump, product water storage tank, VFD, and water level sensors. The capacity of the tank was 2.0 m^3 at a height of 1.8 m. A water overflow pipe was installed in the water storage at 1.8 m height. The level sensors were installed at 1.8 m (HLS) and 0.2 m (LLS) of the water storage tank. The water tank was connected to the water end users. The experimental run, duration of the experiment, and experimental time are present in

Table 1. The experimental data were used to estimate Eq. (6) and (7), which are presented in Table 4. Note that all quantities in Table 4 are given per number of total experimental runs, i.e., ϕ^{-1}.

Table 4
Data when the plant operates with a process control device at 1170 RPM

ϕ	Q_{in} [m^3]	Q_{out} [m^3]	$E_{\mathrm{avr(wc)}}$ [kW/m^3]	$E_{\mathrm{ave(wc)}}$ [kW/m^3]
1	0.78	0.4	0.42	0.425
2	0.78	0.5	0.43	
3	0.78	0.6	0.43	
4	0.78	0.8	0.42	
5	0.78	0.9	0.42	
6	0.78	1	0.43	
7	0	0.9	0	
8	0.78	0.8	0.42	
9	0.78	0.8	0.42	
10	0.78	0.8	0.43	
11	0.78	0.7	0.43	
12	0.78	0.6	0	
13	0.78	0.5	0.42	
14	0.78	0.4	0.43	

Here, Q_{in} [m^3] is the flow rate of water into the tank from UFM in an experimental run, Q_{out} [m^3] is the water supplied to end users, $E_{\mathrm{avr(wc)}}$ [kW/m^3] is the average energy consumption by UFM's pump for each experimental run, and $E_{\mathrm{ave(wc)}}$ [kW/m^3] is the average energy consumption by the UFM's pump during the entire experiment. The energy consumption pattern is presented in Figure 5.

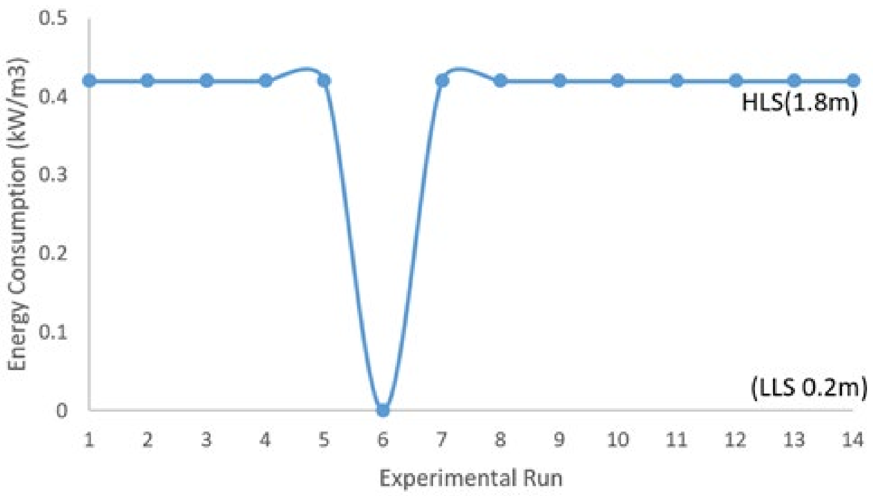

Fig. 5. Energy consumption pattern with the process control device

Figure 5 demonstrates that the total pump operating time in a cycle was 6.5 hours. At the experimental run, the UFM's pump did not operate as the tank at HLS was full of water. The total energy of the UFM is presented in Table 5. Using Eq. (9), the total energy consumption of UFM with PCD is computed as 5.52 kW. Then, using Eq. (14), the efficiency of water production with PCD is estimated to be 96%.

Table 5
Average energy consumption and efficiency by the UFM with PCD

Equation	Data source	Result
Required water output from UFM, i.e., Eq. (8)	Table 4	$Q_t = 10.1\ \mathrm{m}^3$
Total energy consumed by UFM, i.e., Eq. (9)	Table 4, Table 5	$E_t = 4.3\ \mathrm{kW}$
The efficiency of UFM, i.e., Eq. (14)	Table 5	$\eta_{\mathrm{wc}} = 98.6\%$

The average energy consumption rate was 0.425 kW/m^3 - presented in Table 5 - over the 6.5 pump operating hours. Eq. (3) - (4) are estimated to determine total energy consumption during 6.5 hours of plant operation. Eq. (8) is estimated to determine the required water flow $Q_{t(\mathrm{wc})}$.

Table 5 and Figure 5 are presenting the outcomes of research when conducted with process control devices. The research findings demonstrate that with the use of process control devices, the pump operating period was reduced by 0.5 hours in a set of experiments (14 experimental runs), which contributes to a decrease in energy consumption rate and water wastage.

4.3 Impact Evaluation of Process Control Devices on UFM's Energy Consumption and Overall Performance

Evaluating the impact of process control devices on UFM's energy consumption is estimated by Eq. (12). The findings are presented in Table 6. Importing the value of $E_{t(\mathrm{wc})}$ and $E_{t(oc)}$ from Eq. (13) and then to Eq. (12), the impact ΔE, is calculated to be $\Delta E = (7.7 - 4.3)\ \mathrm{kW} = 3.40\ \mathrm{kW}$.

Table 6
Impact analysis in energy consumption of the UFM

Equation	Data source	Result
Impact of the process control device on energy consumption ΔE, i.e., Eq. (12)	Table 3	$\Delta E = 4.3\ \mathrm{kW}$
Impact of the process control device on overall efficiency $\Delta\eta$, i.e., Eq. (14)	Table 3, Table 5	$\Delta\eta = 27.2\%$

Impact *ΔE* (3.40 kW) demonstrates that the process control devices have contributed to reducing 3.40 kW of energy (44.15%) in producing 10.14 m^3 water. These findings indicate that when UFM's pump operates with process control devices, the system can reduce 44.15% of energy consumption, and 40% of water wastage by increasing 27.2% of overall efficiencies compared to the UFM plant operation without process control devices. This research concludes that process control devices have contributed to increasing UFM's performance in clean water production by reducing energy consumption and water wastage.

4.4 Scenario Analysis of Research Findings

Several research findings reveal that the UFM's performance in clean water production and energy consumption depends on feed water pressure and the effectiveness of the process control devices (ref). The overall performance of the UFM is also dependent on the process control devices. Research findings listed in this paper demonstrate that the energy consumption rate in clean water production is 0.56 kW/m^3 and 0.425 kW/m^3 respectively when the plant operates with and without process control devices. This scenario is presented in Figure 6.

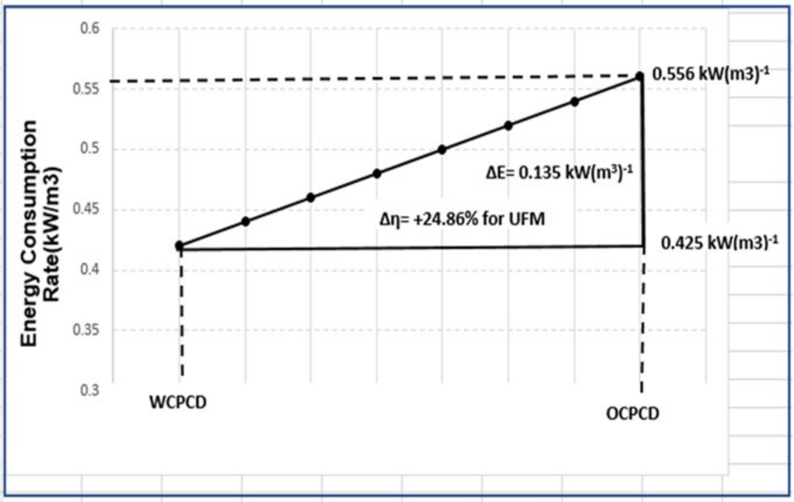

Fig. 6. Energy consumption rate in conjunction with pump's RPM

Here, WCPCD represents a plant operated with PCD. On the other hand, OCPCD represents for a plant operated without PCD. Figure 6 demonstrates that the process control devices have allowed the UFM plant to operate within scopes that reduce the energy consumption rate (24.28 %) and water wastage in producing clean water. This study has also revealed that process control devices are positively associated with the UFM's efficiency and productivity in clean water production.

5. Conclusion

This paper analysis experimental data that addressed a problem of higher energy consumption rate and poor performance of ultrafilter membrane (UFM) in producing the clean water. Research findings listed in this paper demonstrate that the energy consumption rate in clean water production is 0.56 kW $(m^3)^{-1}$ and 0.425 kW $(m^3)^{-1}$ respectively when the plant operates with and without process control devices.

The outcomes of this experimental research are:

i. A method has been developed to reduce energy consumption rates, which could decrease carbon emission rates in achieving environmental sustainability (SDG13);
ii. Development of a method of reducing clean water wastage, which could contribute to achieving a sustainable clean water supply for all (SDG6);
iii. A technique has been established to increase economic performance (SDG8) in water treatment by increasing productivity efficiency in clean water production (SDG 12)

The research outcomes have several implications in the water industry, engineering, and policy implementation domains relating to the use of process control devices in water treatment, especially in UFM systems. Regarding the research outcomes listed in this paper, it could conclude that further research shall continue on the use of process control devices for the water treatment plants to increase overall performance and contribute to achieving the Sustainable Development Goal (SDG).

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