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Submerged hollow fiber membrane system is widely used in water and wastewater treatment plants. One of the major problems of the microfiltration/ultrafiltration (MF/UF) process is membrane fouling. Few techniques have been developed to reduce membrane fouling and increase critical flux of the filtration process. In this study, membrane vibration was applied to improve the critical flux in a submerged hollow fiber MF system. A bench scale unit was especially built for this purpose and different vibrating speed was tested. The effect of the feed concentration and vibrating speed on the critical flux measurement were investigated. The critical flux was measured at different vibrating speeds varied from 0–500 oscillation per minute (opm) (5.83 Hz). The lowest critical flux was 15 $L \cdot m^{-2} \cdot h^{-1}$ when no membrane vibration was used and then increased gradually from 27 to 56 $L \cdot m^{-2} \cdot h^{-1}$ when the vibrating speed increased from 100 to 500 opm (8.35 Hz). A sharp drop in the critical flux was noticed when the concentration of feed suspension doubled from 5 g/L to 10 g/L. However, the increase in the critical flux was insignificant at higher feed concentration even when a high membrane vibrating speed was applied. This signifies that there is a limit for flux improvement in a vibratory system which is strongly dependent on the feed concentration.

Keywords critical flux; microfiltration; submerged hollow fiber; ultrafiltration; vibratory system

INTRODUCTION

A submerged hollow fiber membrane system is an emerging technology for water and wastewater treatment. A combination between the conventional process of activated sludge and membrane filtration technology is now widely used for municipal water and waste water treatment (1–3). The new technology is known as membrane bioreactors (MBRs) and it has an advantage over the conventional activated sludge process of providing a better quality filtered water. However, the major disadvantage of MBRs is membrane fouling due to concentration polarization, colloids adsorption, cake build-up, and biofouling (4). Altogether, membrane fouling causes a sharp increase in the transmembrane pressure (TMP) which leads to a reduction in the effluent flux especially when the process is operating under constant flux condition. Because the performance of any membrane process is a function of the membrane properties and the hydraulic and operating condition, researchers tried to use different techniques to combat and minimize fouling problems. Amongst the techniques used to overcome fouling problems are pulsed flow, air bubbling, a vibratory system, and rotating system (5–7).

The concept of the vibratory shear-enhanced process (VSEP) was first proposed by Armando and co-workers (New Logic International, CA) during the early 90's of the last century (8,9). According to Armando et al. (8), concentration polarization can be minimized and reduced to a great extent by moving the membranes which are submerged in the suspension fluid. The earliest system consisted of a stack of parallel circular flat sheet membranes fixed in a cylindrical compartment which is spun in torsional vibration at a frequency of few tens hertz. As a result of the high shear rate at the membrane-water interface, the concentration polarization problem can effectively be reduced. The VSEP can be applied to flat sheet membrane as well as hollow fiber membranes. Krantz et al. (10) demonstrated the applicability of the technique to hollow fiber membranes and the experimental work related to this group showed an improvement in the filtration process when the vibrating force was used. Genikin et al. (11) demonstrated the potential of critical flux increase on the addition of a coagulant such as aluminium chlorhydrate (ACH). Almost three times increase in the critical flux was achieved (from 17 to 46 Lm^2h^{-1}) when 34 mg/l of ACH was used. This is all done at a vibrating speed as low as 100 opm (1.67 Hz) which is equivalent to 1.7 Hz. Further flux improvement was achieved when combined axial and transverse vibrations were used. More than 5 times critical flux enhancement (from 17 to 86 Lm^2h^{-1}) was obtained at 100 opm (1.67 Hz) and in the presence of

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34 mg/L ACH. In a separate work, Beier et al. (12) showed around 325% improvement in the critical flux when a maximum vibrating speed was employed. The study also showed that the critical flux was increased more when the frequency is raised by a factor of 6, than when the amplitude is increased by a factor of 6. However, it is always advantageous to work at high vibration frequency and amplitude to increase the critical flux and reducing membrane fouling problems (12).

Nowadays, a vigorous air bubbling system is used, especially in membrane bioreactors, to control concentration polarization and/or fouling in the membrane filtration process. However, membrane vibration has an advantage over the air bubbling technique (13). The latter technique suffers from several limitations which are in general affecting the efficiency of the air bubbling concept for flux improvement. These disadvantages are:

1. The shear forces experienced by the membranes are relatively weak so that only moderate fluxes can be used.
2. Difficulties to achieve an effective bubbling distribution.
3. There is a level of bubbling intensity beyond which no further improvement can be achieved with increasing the bubbles flow.

In the vibratory shear-enhanced process the shear rate is created by the inertial-induced relative motion of the fluid. Therefore, the application of vibrational motion potential to the membranes has the potential to overcome the hydrodynamic limitation of the submerged membranes theory. To date there are only few studies that have been conducted to investigate the effect of vibration on flux improvement in submerged hollow fiber membranes. More studies are required to approve the viability of the VSEP technique on fouling reduction. Some operating parameters need optimization or further investigation in order to improve the process. The current study investigated the performance of VSEP using MF membranes and baking yeast as the suspension fluid. Two different feed concentrations were tested using a range of vibrating speed varied from 100 to 500 opm (1.67 Hz to 8.35 Hz). A bench unit was built for this purpose. Critical flux was calculated from the flux step method. Subcritical flux was also measured as a percentage of the total critical flux. A brief description of the critical flux and the method used to calculate it is explained here.

CRITICAL FLUX MEASUREMENT

The concept of critical flux (f_c) was first suggested by Field et al. (14) who defined the critical flux as the flux below which a decline of flux with time does not occur and above it fouling is observed. In the same work, Field and co-workers identified two forms of the critical flux, namely weak form and strong form. The weak form flux is the flux during subcritical operating condition and it is less than the clean water flux while the subcritical flux in the strong form is equal to the clean water flux. Howell (15) suggested that the subcritical flux as stable filtration operation over an extended period of time without significant increase in transmembrane pressure ($dTMP$). In a separate study Le Clech et al. (6) identified the dependency of critical flux on the procedure used to determine critical flux operation. The study showed that the long-term stability definition of critical flux proposed by Howell ignored the initial flux decline due to fouling. In the same study, Le Clech et al. (6) investigated the effect of step height and time on the critical flux. The study demonstrated that a long time step resulted in a high fouling rate. Likewise, a high fouling rate occurred when the flux height was extended. The study suggested that a number of parameters such as initial change in pressure, membrane permeability, and average TMP during each step should be taken into account to determine the precise value of the critical flux. Kwon and co-workers (16) proposed using the direct observation through the membrane (DOTM) technology to determine the critical flux in cross-flow microfiltration. However, the DOTM method did not account for the fouling due to adsorption and deposition of soluble material on the membrane surface. Cho and Fane (17) used the flux-step method to determine the critical flux in membrane bioreactor.

In the current study, critical flux was determined from flux increase in each step while TMP was monitored. The critical flux step was identified when there was a detectable increase in value of TMP. To date, few studies only focused on investigating critical flux measurement in VSEP. The current study suggested that the critical flux step is reached at $dTMP$ value 0.58 kPa.

METHODOLOGY

Materials and Setup

Baking yeast (average particle size is 5 μm) was added to millipore water and stirred in a magnetic stirrer to get a homogeneous solution before adding to the membrane container. Two polypropylene hollow fiber membranes were prepared before the experiment and glued in a vertical position at the both ends to Plexiglas membrane holders. The membrane holders were fixed on a Plexiglas frame by two screws at each end. Each membrane has an inside diameter (ID) 0.39 mm and an outside diameter (OD) 0.65 mm with a clear length of 41 mm between the membrane holders. The vibrating mechanism is provided by a mechanical device attached to the top of the setup which converts the rotating motion of the electric motor to vertical oscillation as shown in Fig. 1. The membrane rig is connected to the vibrating device by a steel shaft. The vertical displacement (amplitude) of the rotating unit is 4 cm and the length of the shaft is 27 cm. A maximum

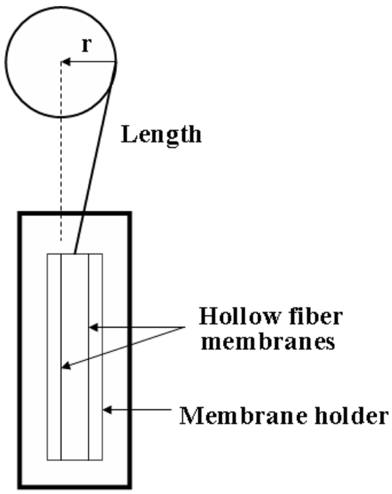

FIG. 1. The submerged hollow fiber membrane unit.

vibrating speed of 600 opm (10 Hz) can be delivered by the mechanical device. The vibrating frequencies used in this study varied between 100–500 opm (1.67–6.68 Hz).

Testing Procedure

A number of VSEP experiments were conducted at different vibrating speeds as shown in Table 1. The vibrating speed varied from 100 to 500 opm (1.67 Hz to 8.35 Hz). A flux-step method was used in the determination of f_c value. The flux-step length and height was 20 minutes and 6–8 $L \cdot m^{-2} \cdot h^{-1}$, respectively. Previous studies showed that the *d*TMP parameter was a reliable indicator of fouling increase during the filtration process (6). Experimental work here showed a sudden drop in the flux when the pressure signal value (*d*V) at any flux-step reached 0.014 mV. *d*V is the pressure signal recorded by the pressure transducer and it is related to the membrane resistance. This value is corresponding to *dTMP* value 0.58 kPa. In the flux-step method as time lapses the value of *d*V drops while the *d*TMP increases indicating a fouling increase (Fig. 2). Accordingly, the value of critical flux can be obtained from the linear equation between two closest data points above and lower the *d*TMP value 0.58 kPa. Subcritical flux was also determined empirically as a 90%, 80%, 70%, and 60% of the critical flux value. Each experiment was conducted for 5.5 hours. The subcritical flux was determined from monitoring the increase in the *d*TMP value during each experiment. During this study the value of TMP_i^n was taken one minute after the beginning of the first flux-step. The average TMP (P_{ave}) was also calculated from the average amount of TMP_f and TMP_i values at the beginning and end of each step-flux. The higher P_{ave} value points to the higher fouling during the step.

RESULTS AND DISCUSSION

Critical Flux Determination (f_c)

Bench scale MF experiments were conducted at different vibrating speed using baking yeast feed solution. The flux-step method was used to determine the critical flux. Experiment K1 was conducted at 100 opm (1.67 Hz) and the concentration of feed solution was 5 g/L. The critical flux step was identified when the *d*TMP value between the beginning and the end of any step was equal to or higher than 0.58 kPa. The *d*TMP value of the two closest data points above and below the *d*TMP value of 0.58 was plotted against the flux values of the same points and the critical flux was calculated from the linear equation between the two selected points. In experiment K1, the *d*TMP values in flux-step 2 and 3 were, respectively, 0.416 kPa and 0.791 kPa. The membrane fluxes for steps

TABLE 1
The submerged hollow fiber membrane unit experiments

Exp.	Vibrating speed (opm)	Feed suspension [yeast g/l]	f_c $[l \cdot m^{-2} \cdot h^{-1}]^*$	f_c $[l \cdot m^{-2} \cdot h^{-1}]^{**}$	f_{subc} 60%	f_{subc} 70%	f_{subc} 80%	f_{subc} 90%
K1	100	5	27	23	15	18	21	
K2	200	5	32	32	19	23	25	29
K3	300	5	33	33				
K4	400	5	42	53				
K5	500	5	56	63				
K6	100	10	23	22				
K7	200	10	24	22				
K8	300	10	26	24				
K9	400	10	27	25				
K10	No	5	15	16				

*Critical flux from *d*TMP = 0.58 kPa.
**Critical flux from $K > 0.9\ K_0$.

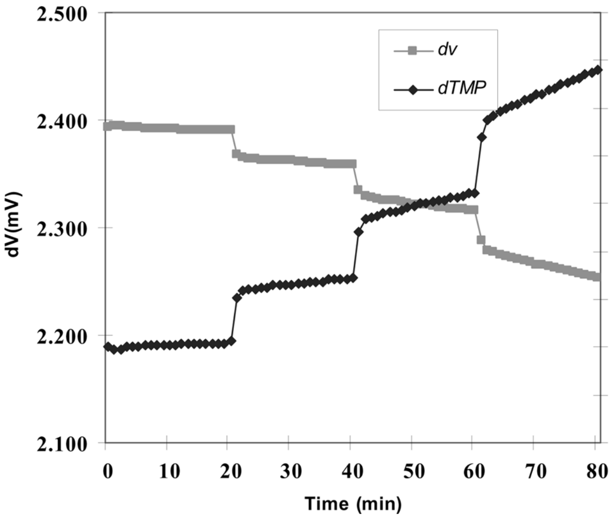

FIG. 2. dV and dTMP vs time at 100 opm.

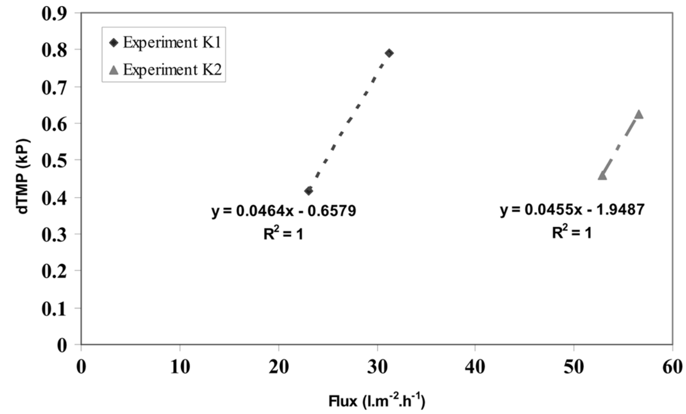

FIG. 3. Flux vs dTMP in flux-steps 2 and 3.

2 and 3 were $23\,L\cdot m^{-2}\cdot h^{-1}$ and $31\,L\cdot m^{-2}\cdot h^{-1}$ respectively (Table 2). The values of dTMP were plotted against those of flux for the same points and a first order linear regression is used to fit the data (Fig. 3). The critical flux (J_c) was found to be $27\,L\cdot m^{-2}\cdot h^{-1}$ according to the following equation:

$$y = 0.0464x - 0.6579, \quad \text{at } y = 0.58\,\text{kPa} \qquad (1)$$

This method was found to be very rigorous and can reliably be applied to estimate the critical flux over a wide range of vibrating speeds and fluxes as shown in Table 1. The critical flux increased from $27\,L\cdot m^{-2}\cdot h^{-1}$ to $56\,L\cdot m^{-2}\cdot h^{-1}$ when the vibrating speed increased from 1.67 and 8.35 Hz respectively.

Critical flux values were also determined from measuring the permeability of the membrane at the critical step (K) which should be higher than 90% of the initial membrane permeability (K_0). As described by Le Clech et al. (5) the critical flux step can be estimated when the membrane permeability (K) at any flux-step is greater than 90% of the permeability value in first flux-step (K_0). The K value can be calculated from dividing the flux value by the average transmembrane pressure drop (P_{ave}). According to this method, the values of critical flux in experiments K1 to K5 were 23, 32, 33, 53, and $63\,L\cdot m^{-2}\cdot h^{-1}$ respectively, which are very close to the values 27, 32, 33, 42, and $56\,L\cdot m^{-2}\cdot h^{-1}$ obtained by the previous method. The maximum critical flux difference was in experiment K5 around $11\,L\cdot m^{-2}\cdot h^{-1}$ or one flux step height as presented in Table 1. It is, therefore, fairly reasonable to consider the dTMP value 0.58 kPa as a reliable for critical flux measurements in VSHM system.

Effect of Feed Suspension Concentration

Separate experiments were conducted to investigate the effect of feed suspension on the critical flux determination. The concentration of baking yeast was doubled to 10 g/L in experiments K6 to K9 (Table 1). The effect of feed suspension concentration on the critical flux was investigated using four different vibrating speeds 100, 200, 300, and 400 opm. The values of critical flux were calculated as previously mentioned in section 3.1 and plotted against the vibrating speed. A comparison between 5 g/L and 10 g/L feed suspension was made to evaluate the membrane performance at high feed concentration. The dashed line represents the results for feed concentration 10 g/L while the solid line represents 5 g/L (Fig. 4). A significant drop in the critical flux was observed when the feed concentration was increased from 5 g/L to 10 mg/L due to the accumulation of fouling materials on the membrane surface which is in turn increased the dTMP

TABLE 2
The testing parameters of Experiment 1

dTMP [kPa]	dTMP/dt [kPa/min]	dTMP/dt [kPa/h]	Flux [$L\cdot m^{-2}\cdot h^{-1}$]	P_{ave} [bar]	K [$L\cdot m^{-2}\cdot h^{-1}$ /mbar]
	0.0088	0.53	15.43	206.25	74.81
0.416	0.0208	1.25	23.14	325.00	71.20
0.791	0.0440	2.64	31.22	481.25	64.87
	0.0746	4.47	39.67	708.33	56.00

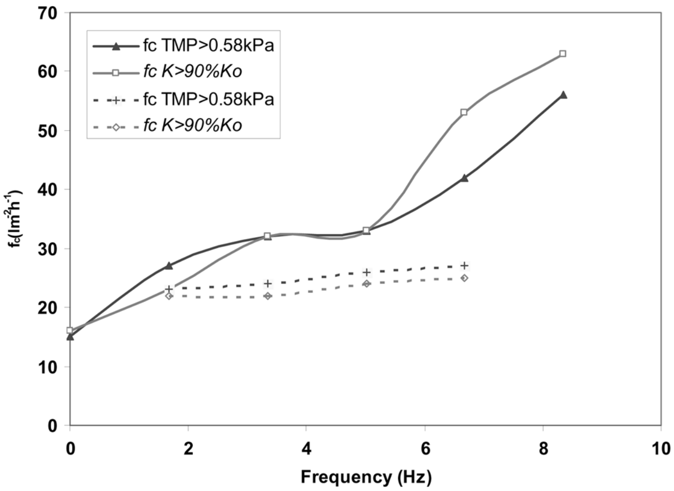

FIG. 4. Effect of vibrating speed on the critical flux (dashed line: suspension feed 10 g/L, solid line: suspension feed 5 g/l).

across the membrane surface. The effect of concentration polarization and cake layer thickness was much higher when the concentration of feed suspension increased from 5 g/L to 10 g/L.

Compared to experiments K1-K5, the results from K6–K9 showed a subtle improvement in the critical flux when the vibrating speed was increased from 100 opm (1.67 Hz) to 400 opm (6.67 Hz). This is mainly due to the high feed concentration in experiments K6–K9. The difference in the critical flux was higher at high vibrating speeds indicating the larger effect of fouling materials and concentration polarization on the membrane performance. It is evident that the performance of the membrane system did not significantly increase at high feed concentration even when high vibrating speed was employed. Unfortunately, only a subtle improvement in the critical flux was detected when the feed concentration was doubled to 10 g/L. This limitation can be investigated in future studies using other enhancement techniques like those suggested by Genkin et al., (11). In the latter work the critical flux was increased from 17 to 86 L/m^2h coagulant and vanes were incorporated at relatively low frequency of 100 opm (1.67 Hz). It should be, however, expected that a lower critical flux can be achieved at high feed concentration even when high vibration speeds were employed.

Subcritical Flux Determination (f_{subc})

Typically, f_{subc} is calculated as a percentage of the critical flux value. It has been demonstrated that membrane fouling can be controlled when the system is operating in f_{subc} mode. All f_{subc} tests were conducted for 5.5 hours. Different $dTMP$ percentages 90%, 80%, 70%, and 60% were used for f_{subc} calculation. $dTMP$ parameter was selected as an indicator to fouling formation. Higher dTMP values implies a higher fouling rate.

The subcritical (f_{subc}) values were determined for two critical flux values 32 and 23 $L \cdot m^{-2} \cdot h^{-1}$ obtained from two different tests carried out at vibrating speeds 200 and 100 opm (3.34 and 1.67 Hz), respectively. $dTMP$ was monitored during the tests as an indicator for membrane performance. For a stable membrane process performance the $dTMP$ value should remain unchanged or slightly changed with time. A sudden increase in the $dTMP$ is an indicator of membrane fouling. The first test was carried out at 200 opm (3.34 Hz) vibrating speed. The $dTMP$ values for 90%, 80%, 70%, and 60% were 1.125, 0.834, 0.667, and 0.667 kPa respectively (Fig. 5). At 90% the $dTMP$ was 1.125 kPa and decreased to 0.667 kPa at 70 but it remained unchanged when the f_{subc} value decreased to 60%. This means a stable membrane performance can be achieved at 70%. Since the f_{subc} at 70% was 23 $L \cdot m^{-2} \cdot h^{-1}$ and 60% was 19 $L \cdot m^{-2} \cdot h^{-1}$, the f_{subc} was chosen to be 70% of the calculated f_c. Similar results were obtained when the unit was operating on 100 opm (1.67 Hz). The dTMP values for 80%, 70%, and 60% f_{subc} were, respectively, 1.209, 0.666, and 0.625 kPa (Fig. 6). An insignificant increase in dTMP was observed when the percentage of the subcritical flux was increased from 60% to 70%. However, the f_{subc} was 18 $L \cdot m^{-2} \cdot h^{-1}$ at 70% and 15 $L \cdot m^{-2} \cdot h^{-1}$ at 60% test. This is in agreement with the results obtained from the previous test carried out at 200 opm (3.34 Hz). Accordingly, the f_{subc} value 70% from the critical flux was considered acceptable.

It is apparent from Figs. 5 and 6 that the dTMP values and hence the fouling rates were higher when the unit was

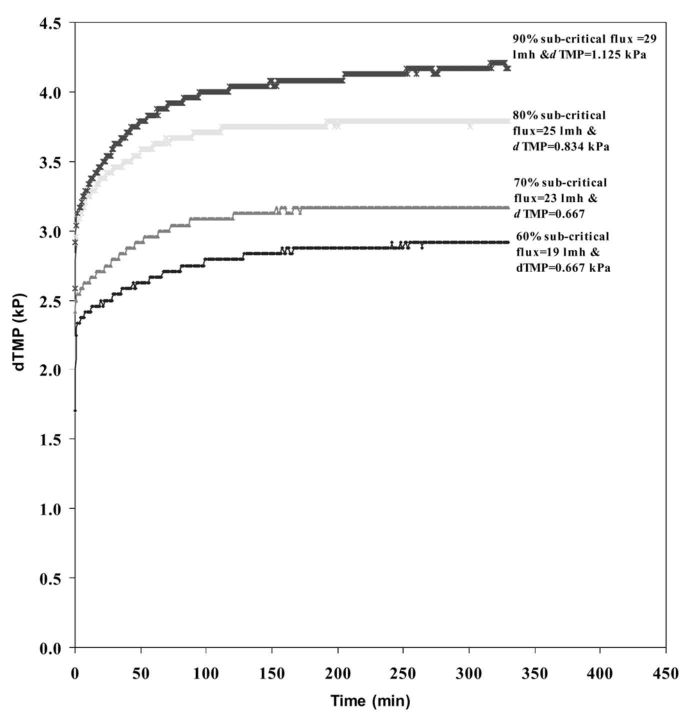

FIG. 5. The subcritical flux (f_{subc}) values in tests 1–4 at 200 opm.

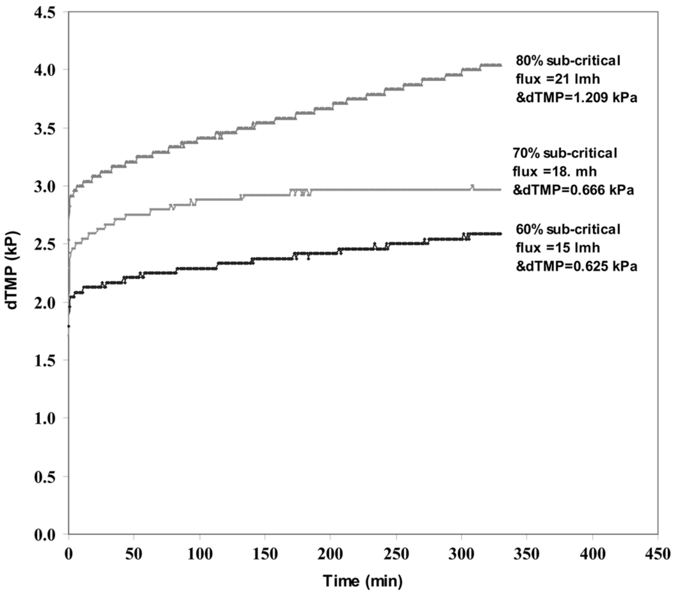

FIG. 6. The subcritical flux (f_{subc}) values in tests 1–4 at 100 opm.

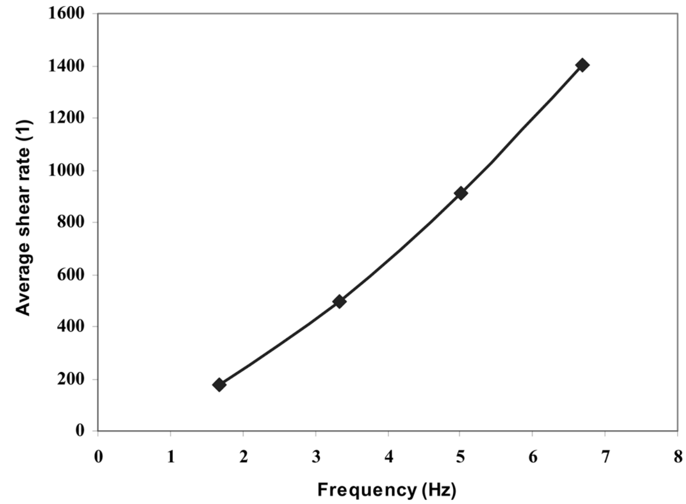

FIG. 7. Shear rate v frequency.

operating at a lower vibrational speed. For example in experiment K2 the dTMP was 1.125 kPa when the f_{subc} was 90% of the f_c while in experiment K1 the dTMP was 1.209 kPa when the f_{subc} was 80% of the f_c value. Therefore, a higher f_c can be achieved when the VSHM unit is operating at higher speeds.

Effect of Frequency

In the VSHM system, the filtration enhancement mechanism is mainly due to the increase in shear force at the membrane-water interface. This simply can be achieved by vibrating the membrane system at different vibrating speeds till the desired flux is obtained. Shear rate can be calculated from the following equation (18):

$$\gamma_{\max} = 1.414 d(\pi f)^{3/2} \nu^{-1/2} \quad (2)$$

Where ν is the feed solution kinematic viscosity (m^2/s), d is the membrane amplitude displacement (m), and$f$ is the vibrating frequency (Hz). Equation (2) represents the shear rate at the periphery of vibrating disc. However, for simplicity it was presumed that the same expression can be used to describe the shear rate existing at the surface or a vibrating fiber (11). The mean shear rate is obtained from averaging the value of maximum shear rate over the membrane area which for hollow membrane is an annular region with radius R_1 and R_2. The average shear rate can be calculated from the following equation:

$$\bar{\gamma} = \frac{2.828(R_2^3 - R_1^3)}{3\pi R_2(R_2^2 - R_1^2)} \gamma_{\max} \quad (3)$$

Figure 7 shows the shear rate values plotted at different vibrating speeds. The shear force at the membrane-water interface increased with the membrane vibrating speed and this in turn resulted in a higher flux because of less fouling problems. As shown in Fig. 4, the critical flux was significantly decreased when no membrane vibration was employed (experiment K10). The critical flux increased from $16\,\mathrm{L \cdot m^{-2} \cdot h^{-1}}$ to $63\,\mathrm{L \cdot m^{-2} \cdot h^{-1}}$ when the vibrating speed increased from 0 to 500 opm (5.83 Hz). This is equivalent to a 400% increase in the critical flux which was achieved at an average shear rate equals to $3300\,\mathrm{s^{-1}}$. Membrane performance was improved at higher shear rate which indicates a stable filtration process with minimum fouling problems.

The current study showed that the membrane performance was more stable when the vibration technique was employed. Around a 400% increase in the critical flux was achieved at an average shear rate equals to $1402\,\mathrm{s^{-1}}$. Soren et al. (12) reported that the critical flux measured at 30 Hz frequency and 1.175 mm amplitude was 325% higher than that measured at 5 Hz frequency and 0.2 mm amplitude. In a similar work William et al. (10) proved that a significant enhancement in the membrane performance was achieved when membrane vibration technology was employed. This was due to the secondary flow induced by membrane vibration.

CONCLUSION

The effect of membrane vibration on the critical flux was evident especially at high vibrating speeds. This was due to the increase in sheer force at the membrane-water interface which in turn enhanced the particles back diffusion mechanism.

On the other hand, the subcritical flux was calculated as a percentage of the critical flux. Different percentages ranged from 60% to 90% of critical flux were applied on the vibratory submerged membrane unit to select an appropriate subcritical flux. It was found that 70% was an acceptable value for subcritical flux operation in the VESP membrane system suggested here. All subcritical flux experiments were carried out 5.5 hours. A longer test is also recommended to obtain a better observation about membrane fouling during the filtration process. However, for a small bench study the five and half hours test was rather reasonable for the f_{subc} measurements.

A vibratory submerged hollow fiber membrane system can find applications in water and wastewater treatment processes. To date, however, membrane vibration is not applied commercially in water and wastewater treatment plants. One of the reasons is the lack of pilot plant experiments. Pilot scale experiments are required to test the performance of a vibratory system and its energy requirements before scaling up into a commercial size plant. As such, real feed water has to be tested and system optimization would be carried out through the experimental work.

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