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A vibration membrane bioreactor

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ABSTRACT

Our previous works suggested that a vibration membrane prevented premature fouling of a membrane in a submerged membrane bioreactor application. A spring-mass system was designed and operated in conjunction with a shaker that allowed a vertically suspended hollow-fibre membrane bundle to vibrate vertically close to the spring's natural frequency. The set-up was used to investigate the fouling of a vibrating hollow-fibre membrane bundle submerged in water with clay suspension. Studies included the effects on membrane fouling due to different vibration parameters with and without aeration. Though cross flow velocity, aeration and vibration all contributed to the anti-fouling behavior of the membrane, vibration was found to be the most effective means. Tests indicated that vibration at low frequency and low amplitude was sufficient to keep the membrane almost free from fouling.

Keywords: Submerged membrane bioreactor; MBR; SMBR; Hollow fibre; Ultrafiltration; Vibration membrane

1. Introduction

The submerged membrane bioreactor (SMBR) gained popularity in wastewater application due to its smaller plant size, shorter waste residence time and ability to be operated in high mixed liquor suspended solids (MLSS) while offering quality effluent. Due to a high MLSS environment, the membrane operated in SMBR fouled easily. One of the most common methods to improve membrane performance was by air bubbling to induce turbulence and fluid motion in order to maintain the relative cleanliness of the external surface of the membrane [1]. New Logic's [2] commercialized vibratory shear enhanced processing (VSEP) oscillated a flat membrane in its plane at high frequency to prevent a flat membrane from fouling. Low et al [3] imposed a 0.5 Hz longitudinal oscillation on a vertically suspended SMBR hollow-fibre ultrafiltration bundle. The mean surface velocity of 0.2 m/s created by the vibration significantly prevented premature membrane fouling. Genkin et al. [4] imposed a longitudinal vibration and used a coagulant on a vertically suspended hollow-fibre membrane. The critical flux was almost directly proportional to the imposed vibration frequency. Low et al. [3] found that the longitudinal vibration was more effective in improving membrane flux than that of transverse vibration. Genkin et al. [4] found that combining the longitudinal and transverse vibration would be most efficient. In this work, only longitudinal vibration was studied.

The objective of this work was to investigate the effects of vibration frequency and amplitude of a vibrating membrane in preventing membrane fouling.

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2. Test set-up

A submerged hollow-fibre membrane bundle with longitudinal vibration is shown in Fig. 1. The membrane was a PAN hollow-fibre bundle using 266 fibres 4.6 feet (1.4 m) long, 0.1" (2.7 mm) outer diameter and 0.06" (1.6 mm) inner diameter. The total flow surface area was 34 ft^2. The specifications of the membrane bundle are given in Table 1.

The fibers were bundled together with a dead end at the bottom and an open end on top. Permeate entered the membrane from the external hollow fibre walls and was sucked out from the centre of the bundle through an open end at the top.

The membrane was immersed in the 'sludge' feed tank with MLSS as high as 8000 mg/l, while the permeate was sucked and filtered through the membrane using a centrifugal pump with suction transmembrane pressure (TMP) adjusted to 3 psi. A large feed tank was used to maintain an almost constant sludge MLSS in the sludge tank while the porous stone with a minimum arbitrary aeration of 1 psi was used to prevent the clay from settling and to maintain an even concentration. In other words, the aeration was kept to a minimum to ensure the sewer is properly mixed for a vibration membrane test. However, for the vibration membrane test with aeration, the air bubbling would be much stronger in terms of the air supply pressure.

The vibration of the membrane bundle was produced from the spring-mass system using a leaf spring, the membrane mass and a shaker. The leaf spring was selected such that the resonance frequency was close to the intended vibration frequency so that it could easily produce the required vibrations to shake the membrane bundle. The shaker vibration frequency and the adjustment of the length of the leaf spring controlled the membrane vibration frequency and amplitude.

Since sewer sludge could pose a potential health hazard inside the laboratory, it was decided to simulate the sewer sludge by wet toilet paper blended into fine particles by a food blender. However, it proved to be unsatisfactory because the paper fibre was not fine enough to create the small particles required to effectively foul the membrane. Later, it was decided to use pottery clay with high kaolin content to simulate the sludge suspension. The pottery clay suspension had very fine solid particles that fouled the membrane surface very quickly causing a significant reduction of MLSS in the sludge tank. Therefore, a high MLSS feed tank was used to feed the sludge tank so that the membrane was immersed in an environment of high suspended solid content throughout the test. Regular samples from the sludge tank were taken to ensure the correct MLSS. The feed tank was also made large enough to maintain a constant MLSS in the test rig.

Table 1
Membrane bundle specifications

Description	Dimensions
Type of membrane	PAN ultrafiltration
Outer diameter of fiber	0.1" (2.7 mm)
Inner diameter of fiber	0.06" (1.6 mm)
Length of hollow fiber	4.6 ft (1.4 m)
Number hollow fibers	266
Bundle diameter	1.97" (0.05 m)
Porting	1 dead end and 1 open end
Membrane area	34 ft^2
Pore size	4–8 micro inch (0.1–0.2 μm)

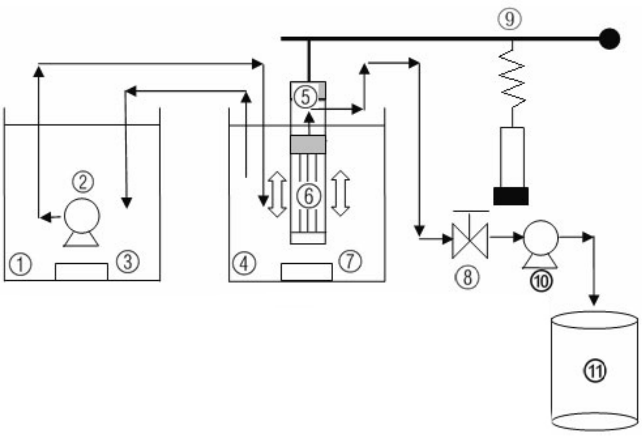

Fig. 1. SMBR hollow-fibre membrane with longitudinal vibration. 1 feed tank, 2 circulation pump, 3 porous stone, 4 sludge tank, 5 aluminium bracket, 6 hollow-fibre bundle, 7 porous stone, 8 flow control valve, 9 spring-mass vibration shaker, 10 pump, 11 permeate tank.

3. Results

3.1. Membrane without vibration

Fig. 2 shows the permeate flux in gallon per square foot per day (GFD) of the hollow-fibre membrane bundle

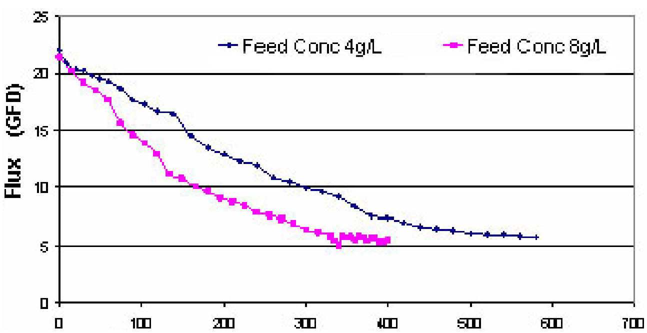

Fig. 2. Flux of a stationary membrane bundle submerged in different feeds. Permeate flow rate vs. time.

without vibration in a fluid of MLSS around 4000 and 8000 mg/l. In the case of 8000 mg/l MLSS, the fouling was more rapid as compared with that of 4000 mg/l MLSS. The time taken to reach a steady-state flux for the 8000 mg/l case was roughly two-thirds that of the 4000 mg/l case. The steady flux for both cases was nearly 26% of the initial flux.

These results implied that one could accelerate the membrane fouling in the test by choosing a high MLSS flow. The subsequent tests were confined to the fluid of 8000 mg/l in MLSS to reduce test time.

3.2. Vibration frequency

Although past research showed that axial vibration of submerged hollow-fibre membranes was effective in preventing membrane fouling with vibration frequencies as low as 10 Hz, this work further quantified how effective these same axial vibrations were on hollow-fibre membrane bundles.

Fig. 3 shows the permeate flux of the same membrane submerged in a feed MLSS of 8000 mg/l. However, the vibration frequency was varied from 0 to 8 Hz while a constant amplitude of 8 mm was maintained. In general, it was observed that the frequency of vibration affects the permeate flux. However, low frequencies below 4 Hz did not have significant effects on the permeate flux. Noticeably, there was a quantum jump in flux from 4 to 5 Hz. From 6 Hz onwards the steady-state flux did not deteriorate with time and maintained an almost constant flux rate. In other words, vibrating the membrane from 6 Hz onwards, the membrane was free from fouling. The same results were obtained for the vibrating membrane up to frequencies as high as 20 Hz. The permeate flux was almost four times that of the case without vibration.

Fig. 4 shows the effects of vibration frequency on the flow rate (directly proportional to flux). At low frequencies, the vibration-induced shear forces on the foulant might be small compared with its adhesion forces

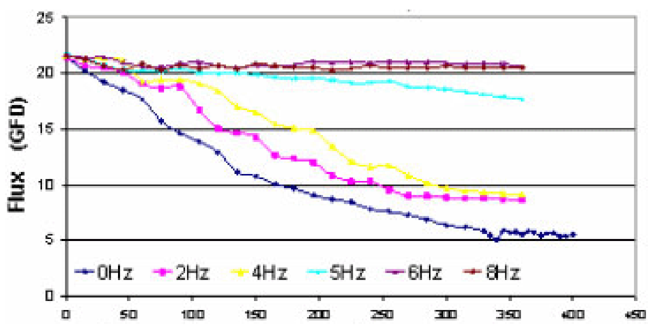

Fig. 3 Flux of a vibrating hollow-fibre membrane bundle subjected to an 8 mm fixed amplitude and different frequencies. Permeate flow rate vs. time (comparison of vibration frequencies of) to 8 Hz with deflection of 0.8 cm).

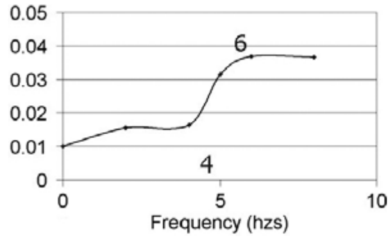

Fig. 4. Permeate flow rate (l/s) affected by vibration frequency.

to the membrane surface. As the frequency increased, this induced shear force on the foulants reached a critical state where the shear forces becomes stronger, balancing the foulants adhesion force to the membrane surface. The frequency where this happened was likely to be found between 4 to 5 Hz. For vibration frequencies beyond 5 Hz, the foulants were practically shaken off from the membrane surface as shown in Figs. 5 and 6.

Nonetheless, it is worthy to note that the vertical oscillation frequencies of 6 and 8 Hz performed exceptionally well. The steady-state fluxes were 96% and 97% of the initial flux, respectively. The small difference in flux suggests vibration at 6 Hz is the preferred frequency due to lower energy consumption.

In Fig. 7, it can be seen that doubling the vibration amplitude, from 4 mm to 8 mm, apparently enhancing the membrane resilience against fouling. The steady-state permeate flux increased from 41% to 62% of the initial flux. The increase in flux from doubling the amplitude while keeping the frequency constant was more than that from keeping the same amplitude but doubled the frequency as demonstrated in the same diagram. It indicates that the increase in vibration amplitude was more effective in preventing fouling than increasing in frequency at low frequency vibration, though both cases had the same mean flow velocities on the membrane surface. However, the low frequency but higher amplitude vibration dragged the membrane for a longer distance at the same mean velocity in each cycle of vibration. Dragging the membrane against the foulants for longer distance allowed more time for the foulants to be dislodged from the membrane surface.

3.3. Effects of aeration

Bubble-induced fouling control was described to minimize fouling of hollow-fibre membrane modules by three modes of operation: firstly, the upward moving bubbles sheared against the membrane surface; secondly, the liquid movement (both vertically and laterally) induced by bubbles imparted shear force on the membrane surface; and lastly, fluid motions caused movement of the fibres which influenced surface shear.

Fig. 5. Membrane coated with a thick sticky clay film after 2 and 4 Hz vibration.

Fig. 6. Clean state of membrane with a very thin clay layer after 6 and 8 Hz vibration.

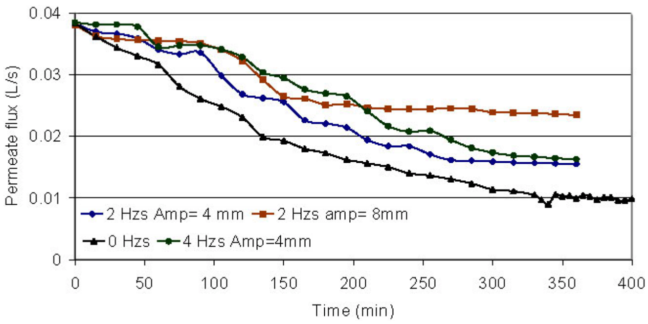

Fig. 7. Permeate flux affected by vibration amplitude. Increases in amplitude lead to higher flux.

In Fig. 8 it is seen that for the same gas flow rate, bubbling with coarser bubbles was more effective in preventing fouling. In any case, bubbling of the fluid

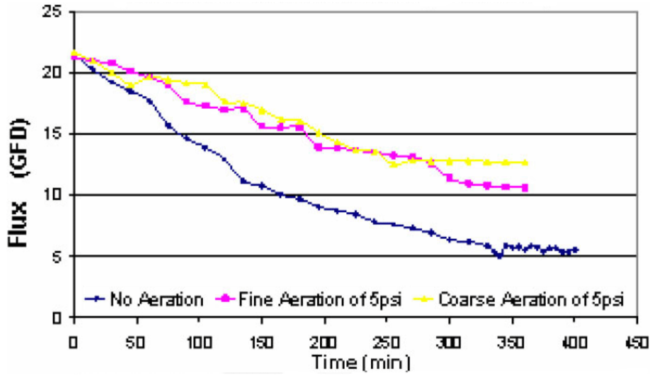

Fig. 8. Flux with aeration and no vibration. Permeate flow rate vs. time (effects of aeration on stationary membrane).

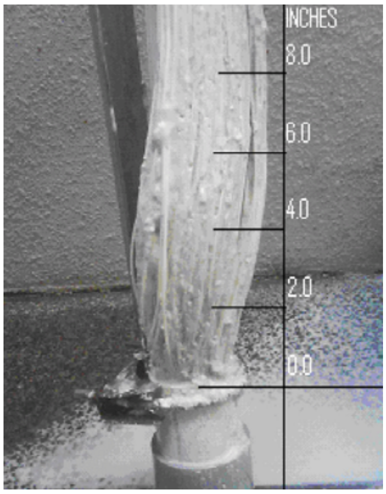

Fig. 9. Large amounts of clay stuck to the bottom of the membrane after the aeration test.

produced greater flux compared with the situation without bubbling as shown in Fig. 8. At the initial stages of operation, both fine bubbling and coarse bubbling offered similar flux. Only after 5 h of continuous operation, the flux of coarse bubbling case overtook that of the fine bubbling case. The steady state flux for the bubbling fluid were 59% and 50% of the initial flux for the coarse bubbling case and the fine bubbling case, respectively.

At the end of the fine bubbling test, the membrane was taken out for inspection, as shown in Fig. 9. It was observed that most of the fouling occurred near the bottom end of the membrane close to the source of the air bubbling. The top part of the membrane bundle was visibly cleaner than the bottom portion where chunks of clay stuck to the membrane surface fouled the bottom portion of the membrane. An interpretation could be that fine bubbling dislodged the clay particles from the upper portion much better than the lower portion of the membrane where the complicated geometrical profile makes it less accessible to the bubbles. Eventually, the

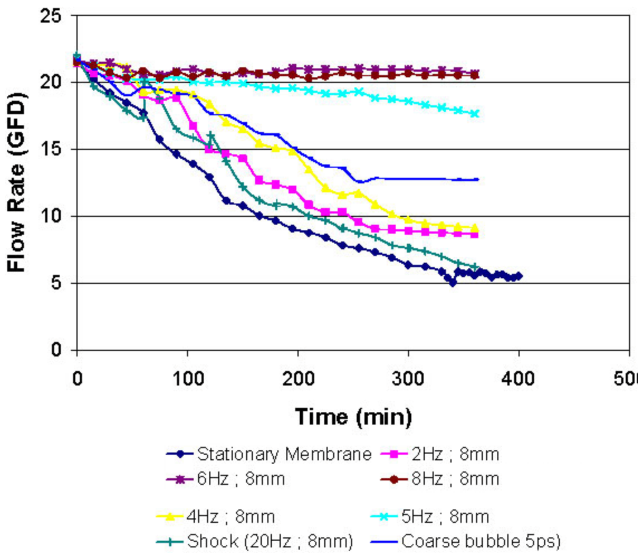

Fig. 10. Comparison of flux due to vibration, aeration and shock. Permeate flow rate vs. time (comparison of vibration freuencies from 0 to 8 Hz with deflection of 0.8 cm).

dislodged clay particles found their way to the relatively inactive lower portion of the membrane. Better design of the hollow-fibre membrane module would allow better use of the bubbling in this situation but restricts the effectiveness of the membrane vibration. This observation also implies that aeration might work better for a hollow-fibre membrane bundle suspended horizontally where the settling of the dislodged foulants at the bottom portion as observed in the vertically suspended membrane could be completely avoided.

Fig. 10 compares the permeate fluxes of the different anti-fouling methods. The flux due to coarse bubbling exceeded the effect of vibration at low frequency (2 Hz) and low amplitude (8 mm). The same flux was found to be closer to that using the same low vibration frequency of 2 Hz but greater amplitude (16 mm). The aeration method was no doubt effective, but it was limited by the void volume of the air in water— one just could not keep on increasing the air volume for more violent and turbulent aeration as well as the facility to contain it. To achieve greater cleanliness of membranes in SMBR, longitudinal vibration would be the option as demonstrated by the cases having frequencies of 6 Hz and above where the membrane was almost clean for long periods of use.

3.4. Test in a sewer system

In order to determine whether membrane performance with vibration in clay suspended water also behaved in a similar manner when in sewer water, a test was designed to be conducted in a sewer treatment plant. Fig. 11 shows the system block diagram. The MLSS for the test was 4000 mg/L and the TMP was kept at 4 psi. The results showing the vibration frequency of 8 Hz would be good enough to keep the membrane clean, as shown in Fig. 12.

Fig. 13 shows the permeate flux for different membrane vibration amplitudes of 5 mm. The permeate flux

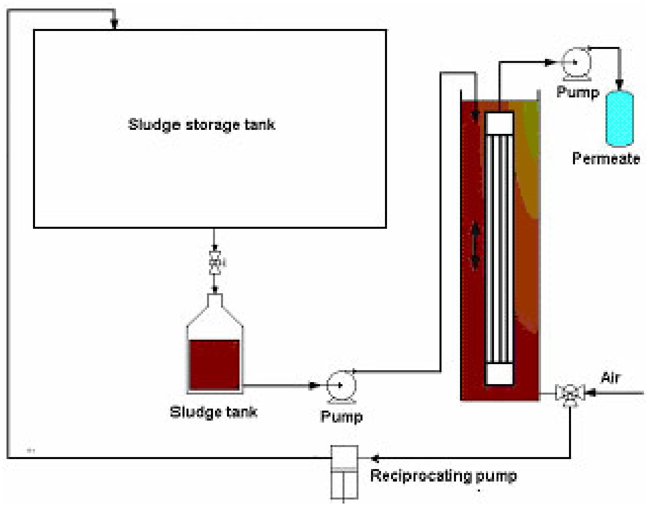

Fig. 11. Vibration membrane test in sewer sludge fluid.

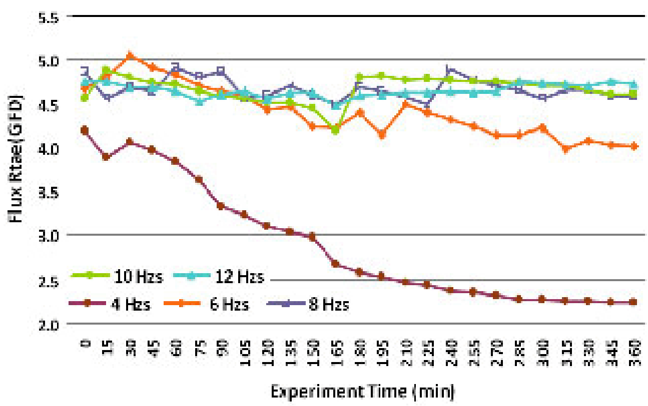

Fig. 12. Flux rate (GFD) against time. Trend of flux permeate for different vibration frequencies with 5 mm amplitude.

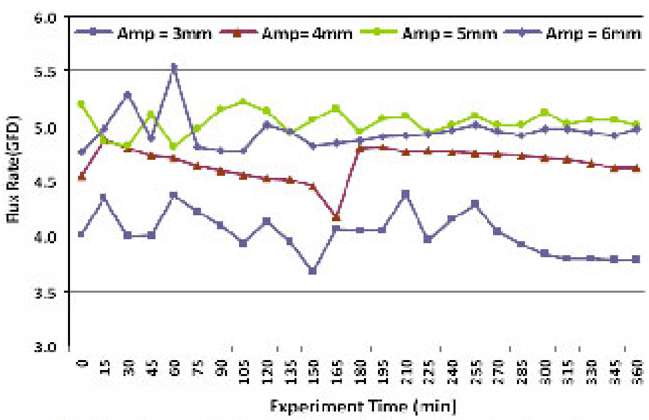

Fig. 13. Rate flux vs. time. Trend of permeate flux for different vibration amplitudes and frequency at 10 Hz.

was kept almost constant throughout the 6-h continuous test.

3.5. Effect of shock vibration

In an effort to conserve electrical energy and costs, membrane vibration was carried out intermittently instead of continuously. A shock vibration of 1 min of short vibration was introduced for every single hour interval of membrane operation in the stationary fluid. The results are displayed in Fig. 10. The first hour's shock vibration treatment was effective. After the first shock vibration, the flux almost recovered to its initial value. However, as the membrane fouled further, the effect of the second hour shock vibration was still visible but of less significant flux change. The effects of the third hour's shock were almost non-existent. It can be concluded that the shock vibration helped the membrane from recover the flux due to fouling momentarily. Shock vibration is effective if the membrane was not badly fouled.

Further investigation of the shock vibration was conducted for a membrane in a sewer system with MLSS of about 4000 mg/L and TMP of 3 psi. The results are shown in Fig. 14. The test was to investigate the flux change due to intermittent vibration. The test was conducted with a repetitive cycle comprised of a short vibration followed by a 45-min stationary period.

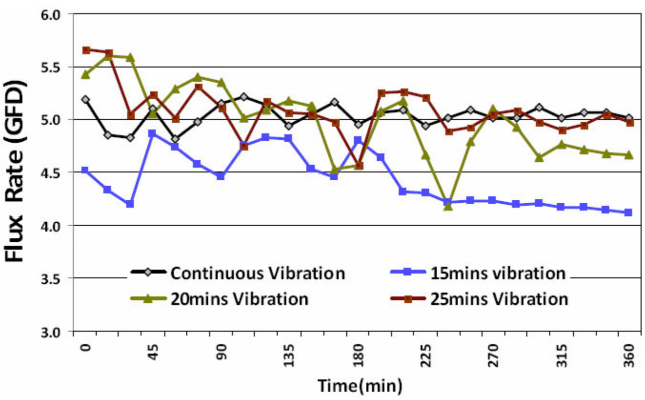

Fig. 14 .Flux for intermittent vibration followed by a 45-min stationary period.

The results indicated that the continuous vibration would sustain the flux for the 6-h test, whereas the 15 min of vibration followed by the 45-min stationary cycle test showed a continuous decline in flux after about 3.5 h of the test. However, 25 min vibration followed by the 45-min stationary cycle test compared favorably with the continuous vibration case in terms of the flux after the 6-h test. It maintained flux quite similar to that of the continuous vibration test. We can conclude that with a cycle of an appropriate combination of vibration and stationary time, the membrane in MBR can still be quite free from fouling. This consideration would help saving energy if vibration membrane for MBR should be adopted.

4. Conclusions

Longitudinal vibration for a vertically suspended hollow-fibre membrane bundle was tested in this work. Frequencies as low as 6 Hz and small amplitudes of 8 mm would be sufficient to keep the SMBR membrane clean for long periods of operation in a high MLSS of 8000 mg/l. The aeration method was commonly adopted for MBR. Its performance was better than the vibration membrane at low frequency and small amplitude of vibration. However, when appropriate vibration is applied, the anti-fouling ability of the vibration method is far superior than the pure aeration method. Intermittent vibration would help to save energy for vibration membrane for MBR. For the case presented, 25 min of vibration to be followed by a 45-min stationary period would mean a 70% reduction in energy in keeping the membrane clean through vibration.

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