Submerged hollow fibre membrane filtration with transverse and longitudinal vibrations

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ABSTRACT

A comparative study of transverse and longitudinal vibrations of submerged hollow fibre membranes for fouling control was carried out in this paper. The same membrane module was adopted in the comparison, and the reactor geometry was identical. The orientation between the vibration and membrane fibre directions was the only difference between the two. The feed suspensions included both inorganic Bentonite and organic yeast suspensions. The results showed that transverse vibrations were generally more effective in terms of fouling reduction even at a very low vibration frequency of 1 Hz, which may be attributed to the separating boundary layers and the associated secondary flows around the cylindrical membrane fibres. The difference between the two orientations was very substantial in Bentonite suspensions, but less so in yeast suspensions due to the main membrane foulants of cell debris in the yeast components which caused the pore blockage of the membrane. A small degree of fibre looseness was found to further improve membrane performance with transverse vibrations in both Bentonite and yeast suspensions due to additional lateral fibre movement. The effect of packing density of the membrane bundle in transverse vibrations was also examined. The results showed that at larger vibration amplitudes, a high packing density of fibres can be operated with little membrane fouling, which indicated that the secondary flow generated could overcome the strong permeate flux competition within the bundle under vibrations. Finally, vibration relaxation was tested experimentally in half-on/off switching mode with the energy reduction due directly to the 50% stoppage. The results showed that a short relaxation time interval was generally more favourable for fouling reduction.

Keywords: Transverse vibration; Longitudinal vibration; Fibre looseness; Packing density; Vibration relaxation.

1. Introduction

Submerged hollow fibre membranes are now widely used in water and wastewater treatment processes owing to their cost effectiveness and relatively large packing density which can produce high quality effluent with smaller reactor footprints. However, their application is still hindered by issues associated with concentration polarization and membrane fouling. At present, air sparging, with shear stresses generated by the rising bubbles on the membrane surface to sweep away the foulants deposit, is commonly used for fouling mitigation in membrane filtration processes. However, the flux improvement by air sparging can be limited [1] and its energy consumption can be as high as 70% of the total cost [2,3]. Hence, alternative techniques that offer the potential of better efficiencies continue to be explored. Among these techniques are turbulence promoters, Couette motion, pulsations, and vibrations [4]. Turbulence in the reactor can reduce membrane fouling, as it can generate rotational or swirling secondary flows that increase the shear stresses on the membrane, thus enhancing the scouring of the membrane surface [5]. The Couette motion [6,7] and pulsations [8,9] have been used mainly in biotechnological and medical areas.

The present study focuses on the use of membrane vibrations as a fouling control technique for submerged hollow fibre membranes. During vibration, shear stress is generated on the membrane surface by the relative motion between the membranes and liquid, thus the concentration polarization and membrane fouling can be alleviated. The concept of Vibratory Shear Enhanced Process (VSEP) was first presented by Armando et al. in 1992 [10]. It used the torsional vibration of a stack of circular polymer membranes at their resonant frequencies of around 60 Hz, which produced a shear rate at the membrane-liquid interface of about 150,000 s^{-1} to treat a feed suspension containing high solid concentrations. The high shear rate generated was about ten times that obtainable in the typical cross-flow membrane systems, and was effective for foulant removal.

Postlethwaite et al. [11] studied the flux characteristics of a vibrating microfiltration membrane system at a high biomass loading for protein recovery with a model biological feed stream containing 200-500 g/L *Saccharomyces cerevisae* wet weight and

0.75 g/L bovine serum albumin (BSA). The results showed that the generated shear rate was effective for fouling reduction and can be increased as the amplitude and frequency increased. They also showed that the vibrating system was able to handle broths with high solid loads, thus demonstrating the practicality for industrial applications. Similar results were also obtained by Low et al. [12] for the treatment of fine carbon-loaded wastewater using VSEP. Beier et al. [13] carried out experiments with a vibrating hollow fibre membrane module using yeast suspensions. They confirmed that higher critical fluxes could be achieved through higher vibration frequencies and amplitudes, and the critical flux improved 325% at the maximum vibration frequency and amplitude compared to that at the minimum frequency and amplitude. Recently, Bilad et al. [14] also confirmed the clear advantages of vibrations over conventional aeration process using vibration frequencies of up to 60 Hz for magnetically induced vibration in a submerged membrane bioreactor for treating synthetic wastewater.

The vibration of hollow fibre membranes can be done longitudinally (i.e. along the fibre length) or transversely (i.e. perpendicular to the fibre length). Low et al. [15] rotated the vertical fibres and observed that transverse vibration was less effective because of the unequalled shear forces on the membrane bundle compared with longitudinal vibration. On the other hand, by moving vertical hollow fibres horizontally, Kola et al. [16] observed that the transverse vibration can perform effectively for alginate, yeast, Bentonite, as well as anaerobic mixed-feed suspensions. They suggested that transverse vibration produces more effective shear stress by providing a more disruptive flow regime, which has the potential to induce boundary-layer separations and minimize membrane fouling. Genkin et al. [17] evaluated the effect of longitudinal vibrations over the range of 0-10 Hz frequency and 20 mm amplitude and also with coagulant addition on the filtration performance of submerged hollow fibre membranes. Their results showed that at the vibration frequency of 1.7 Hz, the critical flux increased from 17 to 46 LMH with the coagulant addition of 34 mg/L Aluminium Chlorhydrate (ACH). With combined longitudinal and transverse vibrations, a fivefold enhancement in critical flux to 86 LMH was also achieved at 1.7 Hz with the same concentration of ACH addition. They attributed the effect of coagulation to the aggregation of fine particles and evacuation of aggregates away from the membrane surface due to inertial and gravitational forces.

As discussed above, there have been contradictory reports on the relative merits of longitudinal and transverse vibrations for membrane fouling mitigation. The objective of the present study is to further examine the effectiveness of vibration towards membrane fouling control, and to provide a direct quantitative comparison between the two vibration modes. In addition, the vibratory parameters for optimal fouling mitigation in submerged hollow fibre membranes are also further investigated. The parametric scope of our study is wider than that of previous studies of Low et al. [15], Kola et al. [16] and Genkin et al. [17]. Various combinations of feed characteristics, fibre orientations, looseness, fibre spacing and packing density, as well as vibration relaxation were examined in a series of comprehensive laboratory experiments. The results will be discussed in details in the following after the description of the experimental setup and procedures.

2. Vibration setup

A schematic diagram of the vibration setup is shown in **Fig. 1**. The setup included the vibration mechanism and the permeate measurement equipment. The test tank was made of Persplex with sizes of 600 mm (L) × 500 mm (W) × 600 mm (H). During the experiments, a small background air bubbling (50 mL/min) was maintained in the tank to keep the feed particles suspended in the reactor. Longitudinal or transverse vibrations were achieved by positioning the fibres vertically or horizontally, respectively. The centre positions of the vertical and horizontal fibres were identical. The membrane module holder was driven by a brushless DC motor (BXM 6200-A, Oriental Motor Co., Ltd) with a crank moving mechanism. The vibration amplitude could be manually adjusted from 0 to 28 mm at 4 mm intervals, while the vibration frequency could be varied from 0 to 10 Hz. The permeate flow was controlled by a master flex peristaltic pump (Cole-Parmer Instrument Company) together with a needle valve (Swagelok). The suction pressure was measured with a pressure transducer (Precision digital), and the permeate flux with a digital balance (UX 6200H, Shimadzu).

3. Materials and operating procedures

3.1. Hollow fibres

Polyacrylonitrile (PAN) hollow fibres made by Ultrapure Pte Ltd in Singapore with inner/outer diameters of 1 mm/1.7 mm and nominal pore size of 0.1 μm were used in the experiments. They were aligned in parallel with both ends fixed to the C shape holding frame using Araldite epoxy. The length of the rod connecting to the motor determined the submergence of the hollow fibres.

3.2. Preparation of feed suspensions

In this study, two kinds of feed suspensions, the inorganic Bentonite (Sigma-Aldrich) and organic dry yeast (Levure Sèche de Boulanger, France) were mixed with tap water as the feed suspensions. They represented the inorganic and organic feeds, respectively. Their characteristics are described in the following.

3.2.1. Bentonite suspension

The formula of Bentonite is $H_2Al_2O_6Si$, with the molecular weight of 180.1 g/mol. The average particle diameter was 5.83 μm with a relative density of 2.4 g/cm^3. The Bentonite particles were first added to tap water and mixed with a magnetic stirrer at 300 rpm for 30 min. After complete mixing, they were diluted to make a 4 g/L suspension (pH 6.0-9.0) as the inorganic feed.

3.2.2. Yeast suspension

The yeast (so-called unwashed yeast) used in the experiments had an average particle diameter of 4.95 μm and a relative density of 1.2 g/cm^3. It was first mixed with 10 times volume of milli-Q water and stirred at 300 rpm for 10 min. After complete mixing, the suspension was further diluted with tap water to 4 g/L as the organic filtration feed. The motive for choosing the yeast suspension was its widespread use in the biotechnology industry and food chemistry, easy availability and large number of studies conducted using yeast with microfiltration [17-20]. A yeast suspension can also be separated into washed yeast and supernatant by the washing procedures as described below.

3.2.2.1. Washed yeast

Washed yeast was used as the feed in some experiments as a comparison to the unwashed yeast but without the supernatant. The washing procedures were adopted from an earlier reference of Negaresh et al. [21] who removed the cell debris and soluble macromolecules (such as extracellular polymeric substances, EPS) which had been reported before as potential foulants [22]. Around 5 g of the unwashed yeast was placed in a 50 mL centrifuge tube, and then mixed with 10 times volume of milli-Q water. The suspension was then placed in a centrifuge (Thermo Scientific, Legend Mach 1.6R) at 2000 rpm for 15 min. After centrifugation, the supernatant was discarded. The same procedure was repeated three times by adding an extra 10 times volume of milli-Q water each time. Later, the washed yeast was dried in an oven at 80 °C. This was repeated until there was no change in the weight of the dried yeast. The averaged wash removal efficiency was found to be 19.7%. This value was used for computation in the washed yeast experiments.

3.2.2.2. Supernatant

After the yeast washing, the supernatant was retained and made into a 1 g/L feed suspension. This feed was also used in some experiments as a comparison to the unwashed yeast suspension.

3.2.3. Particle size distribution

The particle size distributions of the Bentonite suspension, unwashed yeast suspension, washed yeast suspension and supernatant were analyzed using the Mastersizer Hydro 2000SM. The results are summarized in Table 1. A histogram of the size distribution of the unwashed yeast suspension, washed yeast suspension and supernatant is shown in **Fig. 2**. The washed yeast suspension has a smaller average particle size of 4.63 μm and a narrower particle size distribution compared with the unwashed yeast suspension after the washing procedures.

3.3. Operating procedures

Before each experiment, a clean water backwash at 20 mL/min was first performed on the hollow fibre membranes for 20 min. After the backwash, the filtration test was initiated, and the permeate volume was recorded at 20 s intervals by a digital balance. The permeate flux was then calculated as the rate of change of the permeate volume. For all the yeast experiments, the hollow fibres were flushed with 1% enzyme solution (Sigma-Aldrich) for 15 min after each experiment followed by clean water backwash. After the cleaning procedures, the permeability of the membranes was measured. If the permeability recovered to above 95% of the original value, the membranes were then reused, otherwise they were replaced with new ones.

In this study, the constant flux condition was adopted both to elucidate the fouling mechanisms and to monitor the fouling progress as the rate of TMP rise [23]. The corresponding suction pressure was recorded using a pressure gauge at 1-min interval.

4. Results and discussion

4.1. Membrane filtration

Membrane filtration tests of a 5 × 5 membrane module with a length of 18 cm and a spacing of 5 mm at a constant flux of 25 LMH with transverse vibrations were conducted with 4 g/L unwashed yeast suspension, 4 g/L washed yeast suspension and 1 g/L supernatant for 400 min. The TMP values are compared in **Fig. 3.** With a vibration amplitude of 16 mm and a small frequency of 2 Hz, the TMP of the unwashed yeast suspension increased by 72.7 kPa over the 400 min duration, whereas the washed yeast suspension increased more slowly by 35.7 kPa. In contrast, the TMP of the supernatant increased by a larger value of over 77.9 kPa to the water vapour pressure even at a lower concentration of 1 g/L for the same vibration conditions. The differences of the TMP rise values confirmed quantitatively that the presence of cell debris and macromolecules in the supernatant contributed dominantly to membrane fouling in the microfiltration of yeast materials [24]. The cell debris and macromolecules in yeast suspensions are the important EPS components [21,25,26]. EPS has been recognized as a main contributor to membrane fouling, which can cause pore blockage of the membrane. Our experimental findings were consistent with Sur and Cui [27] and Wicaksana [28], who reported that the removal of extracellular polymeric substances in yeast elevated the permeate flux at constant pressure.

4.2 Comparison of longitudinal and transverse vibrations

In the present study, the experimental setup of the longitudinal and transverse vibrations was identical except in the orientation of the fibres. Hence, a direct comparison of the measurements can reveal the relative effectiveness of the two modes of vibrations. Experiments using the same 5 × 5 membrane module were performed for both the inorganic Bentonite and organic yeast suspensions with a constant flux filtration of 25 LMH. **Fig. 4** shows the average fouling rates at a low frequency of 1 Hz. With the amplitude of 28 mm and a 4 g/L Bentonite suspension, the fouling rates were measured to be 21.8 and 4.2 kPa/h with the longitudinal vibration and transverse vibration, respectively. They increased to 24.2 and 15.5 kPa/h in the 4 g/L yeast suspension, respectively. Clearly, the fouling rates for the transverse vibrations were much lower than that of the longitudinal vibration for all the tests performed in the present study. Hence, our study confirms that the transverse vibration is more effective than longitudinal vibration for membrane fouling control. It should be noted that the holding frame did not have much effect on the results [29].

The improvement due to the transverse vibration can be attributed to the separating boundary layers induced by the transversely moving fibres, which is effective in reducing membrane fouling. In addition, with the periodic movement by transverse vibrations, a streaming secondary flow pattern can be produced, which generates vortices that further increase the shear rate in the vicinity of the membrane surface. At the same time, it should be noted that the risk of fibre breakage is obviously higher with the transverse vibration at higher vibration amplitudes and frequencies due to more severe lateral movement and stresses compared with the longitudinal vibration. The potential of damage to the fibres induced by the fibre movement was also pointed out in the earlier studies [20,30]. Further investigation in the damage potential is therefore required before prototype implementation.

The fouling improvements by both longitudinal and transverse vibrations in the 4 g/L yeast suspension were weaker than that in the 4 g/L Bentonite suspension. The yeast particle density was lower than Bentonite particles, so there were a relatively larger number of yeast particles than Bentonite particles for the same mass concentration. For comparison, we also carried out experiments in the reactor with the same theoretical number of particles for the two feed suspensions (4 g/L Bentonite and 1.2 g/L yeast) by assuming that these particles were spherical. The same membrane module was also used in the experiments for two conditions: (a) transverse vibration (see **Fig. 5**(a)); and (b) longitudinal vibration (see **Fig. 5**(b)). From the figures, it can be observed that the yeast suspension induced more severe fouling than the Bentonite suspension even at the same number of particle concentration. With the transverse vibration, the TMP of the yeast and Bentonite suspensions increased by 12.4 and 0.3 kPa respectively in the constant flux tests. In comparison, the TMP of both suspensions increased by 14.4 and 9.3 kPa respectively with the longitudinal vibration. Therefore, these results also suggest that the greater membrane fouling induced by yeast suspension can be attributed to the smaller nominal particle size and the narrower particle size distributions (**Table 1** and **Fig. 2**) in addition to the cell debris in the yeast suspension. The small particles have a strong deposit tendency on the membrane surfaces which may easily block the membrane pores and cause severe irreversible membrane fouling [31]. However, this irreversible fouling cannot be easily reduced with vibrations [32]. Furthermore, the higher density of Bentonite also helps remove the particles from the membrane surfaces under vibrations, which leads to lesser fouling than the yeast suspension.

4.3. Effect of fibre looseness in the transverse vibration

For MBRs, the looseness of the hollow fibre membranes was recommended to be in the range of 0.1-5% by Zenon [33]. Wicaksana et al. [20] studied submerged fibre performance with air bubbling and with fibre looseness varying from 1% to 4%. They found that the membrane performance typically improved with increased fibre looseness. In our previous study of Li et al. [29] on longitudinal vibration, we also confirmed that a small degree of fibre looseness can further reduce membrane fouling.

Here, we examined the effect of fibre looseness in the transverse vibration operation. The same membrane module was used as above, with tight, 1% and 2% looseness of fibres mounted on the holding frame and vibrated transversely in the reactor. The experiments were carried out in the Bentonite and yeast suspensions. **Fig. 6** presents the measured fouling rates of both tight and loose fibres. The figures clearly show that the membrane performance was better with the loose fibres. With 20 mm vibration amplitude in 4 g/L Bentonite suspension, the fouling rate reduced from 36.4 kPa/h with tight fibres to 28.8 kPa/h with 1% looseness, and further to 28.4 kPa/h with 2% looseness. The fouling rate also reduced from 19.8 kPa/h to 16.2 kPa/h in 4 g/L yeast suspension with 1% looseness. Bérubé et al. [34] reported no substantial differences in the surface shear forces between the loose or tight fibres in two-phase flow conditions. However, it can be assumed that fibre looseness would induce additional lateral fibre movement by vibrations that may help shake loose the foulants on the membrane surface and thus further reduce membrane fouling.

We also compared the membrane performance of longitudinal and transverse vibrations using the same 5 × 5 membrane module with a length of 16 cm and 1% looseness fibres at a constant flux of 25 LMH and vibration frequencies of 1 - 3 Hz (**Fig. 7**). As expected, the performance of the transverse loose fibres was much better than that of the longitudinal loose fibres, implying that there was more significant lateral movement in transverse vibrations. The lateral displacement of fibres induced by the two different vibrations (as controlled by the vibration mechanism and the set parameter on vibration amplitude) was also measured using a high speed camera (the photos are not included here). It was confirmed that the displacement induced by the transverse vibration was much larger than by the displacement during longitudinal vibration (which was also limited by the looseness). Typically the displacement induced by the transverse vibration could easily reach its maximum, which was 7% of the fibre length for 1% looseness fibres. However, there was only around 2-4% of the fibre length of displacement induced by longitudinal vibrations for the same 1% looseness fibres.

4.4. Fibre spacing

Membrane spacing is an important parameter in industrial applications. Greater spacing between the membrane elements can increase the permeate flux and solids handling capability as illustrated by Postlethwaite et al. [11]. They investigated the VMF performance using both Bacillus and Aspergillus fermentation broths and found a pronounced increase in performance when the gap width was increased. In this study, we first tested the fouling of hollow fibre membranes with two fibre spacings of 2 mm and 15 mm of a single row of membranes with a length of 20 cm under longitudinal vibrations. **Fig. 8** shows the TMP of hollow fibre membranes with 2 mm and 15 mm spacing at vibration frequencies of 6 Hz and 10 Hz. With 6 Hz, the TMP of hollow fibres having the 2 mm spacing increased significantly in a short time and reached as high as 80 kPa in 30 min filtration, which was much higher than the 15 mm spacing with only 27 kPa. However, when the vibration frequency increased to 10 Hz, the TMP profile for both became nearly the same. These results confirmed that the membrane fouling was worse with closely spaced fibres at lower frequencies during longitudinal vibration; while there was little difference at higher vibration frequencies. This indicates that the fluid motion induced at high vibrations was able to overcome the greater permeate flux competition between neighbouring fibres with the smaller spacing. The phenomenon of permeate flux competition was also observed in the experiments by Yeo et al. [35] and Fulton and Bérubé [36]. A recent numerical study by Zamani et al. [37] also suggested that there is an optimal spacing in a vibrating system.

4.5. Fibre packing density

With more hollow fibre membranes in the reactor, the permeate flow can be increased with a high packing density. However, there is more flux competition with the smaller fibre spacing [35]. The flow velocity between the bundle also increases during vibrations.

In this study, four fibre bundles (5 × 5, 6 × 6, 7 × 7, and 8 × 8) with 1% looseness were uniformly mounted on a 20 mm × 20 mm area of a 40 mm × 40 mm plate to make a packing density of 12%, 17%, 24% and 31% **(Fig. 9).** They were vibrated transversely at different vibration amplitudes in both 4 g/L Bentonite and yeast suspensions **(Fig. 10)**. With the smaller vibration amplitude of 20 mm, the fouling rate increased from 7.4 to

95.2 kPa/h when the packing density increased from 5 × 5 to 8 × 8 in the Bentonite suspension (**Fig. 10**(a)). However, the increase became smaller when a greater vibration amplitude of 28 mm was applied. The results confirmed that at lower vibration amplitudes, there was strong permeate flux competition for highly densely packed fibres; however, at higher vibration amplitudes, the flux competition was less severe.

A similar trend was observed in the 4 g/L yeast suspension vibrating at 2 Hz (**Fig. 10**(b)). With the vibration amplitude of 24 mm, the fouling rate increased from 18.1 to 34.8 kPa/h when the packing density increased from 6 × 6 to 7 × 7, but dropped back to 18.1 kPa/h when the packing density increased further to 8 × 8. The reason for the pressure drop can be attributed to the fact that the gap of the adjacent fibres for the 8 × 8 bundle was as small as 1.2 mm. With such a small gap, a synergetic sweeping and scouring effect of adjacent fibres (i.e. the bundle now acting as a whole unit) under the larger transverse vibration frequency of 2 Hz could overcome the flux competition restraint induced by the narrower fibre spacing, thus enhancing the mass transfer and producing lesser membrane fouling. Buetehorn et al. [38] studied the submerged hollow fibre movement by aeration. They found that more frequent fibre collisions induced by high packing densities promoted cake removal, but at the same time reduced the lateral surface shear due to the hindered fibre motion. However, a recent numerical study by Zamani et al. [37] pointed out that an increase in shear rate was obtained when the fibre distance was decreased to an optimal value in a small region. This enhanced shear rate can also reduce membrane fouling. Overall, the results also confirmed that the secondary flows induced by the higher packing densities of fibres were more significant and in fact dominant at higher vibration amplitudes.

4.6. Vibration relaxation

In previous work, without vibrations, intermittent operation of membrane filtration in MBRs, or so-called relaxation, was found to lead to a slower flux decline due to the enhanced removal of foulants accumulated on the membrane surface with the back transport of foulants under the release of suction pressure [39]. Vibration relaxation was found to be effective if the membrane was not badly fouled [40]. However, the optimized time interval and energy conservation of vibration relaxation have not been fully evaluated to date. Here, the vibration relaxation (in comparison with continuous vibration) was explored to reduce the energy consumption and costs.

In this study, the vibration relaxation of the 5 × 5 membrane module with 1% looseness was carried out by setting the motor to work intermittently in a half on/off switching mode. A PLC system (M-90, Unitronics) was used to control the motor to rotate and stop periodically at an equal time interval. The time intervals of 1 min and 5 min were tested in a 4 g/L Bentonite suspension, and 10 s, 20 s, 30 s and 1 min in a 4 g/L yeast suspension. The results of the total filtration resistance are shown in **Fig. 11** by applying the equation below.

$$R_t = \frac{TMP}{\mu J} \tag{1}$$

where μ is the dynamic viscosity of permeate and J is the permeate flow velocity calculated from the flux. It can be seen that there was a slow increase in the membrane filtration resistance with continuous vibration, and a huge jump without vibration. For the 4 g/L Bentonite suspension (**Fig. 11**(a)), with the relaxation interval of 1 min, the total filtration resistance of the hollow fibre membranes doubled in the first 3 h, while with a relaxation interval of 5 min, the total filtration resistance increased further.

For the 4 g/L yeast suspension (**Fig. 11**(b)), with the relaxation interval of 10 s, the total filtration resistance of the hollow fibre membranes increased 90% in 150 min, while there was only 50% increase with continuous vibration correspondingly. In contrast, the time to double the resistance reduced to 30 min for the relaxation interval of 60 s. This implied that the membrane fouling can be further reduced with the shorter time interval of the vibration relaxation. The total filtration resistance of hollow fibres with 10 s relaxation interval was much lower than 30 s, and only slightly higher than continuous vibration. Vibration relaxation can therefore help the membrane recover the flux and reduce the energy consumption. It should be noted that the total filtration resistance stayed very high with the longer time intervals of 30 s and 1 min in the yeast suspension, and was nearly the same as no vibration, which indicated that the long time intervals of vibration relaxation were ineffective. These results are consistent with those reported by Bilad et al. [14] but substantially more extensive.

5. Conclusions

In the present study, the transverse and longitudinal vibrations of submerged hollow fibre membranes for fouling control were investigated in both inorganic Bentonite and organic yeast suspensions. A direct comparison of fouling performance between the two vibration orientations was performed. The results confirmed that transverse vibrations were more effective than longitudinal vibrations in terms of fouling reduction even at a low vibration frequency of 1 Hz, which may be due to the separating boundary layers and associated secondary flows around the cylindrical membrane fibres by transverse vibrations. This improvement was however less obvious in yeast suspensions due to the dominant membrane foulants of cell debris in the yeast components. A small degree of fibre looseness was confirmed to further reduce the membrane fouling and enhance the membrane performance with transverse vibrations in both feed suspensions due to the extra lateral fibre movement. The effect of packing density of the membrane bundle by vibrations was also examined. It was found that lesser membrane fouling was induced by high packing density of fibres with transverse vibration at higher vibration amplitudes, which implied that there were greater fibre-fibre collisions with closely positioned fibres under vibrations. In addition, it also implied that the secondary flow generated by the transverse vibration was able to overcome the permeate flux competition induced by the smaller fibre spacing. Finally, a short relaxation time interval of the vibration relaxation was found to be more effective for fouling control and energy reduction under the half on/off operating mode.

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List of symbols

Nomenclature

ACH	Aluminium Chlorhydrate
BSA	bovine serum albumin
dTMP/dt	rate of TMP increase (or fouling rate)
EPS	extracellular polymeric substances
J	permeate flux (LMH)
MBR	membrane bioreactor
PAN	polyacrylonitrile
R_t	total resistance of hollow fibre membranes (m^{-1})
TMP	transmembrane pressure
VMF	vibrating microfiltration
VSEP	vibratory shear-enhanced processing system

Greek symbols

μ	fluid dynamic viscosity

References

[1] L.J. Xia, A.W.K. Law, A.G. Fane, Hydrodynamic effects of air sparging on hollow fiber membranes in a bubble column reactor. Water Res. 47 (2013) 3762-3772.

[2] S. Judd, The MBR Book, Elsevier, Amsterdam, 2006.

[3] A. Drews, Membrane fouling in membrane bioreactors - characterisation, contradictions, cause and cures. J. Membr. Sci. 363 (2010) 1-28.

[4] F. Vigo, C. Uliana, E. Ravina, A. Lucifredi, M. Gandoglia, The vibrating ultrafiltration module - performance in the 50-1000 Hz frequency-range, Sep. Sci. Technol. 28 (1993) 1063-1076.

[5] D.M. Krstić, M.N. Tekić, M.Đ. Carić, S.D. Milanović, The effect of turbulence promoter on cross-flow microfiltration of skim milk, J. Membr. Sci. 208 (2002) 303-314.

[6] K. H. Kroner, V. Nissinen, Dynamic filtration of microbial suspensions using an axially rotating filter, J. Membr. Sci. 36 (1988) 85-100.

[7] G. Beaudoin, M. Y. Jaffrin, Plasma filtration in Couette-flow membrane devices, Artif. Organs 13 (1989) 43-51.

[8] J. L. Philp, M. Y. Jaffrin, L. H. Ding, Protein adsorption and trapping during steady and pulsed flow plasma cross-flow filtration. J. Membr. Sci. 88 (1994) 197-209.

[9] M. Y. Jaffrin, L. H. Ding, M. Defossez, J. M. Laurent, Interpretation of transient ultrafiltration and microfiltration of blood and protein solutions. Chem. Eng. Sci. 50 (1995) 907-915.

[10] A.D. Armando, B. Culkin, D.B. Purchas, New separation system extends the use of membranes, in: Proceedings of the Euromembrane'92, vol. 6, Lavoisier, Paris, 1992, 459–462.

[11] J. Postlethwaite, S.R. Lamping, G.C. Leach, M. F. Hurwitz, G. J. Lye, Flux and transmission characteristics of a vibrating microfiltration system operated at high biomass loading, J. Membr. Sci. 228 (2004) 89-101.

[12] S.C. Low, H.J. Han, W.X. Jin, Characteristics of a vibration membrane in water recovery from fine carbon-loaded wastewater, Desalination 160 (2004) 83-89.

[13] S. Beier, M. Guerra, A. Garde, G. Jonsson, Dynamic microfiltration with a vibrating hollow fiber membrane module: filtration of yeast suspensions, J. Membr. Sci. 281 (2006) 281-287.

[14] M.R. Bilad, G. Mezohegyi, P. Declerck, I.F.J. Vankelecom, Novel magnetically induced membrane vibration (MMV) for fouling control in membrane bioreactors, Water Res. 46 (2012) 63-72.

[15] S.C. Low, H.H. Juan, L.K. Siong, A combined VSEP and membrane bioreactor system, Desalination 183 (2005) 353-362.

[16] A. Kola, Y. Ye, A. Ho, P. Le-Clech, V. Chen, Application of low frequency transverse vibration on fouling limitation in submerged hollow fibre membranes, J. Membr. Sci. 409 (2012) 54-65.

[17] G. Genkin, T. Waite, A. Fane, S. Chang, The effect of vibration and coagulant addition on the filtration performance of submerged hollow fibre membranes, J. Membr. Sci. 281 (2006) 726-734.

[18] H.W. Sur, Z.F. Cui, Experimental study on the enhancement of yeast microfiltration with gas sparging, J. Chem. Technol. Biotechnol. 76 (2001) 477-484.

[19] M. Chandler, A. Zydney, Effects of membrane pore geometry on fouling behavior during yeast cell microfiltration, J. Membr. Sci. 285 (2006) 334-342.

[20] F. Wicaksana, A.G. Fane, V. Chen, Fibre movement induced by bubbling using submerged hollow fibre membranes, J. Membr. Sci. 271 (2006) 186-195.

[21] E. Negaresh, P. Le-Clech, V. Chen, Fouling mechanisms of model polymeric substances, Asia-Pac. J. Chem. Eng. 2 (2007) 394-399.

[22] P. Le-Clech, V. Chen, T.A.G. Fane, Fouling in membrane bioreactors used in wastewater treatment, J. Membr. Sci. 284 (2006) 17-53.

[23] R.W. Field, D. Wu, J.A. Howell, B.B. Gupta, Critical flux concept for microfiltration fouling, J. Membr. Sci. 100 (1995) 259-272.

[24] V.T. Kuberkar, R.H. Davis, Effects of added yeast on protein transmission and flux in cross-flow membrane microfiltration, Biotechnol. Prog. 15 (1999) 472-479.

[25] D.Hughes, R.W. Field, Crossflow filtration of washed and unwashed yeast suspensions at constant shear under nominally sub-critical conditions, J. Membr. Sci. 280 (2006) 89-98.

[26] S.P. Beier, G. Jonsson, A vibrating membrane bioreactor (VMBR): macromolecular transmission-influence of extracellular polymeric substances, Chem. Eng. Sci. 64 (2009) 1436-1444.

[27] H.W. Sur, Z.F. Cui, Enhancement of microfiltration of yeast suspensions using gas sparging - effect of feed conditions, Sep. Purif. Technol. 41 (2005) 313-319.

[28] F.Wicaksana. Submerged hollow fibre membranes in bubbling systems, The University of New South Wales, Australia, 2006. (Ph. D. thesis).

[29] T. Li, A.W.K. Law, M. Cetin, A.G. Fane, Fouling control of submerged hollow fibre membranes by vibrations, J. Membr. Sci. 427 (2013) 230-239.

[30] A.P.S. Yeo, A.W.K. Law, A.G. Fane, The relationship between performance of submerged hollow fibers and bubble-induced phenomena examined by particle image velocimetry, J. Membr. Sci. 304 (2007) 125-137.

[31] Z. Wang, Z. Wu, X. Yin, L. Tian, Membrane fouling in a submerged membrane bioreactor (MBR) under sub-critical flux operation: membrane foulant and gel layer characterization, J. Membr. Sci. 325 (2008) 238-244.

[32] C.C.V. Chan, P.R. Bérubé, E.R. Hall, Relationship between types of surface shear stress profiles and membrane fouling, Water Res. 45 (2011) 6403-6416.

[33] Zenon Environmental Inc., Burlington, Canada, Vertical Skein Of Hollow Fiber Membranes and Method of Maintaining Clean Fiber Surfaces While Filtering a Substrate to Withdraw a Permeate, US Patent 5639373, 1997.

[34] P.R. Bérubé, G. Afonso, F. Taghipour, C.C.V. Chan, Quantifying the shear at the surface of submerged hollow fibre membranes, J. Membr. Sci. 280 (2006) 495-505.

[35] A.P.S. Yeo, A.W.K. Law, A.G. Fane, Factors affecting the performance of a submerged hollow fiber bundle, J. Membr. Sci. 280 (2006) 969-982.

[36] B.G. Fulton, P.R. Bérubé, Optimizing the sparging condition and membrane module spacing for a ZW500 submerged hollow fiber membrane system, Desalination Water Treat. 42 (2012) 8-16.

[37] F. Zamani, A.W.K. Law, A.G. Fane, Hydrodynamic analysis of vibrating hollow fibre membranes, J. Membr. Sci. 429 (2013) 304-312.

[38] S. Buetehorn, M. Brannock, P. Le-Clech, G. Leslie, D. Volmering, K. Vossenkaul, T. Wintgens, M. Wessling, T. Melin, Limitations for transferring lab-scale microfiltration results to large-scale membrane bioreactor (MBR) processes, Sep. Purif. Technol. 95 (2012) 202–215.

[39] S.P. Hong, T.H. Bae, T.M. Tak, S. Hong, Fouling control in activated sludge submerged hollow fiber membrane bioreactors, Desalination 143 (2002) 219-228.

[40] S.C. Low, K.T. Cheong, H.L. Lim, A vibration membrane bioreactor, Desalination Water Treat. 5 (2009) 42-47.

List of tables

Table 1

Summary of unwashed yeast suspension, washed yeast suspension, and supernatant size distribution analysis (μm).

Types	D (10%)	D (50%)	D (90%)
Bentonite	2.07	5.83	14.53
Unwashed yeast	2.66	4.95	10.94
Washed yeast	3.28	4.63	6.50
Supernatant	2.59	4.38	7.67

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Fig. 11. Total filtration resistance of hollow fibre membranes with vibration relaxations with different time intervals (1% looseness fibres, 5 × 5 fibre bundles, fibre length = 18 cm, permeate flux = 25 LMH, transverse vibrations, vibration amplitude = 16 mm).

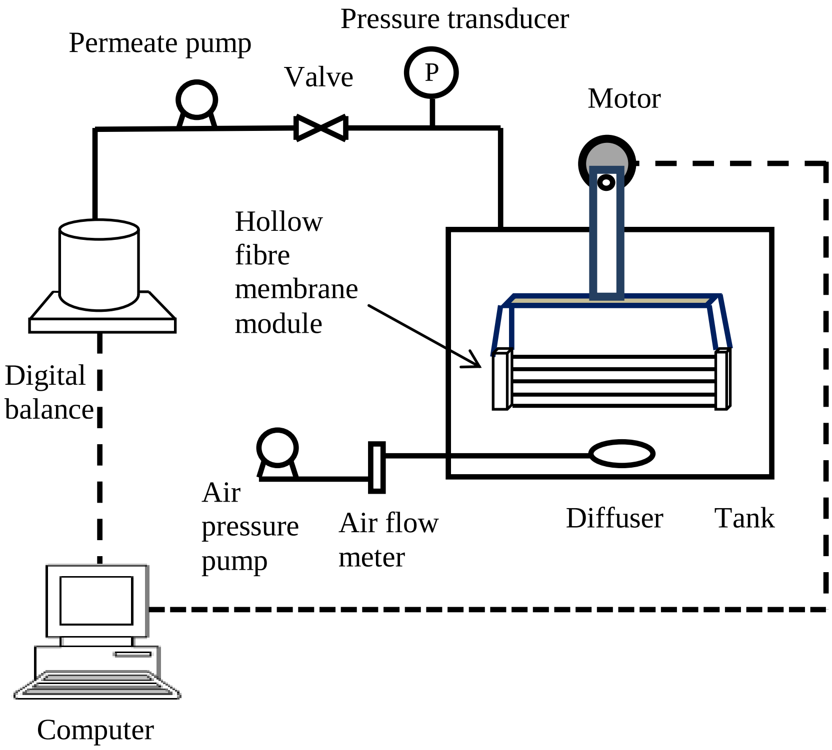
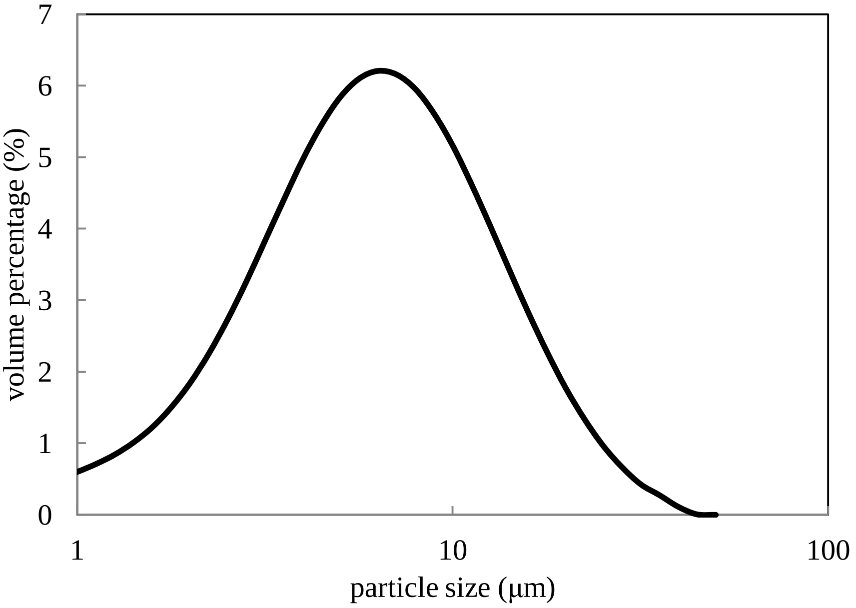
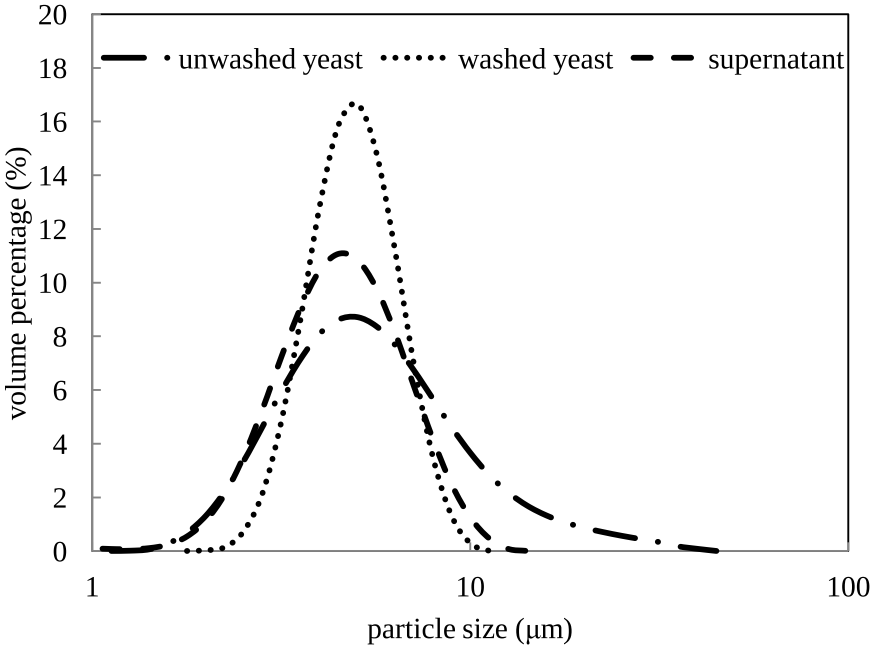


Fig. 1. Schematic diagram of vibration setup.



(a) Bentonite suspension



(b) Yeast suspension

Fig. 2. Particle size distribution of Bentonite suspension, unwashed yeast suspension, washed yeast suspension, and supernatant.

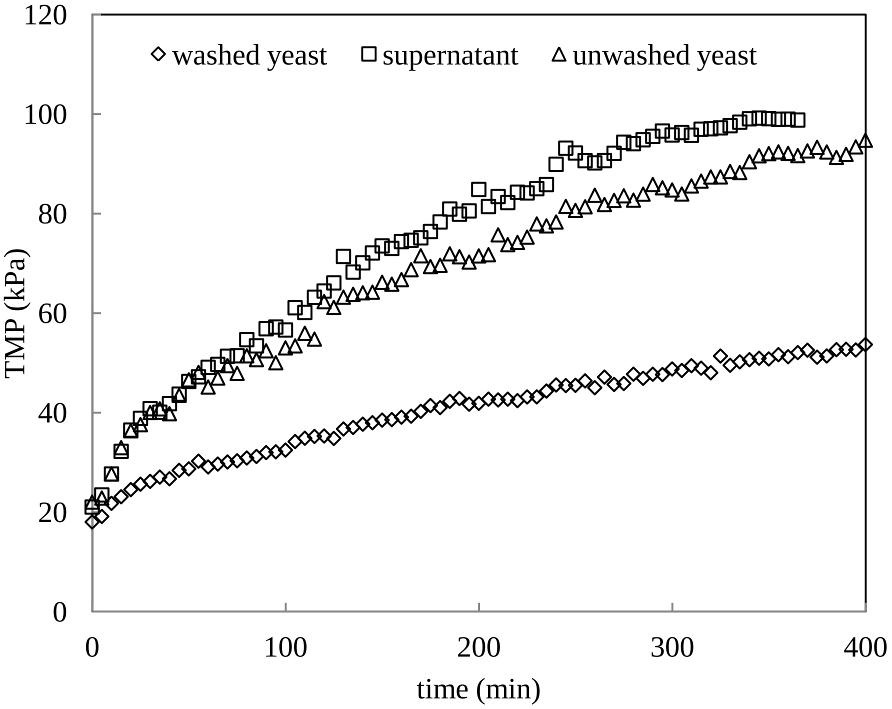
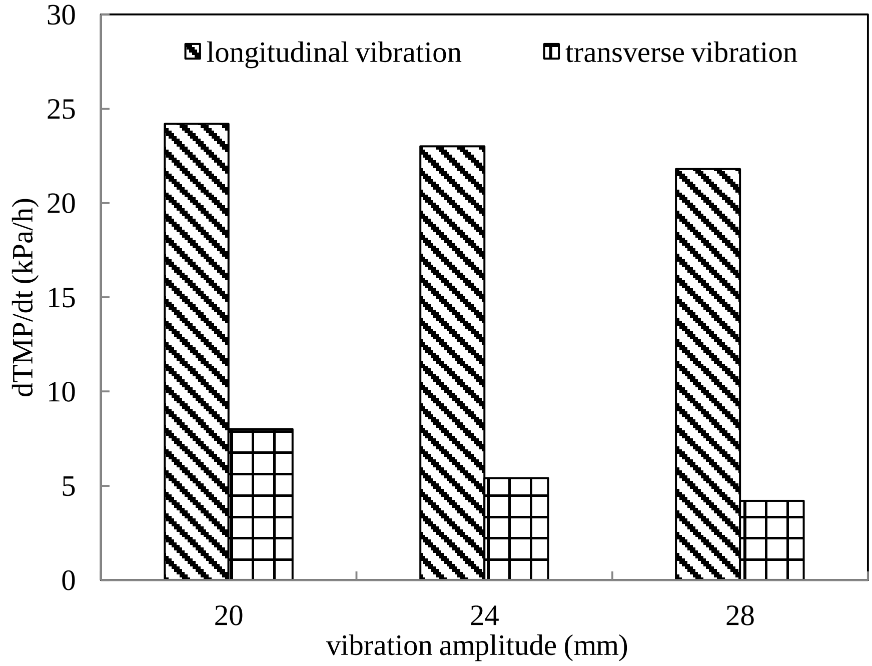
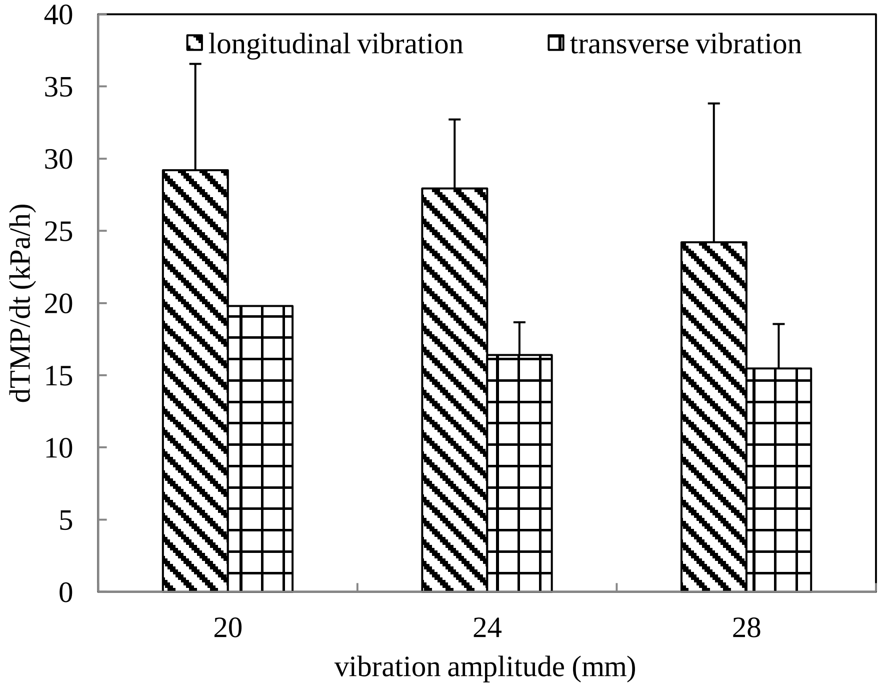


Fig. 3. TMP of unwashed yeast, washed yeast suspension and supernatant (concentration of unwashed and washed yeast suspension = 4 g/L, concentration of supernatant = 1 g/L, 5 × 5 fibre bundles, fibre length = 18 cm, constant permeate flux = 25 LMH, transverse vibrations, vibration amplitude = 16 mm, vibration frequency = 2 Hz).

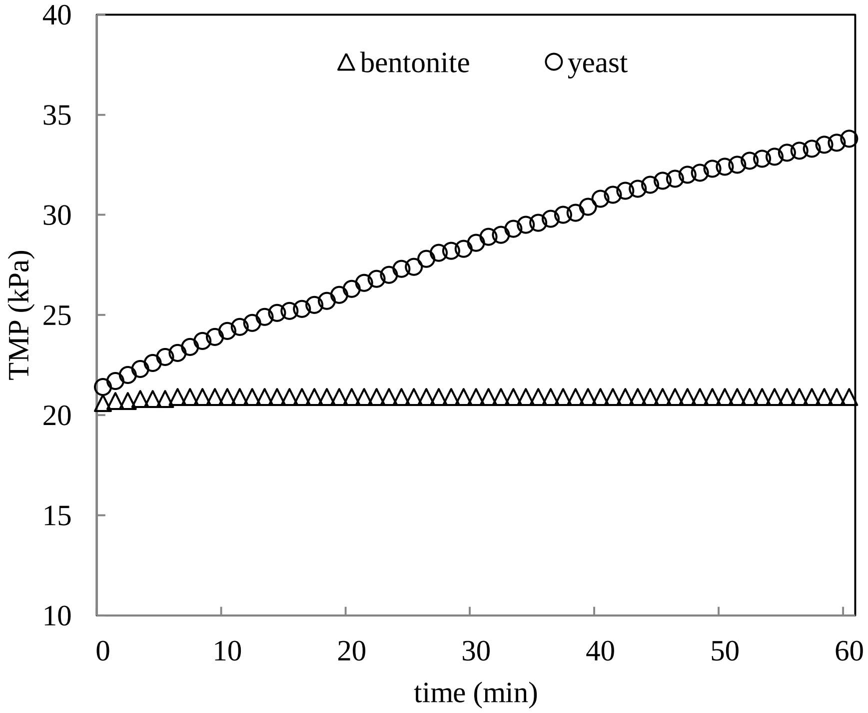


(a) 4 g/L Bentonite suspension

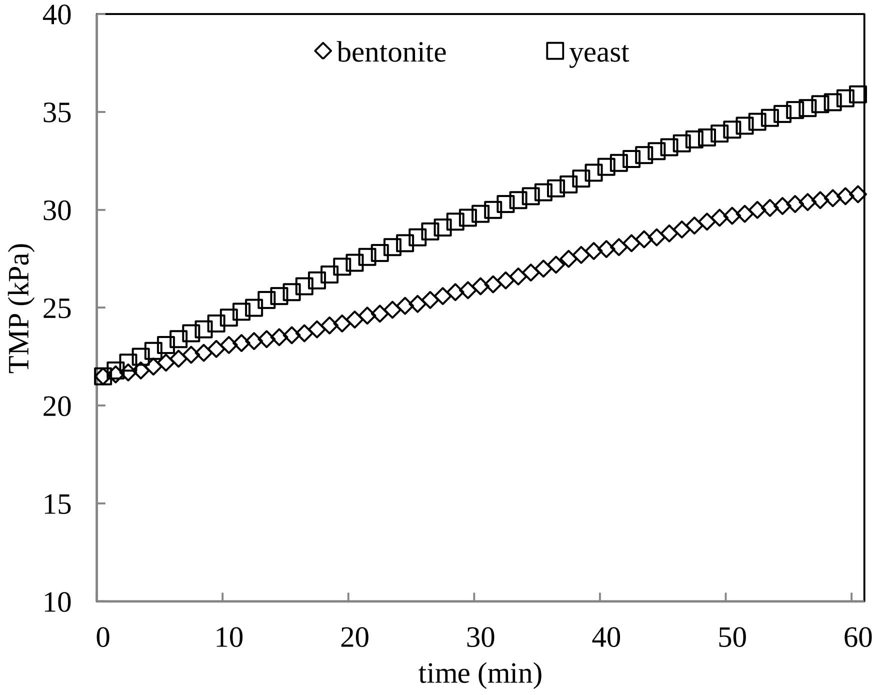


(b) 4 g/L unwashed yeast suspension

Fig. 4. Comparison of fouling rate of longitudinal and transverse vibrations (5 × 5 fibre bundles, tight fibres, fibre length = 18 cm, constant permeate flux = 25 LMH, vibration frequency = 1 Hz).

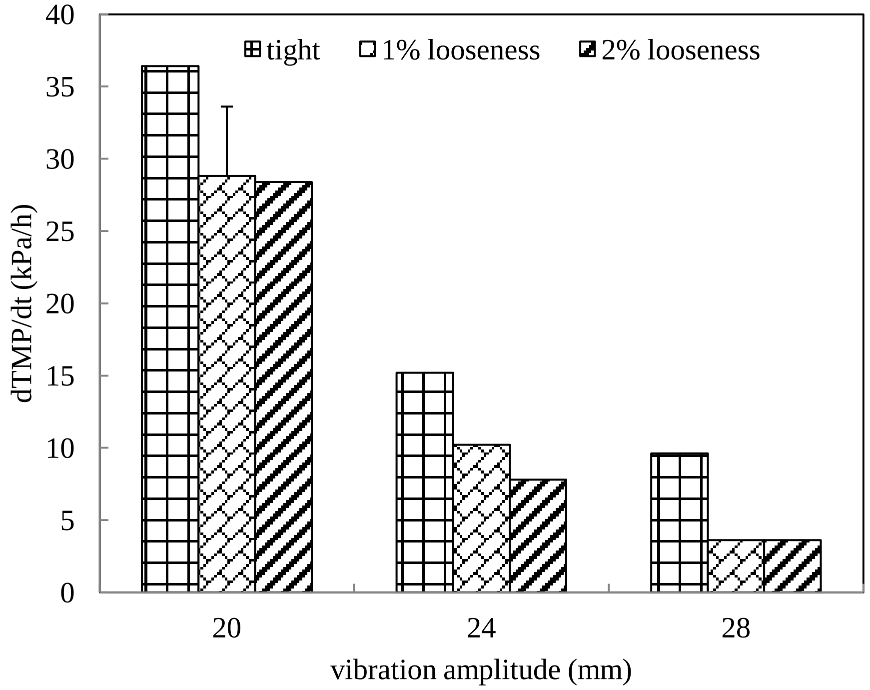


(a) Transverse vibration

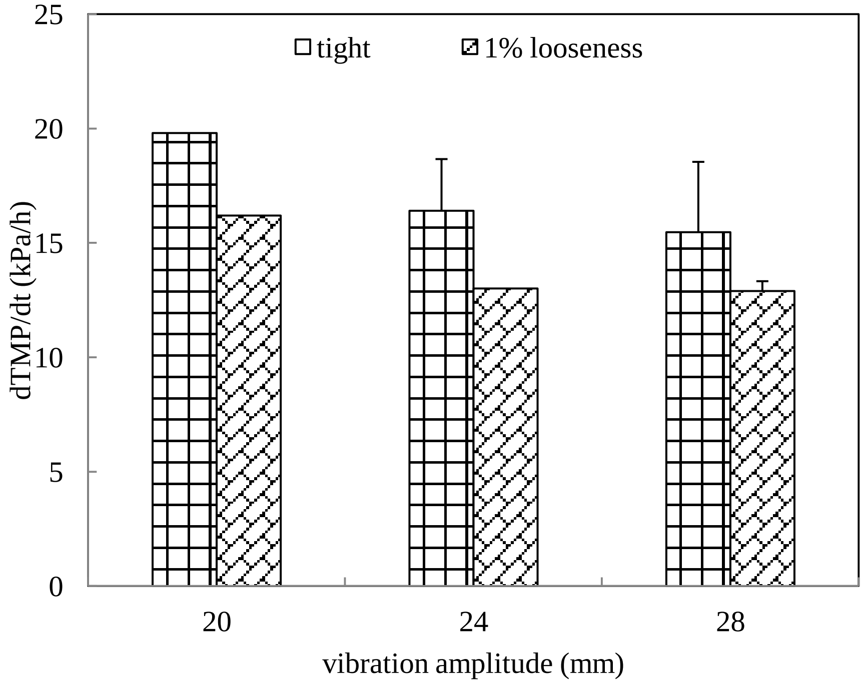


(b) Longitudinal vibration

Fig. 5. TMP of feed suspensions with the same number of particles of Bentonite and unwashed yeast suspension (concentration of Bentonite suspension = 4 g/L, concentration of unwashed yeast suspension = 1.2 g/L, constant permeate flux = 25 LMH, vibration amplitude = 28 mm, vibration frequency = 2 Hz).



(a) 4 g/L Bentonite suspension, constant flux = 30 LMH



(b) 4 g/L yeast suspension, constant flux = 25 LMH

Fig. 6. Fouling rate of tight and loose fibres of Bentonite and unwashed yeast suspension with transverse vibrations (5 × 5 fibre bundles, fibre length = 18 cm, vibration frequency = 1 Hz).

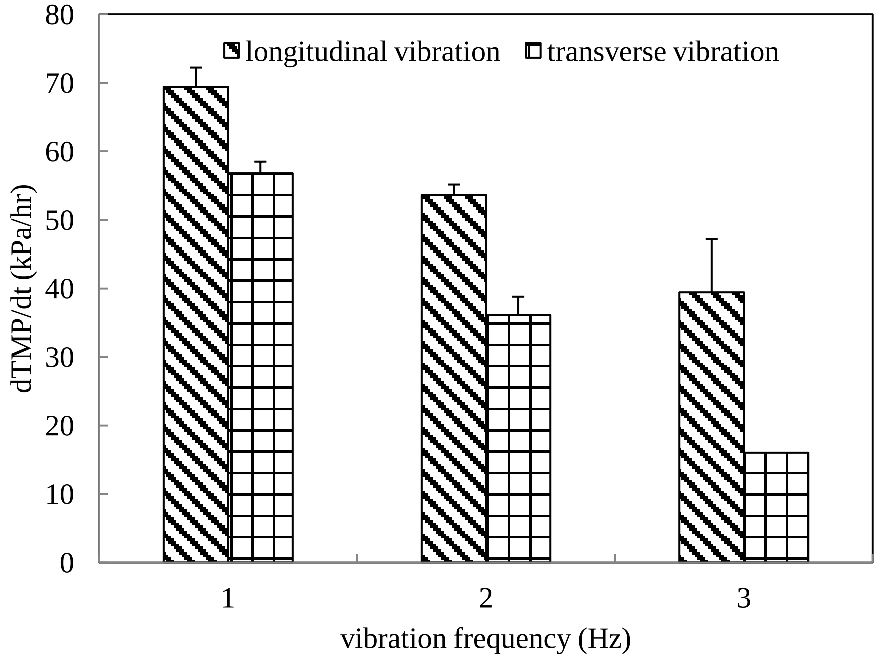


Fig. 7. Fouling rate of longitudinal and transverse loose fibres in 4 g/L unwashed yeast suspension (5 × 5 fibre bundles, fibre length = 16 cm, constant permeate flux = 25 LMH, vibration amplitude = 16 mm).

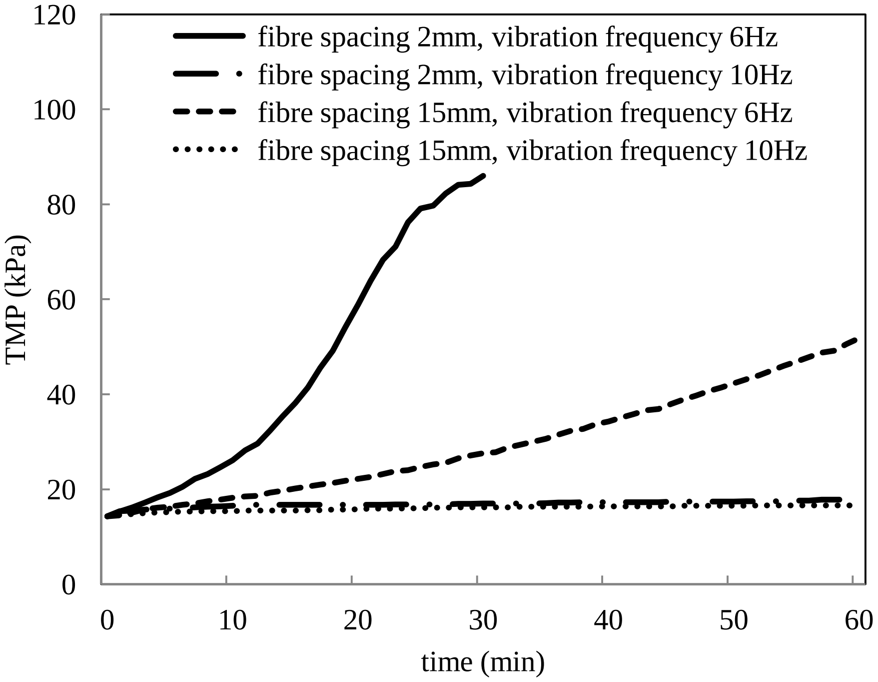
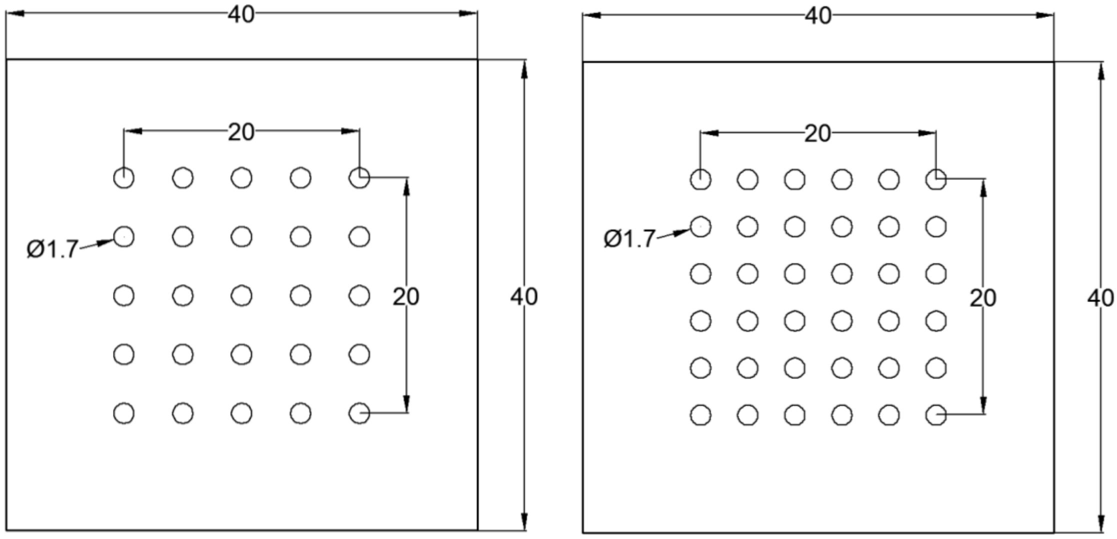
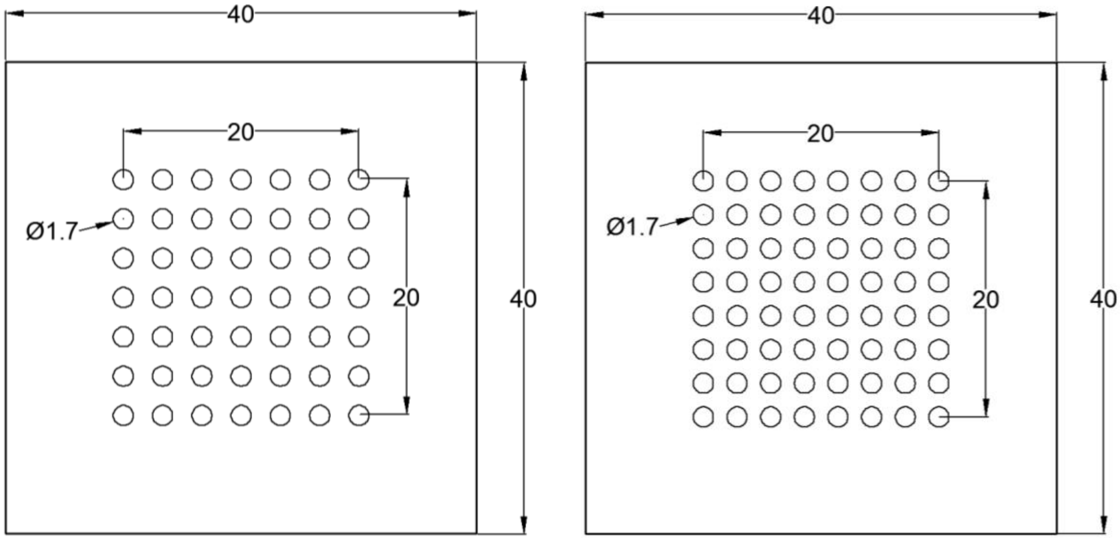


Fig. 8. TMP of hollow fibre membrane with 2 mm and 15 mm spacing at vibration frequency of 6 Hz and 10 Hz in 4 g/L Bentonite suspension (single fibres, tight fibres, fibre length = 20 cm, permeate flux = 30 LMH, longitudinal vibrations, vibration amplitude = 8 mm).

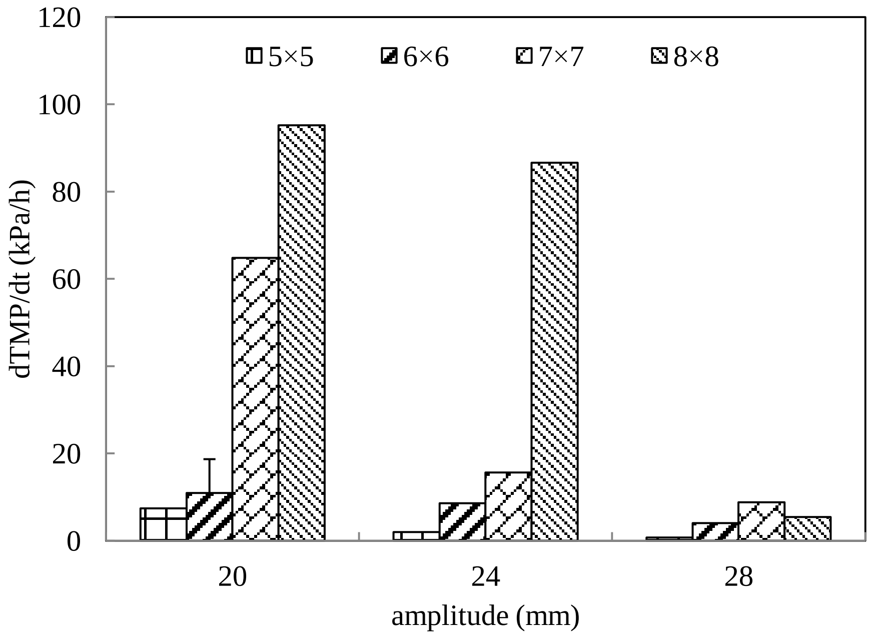


(a) 5 × 5 (b) 6 × 6

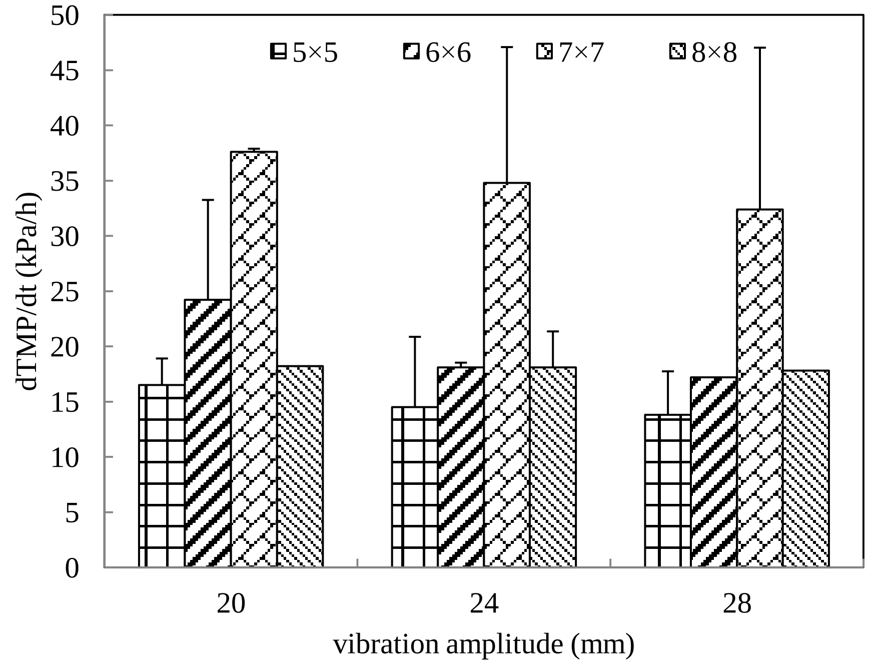


(c) 7 × 7 (d) 8 × 8

Fig. 9. Layout of fibre bundles (mm).

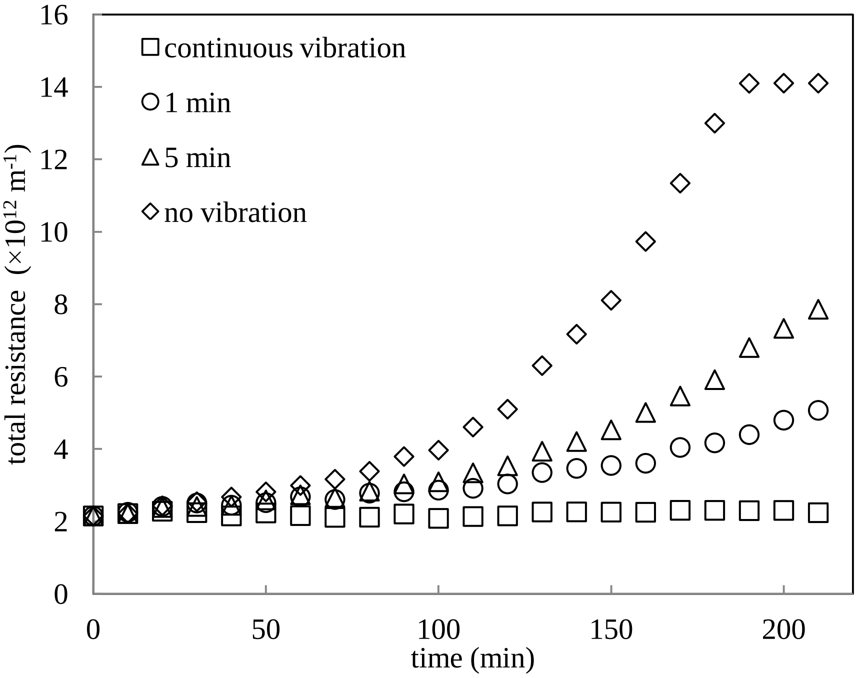


(a) 4 g/L Bentonite suspension, constant flux = 30 LMH, vibration frequency = 1.2 Hz

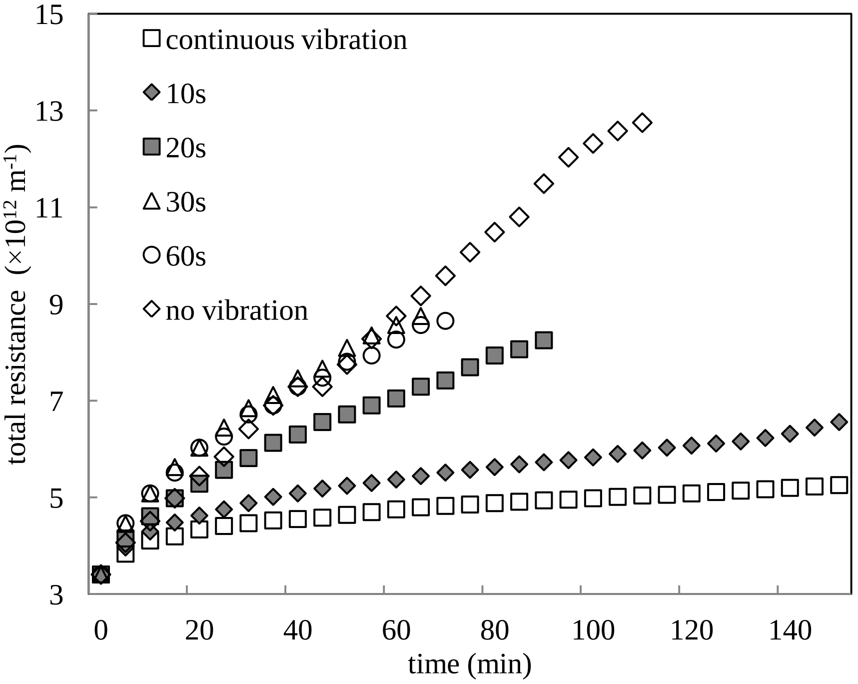


(b) 4 g/L unwashed yeast suspension, constant flux = 25 LMH, vibration frequency = 2 Hz

Fig. 10. Fouling rate of different packing densities of hollow fibre membrane bundles (1% looseness, fibre length = 18 cm, transverse vibrations, vibration amplitude = 20 mm).



(a) 4 g/L Bentonite suspension, vibration frequency = 1 Hz



(b) 4 g/L unwashed yeast suspension, vibration frequency = 2 Hz

Fig. 11. Total filtration resistance of hollow fibre membranes with vibration relaxations with different time intervals (1% looseness fibres, 5 × 5 fibre bundles, fibre length = 18 cm, permeate flux = 25 LMH, transverse vibrations, vibration amplitude = 16 mm).