Low energy consumption vortex wave flow membrane bioreactor
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ABSTRACT
In order to reduce the energy consumption and membrane fouling of the conventional membrane bioreactor (MBR), a kind of low energy consumption vortex wave flow MBR was exploited based on the combination of biofilm process and membrane filtration process, as well as the vortex wave flow technique. The experimental results showed that the vortex wave flow state in the membrane module could be formed when the Reynolds number (Re) of liquid was adjusted between 450 and 1,050, and the membrane flux declined more slowly in the vortex wave flow state than those in the laminar flow state and turbulent flow state. The MBR system was used to treat domestic wastewater under the condition of vortex wave flow state for 30 days. The results showed that the removal efficiency for CODcr and NH3-N was 82% and 98% respectively, and the permeate quality met the requirement of ‘Water quality standard for urban miscellaneous water consumption (GB/T 18920-2002)’. Analysis of the energy consumption of the MBR showed that the average energy consumption was 1.90 ± 0.55 kWh/m³ (permeate), which was only two thirds of conventional MBR energy consumption.

Key words | energy consumption, low Reynolds number, membrane bioreactor, vortex wave flow

INTRODUCTION
Conventional membrane bioreactor (MBR) process is an effective treatment technology for wastewater treatment offering two main advantages, including a significantly improved effluent quality and a substantially small footprint, which has a bioreactor with a membrane module separator in it (Aslam et al. 2017). MBR has been developing for several decades and always broadening its application fields, and it has attracted more and more attention. However, the widespread application is hindered by its relatively high capital investment, high energy consumption as well as severe membrane fouling (Wang et al. 2015). Presently, most of the studies focus on the low-cost filter materials including woven and non-woven to reduce its high capital investment, the hydrodynamic circulation in sub-critical conditions, and economical aeration conditions to reduce its high energy consumption, as well as fouling control strategies (such as critical flux value hydraulic control, chemical control, and biological control) to reduce membrane fouling (Meng et al. 2017).

Currently many scholars focus on the performance of aeration conditions control to reduce the energy consumption, but the economical analysis indicated that about 50 percent of the MBR process operation cost was caused by the aeration consumption and 30 percent was caused by its membrane fouling control (Krzeminski et al. 2017).

The concept of vortex wave MBR was presented in 1996, in which Millward et al. used the vortex wave as an effective aeration technique for application in high density mammalian cell culture (Millward et al. 1996). Montante et al. used particle image velocimetry (PIV) to investigate the fluid-dynamics characteristics of a vortex-ingesting stirred tank for biohydrogen production (Montante et al. 2015). Recently, relatively more attention has been paid to flow field to enhance membrane filtration and mitigate membrane fouling, e.g. turbulence promoter, pulsation, rotating membrane filter and secondary flow (vortex flow) (Hong et al. 2017).

As mentioned above, the traditional MBR is a conventional process combining the activated sludge process and membrane filtration process. Although it was studied to
overcome its membrane fouling and minimize its energy consumption at present (Habib et al. 2017), there were very few investigations on the coupling process of biofilm combined with membrane filtration. To overcome the drawbacks of higher energy consumption and improve the anti-fouling performance of the conventional MBR, a low energy consumption vortex wave flow MBR, combining biofilm process, membrane filtration process and vortex flow in one process, was studied in this paper.

**MATERIALS AND METHODS**

**Experimental set-up**

The vortex wave flow MBR experimental set-up consists of four components: membrane module, recirculation pump, settling tank and circulation tank. A schematic diagram of the experimental facility is shown in Figure 1.

Ten membrane tubes were connected by a connecting pipe to form a membrane module, which was installed in the settling tank by a membrane module frame. Each membrane tube had an effective membrane area of 0.01 m² and the total effective membrane area was 0.1 m². Raw waste water flows into from one end and out from the other end of the membrane module when the system works. The circulation pump in the experiment was a kind of reciprocating plunger metering pump, which could promote liquid to form a pulse flow regime in the membrane tube with different frequency. The parameters of the pump were as follows: piston diameter 15 mm, linkage length 50 mm, piston stroke 0–20 mm, oscillation frequency 0–1.25 Hz. The membrane tube (Figure 2) was assembled with a spiral support structure and polypropylene nonwoven fabric with membrane pore size of 4.0 μm. The material of the spiral support structure was polyvinyl chloride (PVC), the shape of which was cylindrical bar and the diameter was 1.5 mm. The parameters of the spiral support structure were as follows: helical pitch 3.0 mm, inner diameter 10.0 mm, and length 150.0 mm. The polypropylene nonwoven fabric was wrapped on the outer of the spiral support structure as filtration media and biofilm attached media. The volumes of the circulation tank and the settling tank were 8.0 L and 6.0 L respectively. The hydraulic retention time of permeate in the settling tank was about 2 hours.

**Raw waste water quality**

The raw waste water in the experiment was obtained from a dormitory sewage. The raw waste water quality was as follows: temperature 15–20 °C; pH 6.5–7.8; CODcr 150–280 mg/L; NH₃-N 30–65 mg/L. The suspended solids content of the raw wastewater was removed during the process of pretreatment.

**Methods of biofilm formation**

For improving the initial biofilm formation velocity, the method of static state stuffy aeration was used in the initial stage of the experiment. The process was as follows: seeding activated sludge (volume 2 L) and waste water (volume 10 L) was mixed completely, and then the mixed liquid was poured into a culture tank. Two ends of the membrane tubes were sealed and then laid in the culture tank without aeration for 24 hours while the microorganism would colonize on the outer surface of the membrane tube. Then the mixed liquid was aerated for 22 hours and settled for 2 hours, the supernatant was discharged, then an equal volume of waste water was poured into the cultivation tank. When the process was repeated for 7 days, a tawny slime layer of biofilm would be observed on the outer surface of the membrane tube.
Methods of vortex wave flow formation

The vortex wave flow experiment of the MBR system was conducted with clean water. Vortex wave flow is a special flow regime with a discrete boundary layer phenomenon, which can be generated under periodical disturbance and lower Reynolds number conditions. It can reduce the thickness of the boundary layer and enhance the mass transfer effect under laminar flow (Xu 2012). The vortex wave flow regime can be generated by the design of the spiral structure of the membrane tube and adjusting pulse frequency of the liquid in the membrane tube.

The liquid flow velocity and pulse frequency in the membrane tube have great influence on the formation of vortex wave flow. A reciprocating plunger metering pump was used to induce the vortex wave flow by adjusting the pulse frequency, and the liquid flow velocity in the membrane tube was controlled by adjusting the valve in the pipe. A PIV system was used to measure the flow field of the membrane tube. The PIV system was composed of a charge coupled device camera with 2,048 × 2,048 pixel resolution.

The membrane module was installed in the reactor by a membrane module frame when the biofilm had been formed on the outer surface of the membrane tube. The waste water flow was adjusted by the valve in the pipe and the flow pulse frequency was adjusted by the reciprocating plunger metering pump, the object of which was to induce the state of vortex wave flow in the membrane tube. Dissolved organic material in the liquid penetrated to the biofilm through the membrane, and was then adsorbed and biodegraded by the biofilm. As the biofilm thickness increased, it sloughed off and settled at the bottom of the settling tank. Permeate was discharged through an outlet of the settling tank.

RESULTS AND DISCUSSION

Working mechanism

The membrane module of the vortex wave flow MBR is constituted of two parts: one is a spiral support structure made of PVC, which is like a spring, and the other is polypropylene nonwoven fabric with different pore sizes as a filtration media wrapped outside the spiral support structure. The shape of the membrane module is like a tube, so it also could be called a membrane tube. When the raw waste water flows longitudinally inside the membrane tube for a period of time, the biofilm will grow attached on the outer surface of the membrane tube. The dissolved organic matter (measured as chemical oxygen demand, CODcr) in waste water infiltrates through the membrane pores, and is trapped by the biofilm (slime layer) microorganisms on the membrane as growth nutrients, thus the organic matter in waste water could be biodegraded. As the microorganisms grow and the slime layer thickness increases, oxygen is consumed before it can penetrate the full depth, and an anaerobic environment is established near the surface of the membrane. Bacteria in the interior layer can enter an endogenous respiration state and lose their ability to cling to the membrane surface, and the biofilm falls off gradually, then a new biofilm starts to grow on the outer surface of the tube membrane; thus, the biofilm will be renewed gradually (Florjanic & Kristl 2011). The biofilm microorganisms on the outer surface of the membrane are directly in contact with oxygen, which maintains the microorganism growth and metabolism in an aerobic state, making the oxygen transfer rate increase greatly. The biofilm microorganisms consume the nutrients with a much higher availability of oxygen, so the CODcr degradation rate is also at a higher velocity. For the MBR, the aeration is passive and all you have to do is to pump the liquid through the membrane tube. Figure 3 illustrates the mechanisms occurring in the MBR system.

The spiral support structure of the membrane tube can promote the liquid to form a vortex wave flow regime under a lower Reynolds number, which can enhance mass transfer inside the membrane tube under a laminar flow regime (Aparecida Santiago et al. 2011). In other words, it can restrain concentration polarization and mitigate membrane fouling. The process overcomes the high turbulence flow regime in a conventional membrane tube, so it can significantly reduce the energy consumption of the system operation.

Figure 3 | Diagram of MBR working mechanism.
The energy consumption of the vortex flow MBR is only to pump the raw waste water circulating from the raw water tank to the membrane module. Unlike a conventional MBR, it does not need artificial aeration for the microorganism attached on the outer surface of the membrane. The process not only enhances the microorganism's utilization efficiency of oxygen, but also largely reduces the MBR system energy consumption.

**Formation process of vortex wave flow**

The vortex wave flow is characterized by the combination of Reynolds number (Re) and Strouhal number (St) (Chang et al. 2012; Lin & Huang 2012).

\[
St = \frac{\Omega h}{v} \quad \text{and} \quad Re = \frac{v h}{\nu}
\]

where \( \Omega \) is the frequency, \( v \) is the flow velocity, \( \nu \) is the kinematic viscosity, and \( h \) is the characteristic length of the flow channel.

The liquid oscillatory flow in the membrane tube is induced by pistons of the reciprocating plunger pump. The fluid flow fields of the membrane tube could be analyzed by PIV measuring and digital image processing methods.

Under the condition of the pulse frequency \( \Omega \) as 1.25 Hz, the state of vortex wave flow would appear in the membrane tube with the wavelength of the vortexes being about 2.5 mm, when the liquid flow velocity in the membrane tube increased to 0.15 m/s, which is shown in Figure 4(a). It was considered that a steady vortex wave flow started to form in the membrane tube with a Reynolds number of 450, which is shown in Figure 4(b). The structure of the vortexes began to disappear with a Reynolds number of 1,050, when the liquid velocity increased gradually to 0.20 m/s.

In conventional MBR systems with tubular membranes, the concentration boundary layers are disrupted by increasing liquid velocities in the narrow channels of the membrane tubes, which indicates higher energy consumption. An advantage of the vortex wave flow is that it can generate convective mixing in the liquid flow under a lower Reynolds number, which shows that the vortex wave flow regime in the membrane tube can reduce the energy consumption.

**Formation of biofilm**

The biofilm grew successfully attached on the outer surface of the membrane tube, and the permeate was relatively clear by visual observation when the vortex wave flow MBR system had run stably for about one month. Under that condition, if a piece of biofilm layer was peeled off from the outer surface of the membrane tube and observed using an electron microscope, a large amount of *Achromobacter*, *Flavobacterium*, Pseudomonadaceae, *Alcaligenes*, filamentous fungi, as well as bell insects, rotifers, and *Amoeba* can be observed among the bacterial species.

![Figure 4](https://iwaponline.com/wst/article-pdf/76/9/2465/209127/wst076092465.pdf)
composing the biofilm, which indicated that the biofilm grew successfully and worked well.

As shown in Figure 5, the characteristics and composition of the biofilm layer peeled from the outer surface of the membrane tube were analyzed by scanning electron microscopy (SEM). The SEM images indicated the composition of the biomass layer of bacterial colonies and a number of microbes. The cells seemed to appear slightly deformed and contracted to relatively small sizes (0.3–0.5 μm), and were heterogeneously distributed over the outer surface of the membrane tube.

**Influence of liquid flow regime on the membrane flux and TMP**

Membrane fouling significantly affects MBR transmembrane pressure (TMP) and the membrane flux. The TMP represents the liquid permeation driving force and the membrane flux is a main indicator reflecting membrane filtration ability; however, liquid flow velocity and flow regime in the membrane tube have great influence on the membrane flux.

The increasing of cross flow velocity and the turbulence state of the liquid flow in the membrane tube can enhance mass transfer effect, restrain concentration polarization, decrease membrane fouling and increase membrane flux, but a higher flow velocity in the membrane tube will certainly cause higher energy consumption. When the membrane flux value is lower than the critical flux value, filtration can take place in stable conditions during the system working period.

In this experimental study, the liquid flow states in the membrane tube were affected by the liquid flow velocities. The liquid flow state in the membrane tube was the laminar flow state under the velocity of 0.10 m/h, the vortex wave flow state of 0.15 m/h and turbulent flow state of 0.22 m/h by PIV measuring.

When the vortex wave flow MBR system had run for about a month stably, the membrane flux and TMP variation with running time under different conditions of fluid flow states were investigated. The results are shown in Figures 6 and 7 respectively.

The membrane flux variation trends with the system operation time under three liquid flow velocities were investigated as shown in Figure 6. The initial membrane fluxes of three clean nonwoven fabric membrane tubes were 40 L·m⁻²·h⁻¹ under the same initial conditions. The membrane flux declined slowly at the velocity of 0.15 m/h, of

![Figure 5](https://iwaponline.com/wst/article-pdf/76/9/2465/209127/wst076092465.pdf)
which the liquid flow state was the vortex wave flow state, and the membrane flux declined to 26 L·m⁻²·h⁻¹ after the system had run for 30 days. Comparatively, the membrane fluxes under flow velocities of 0.10 m/h and 0.22 m/h declined more rapidly than that at 0.15 m/h. The experimental results indicated the following: firstly, the membrane fluxes declined with MBR system operation time under the three liquid flow states of laminar flow, turbulent flow and vortex wave flow, but the three membrane flux decline rates were different; secondly, the membrane flux declined more slowly in the vortex wave flow state than those in the laminar flow state and turbulent flow state; thirdly, the membrane flux declined more slowly in the turbulent flow state than in the laminar flow state, comparatively.

The other parameter of MBR system operation performance was TMP, which also indicated the degree of membrane fouling. The TMP variation rates with the MBR operation time in this experiment are shown in Figure 7.

All initial TMPs of three velocities in the MBR system were 35 kPa. The TMPs reached 60 kPa at the liquid flow velocity of 0.10 m/h and 65 kPa at the liquid flow velocity of 0.22 m/h respectively when the MBR system had run for 30 days, but the TMP only reached 41.7 kPa at a liquid flow velocity of 0.15 m/h, which showed us that the TMP variation directly related to the liquid flow states in the membrane tube. The TMP experimental results indicated the following: firstly, the membrane fouling degree was lowest when the liquid flow was under the vortex wave flow state; secondly, the membrane fouling degree was comparatively lower in the turbulent flow state than that in the laminar flow state, comparatively; thirdly, the MBR system could run for a longer period stably only in the vortex wave flow state.

Efficiency of waste water treatment

The vortex wave flow MBR system was used to treat domestic wastewater under the condition of liquid flow in the vortex wave flow state in the membrane module, for which the liquid flow velocity was adjusted to 0.15 m/h in the membrane tube. When the biofilm formation was successfully achieved on the outer surface of the membrane tube, the color of the biofilm was dark brown and the thickness of the biofilm was uniform, and in addition the permeate quality was steady.

In the experiment, the vortex wave flow MBR system was used to treat domestic wastewater for 30 days continuously, and the removal efficiencies for CODcr and NH₃-N were investigated. The CODcr and NH₃-N concentration of the influent and effluent were monitored to investigate domestic wastewater treatment efficiency during all the periods of the MBR system’s continuous operation. The experimental results are shown in Figures 8 and 9.

From Figure 8, we can see that the CODcr concentration of the influent ranged from 50 mg/L to 280 mg/L, the maximum and the average value of the permeate was 37.8 mg/L and 28.0 mg/L respectively during the MBR system running period, which showed that the CODcr removal efficiency was more than 82%. The permeate quality was steady during the entire period and met the requirements of ‘The reuse of urban recycling water. Water quality standard for urban miscellaneous water consumption (GB/T 18920-2002)’, although the CODcr
concentration of the influent fluctuated greatly. The experiment results showed that the vortex wave flow MBR was effective in the removal of CODcr by nonwoven fabric filtration and biofilm degradation.

As shown in Figure 9, the NH3-N concentration of the influent ranged from 30 mg/L to 65 mg/L during the experiment period; however, it never exceeded 1.2 mg/L in the effluent throughout the period, which showed that the removal efficiency of NH3-N was stably more than 97%.

Generally, the composition of nitrogen in domestic wastewater is as follows: total Kjeldahl nitrogen (TKN), NO2--N and NO3--N, of which the TKN includes organic nitrogen and ammonia nitrogen (NH3-N). The organic nitrogen can be transformed to NH3-N through ammonification by ammonifying bacteria in anoxic and anaerobic environments; subsequently, the NH3-N may be transformed to NO2--N and NO3--N through nitrification by nitrifying bacteria in an aerobic environment; finally, the NO2--N and NO3--N may be transformed to N2 through denitrification by denitrifying bacteria in an anoxic environment.

The mechanism of the vortex wave flow MBR system with higher NH3-N removal efficiency can be illustrated as follows: a layer of biofilm is grown, attached on the outer surface of the membrane tube, and the biofilm directly connected with oxygen, which maintained the outer layer of the biofilm in an aerobic environment and the inner layer of biofilm in an anoxic or anaerobic environment; in other words, it formed an inverted process of anaerobic – anoxic – oxic (A2/O) compared with the conventional biofilter process.

In the process of NH3-N removal, the soluble organic matter (CODcr) in the wastewater infiltrated through the nonwoven fabric membrane and firstly was used as the organic carbon source for denitrification of NO2--N and NO3--N by the denitrifying bacteria in the inner layer of the biofilm. Simultaneously, the nitrification was also occurring in the outer layer of the biofilm, through which the ammonia was transformed to NO2--N and NO3--N. Although the concentrations of NO2--N and NO3--N were not measured in the experiment, it could be concluded that the biological NH3-N removal processes, including simultaneous nitrification and denitrification (SND), were carried out with higher efficiency in the vortex wave flow MBR system.

Analysis on energy consumption

Energy consumption is an important indicator in a wastewater treatment plant, which can sometimes affect the feasibility of the treatment process. Under the present circumstances, the energy consumption of conventional MBR is normally between 6.0 and 8.0 kWh/m3 (permeate) (Krzeminski et al. 2017). The experimental results showed that the energy consumption of the vortex wave flow MBR fluctuated around 3.0 kWh/m3 (permeate). The average energy consumption was 1.90 ± 0.55 kWh/m3 (permeate). Compared with a conventional MBR, aeration was no longer the energy consumer, for the microorganism directly contacted with oxygen. The energy consumption of the vortex wave flow MBR was only consumed to pump the liquid to circulate from the raw water circulation tank to the membrane module. The liquid flow regime was maintained as a vortex wave flow state in the condition of lower Reynolds numbers in the membrane tube, which avoided a higher turbulent flow regime. Really, the energy consumption of the vortex flow MBR system was that of the plunger pump.
CONCLUSIONS

A low energy consumption vortex wave flow MBR was exploited combining biofilm process, membrane filtration process and vortex flow in one process, which could overcome the conventional MBR disadvantages effectively. The vortex wave flow MBR no longer needs aeration and the liquid flow state in the membrane tube can be maintained as a vortex wave flow regime under a lower Reynolds number condition, which indicates that the energy consumption of the MBR system is significantly lower than that of a conventional MBR.

The liquid flow states in the membrane tube could be maintained as a vortex wave flow regime when the pulse frequency \( \Omega \) was 1.25 Hz and the Reynolds number was 450. The structure of the vortex wave would be decomposed if the liquid flow velocity increased to a critical velocity when the Reynolds number was 1,050.

The membrane fluxes would decline with MBR system operation time, but the membrane flux declined more slowly in the vortex wave flow state than those in the laminar flow state and turbulent flow state. The membrane fouling degree was the lowest among the three liquid flow states of vortex wave flow state, turbulent flow state and laminar flow state. The vortex wave flow MBR system could run for a long time stably in the vortex wave flow state.

The vortex wave flow MBR system was used to treat domestic waste water for 30 days continuously in the experiment. The results showed that the removal efficiency of CODcr and NH3-N was 82% and 98% respectively, and the permeate quality met the requirements of ‘Water quality standard for urban miscellaneous water consumption (GB/T 18920-2002)’. Analysis of the energy consumption of the MBR showed that the average energy consumption was \( 1.90 \pm 0.55 \text{kWh/m}^3 \) (permeate), which was only two thirds of conventional MBR energy consumption.

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