Scientific paper

Effects of Activated Sludge on Hydrodynamic Characteristics of a Hollow Fiber Membrane Bioreactor

Mirjana Čurlin*, Helena Korajlija Jakopović, Ivan Mijatović, Želimir Kurtanjek

University of Zagreb, Faculty of Food Technology and Biotechnology, Pierottijeva 6, 10000 Zagreb, Croatia

** Corresponding author: E-mail: mcurlin@pbf.hr*

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Dedicated to the memory of professor Vojko Ozim

Abstract

A submerged hollow fiber membrane module is a widely accepted wastewater membrane bioreactor. Membrane bioreactor with submerged membrane (HF MBR) is complex multiphase physico-chemico-biological system with internal interactions between process variables and dynamic changes within gas-liquid-solids phases. A study of hydrodynamics in an operating laboratory bioreactor at realistic working conditions is crucial for design and scale up of a bioreactor for wastewater treatment processes. Accumulation of high concentrations of biomass causes the occurrence of heterogeneous regions in a bioreactor. This paper focuses on the effects of activated sludge on average residence time, which is often quite different from the ideally designed hydraulic residence time (HRT) in a submerged hollow fiber membrane bioreactor. In this work, tracer experiments using Dirac δ impulse of the saturated NaCl solution and monitoring electrical conductivity in the outflow with a flow-through conductivity cell were performed. From experiments at liquid flow rate range of 7.2–16.5 L h^{-1}, air flow rate range of 1.7–5.1 m^3 h^{-1}, and activated sludge concentrations MLSS 4.5–7.4 g L^{-1} probability density of residence time distribution (RTD) functions for hollow fiber membrane bioreactor and average residence times τ_{MBR} were calculated The relative residence time defined as the ratio of HF MBR τ_{MBR} and CSTR τ_{id} were evaluated as function of MLSS concentration. Proposed is a linear regression model of the relative residence time with MLSS concentration. The model has negative proportionality coefficient k = –0.0814 g/L of MLSS due to decrease of the relative residence time with increase of active sludge concentration. Statistical evaluation of the model gives the correlation coefficient of R^2 = 0.8374. Decrease of the mean residence time with increase of MLSS is discussed in view of non-uniform membrane fouling.

Keywords: Activated sludge, membrane bioreactor, hydraulic residence time (HRT)

1. Introduction

Membrane bioreactor is a new technology in municipal and industrial wastewater treatment. It has a number of advantages over the classical technology of the activated sludge, and therefore, it takes an important place in development of new systems for treatment of wastewater.

One of the numerous advantages of the membrane bioreactor is its ability to operate under high concentrations of the activated sludge biomass, as well as of MLSS.[1] Many authors have investigated the influence of MLSS on the efficiency of the wastewater treatment process, as well as on the permeability of the membrane, i.e. the process of membrane fouling,[3,4] and they found that aeration plays one of the major roles in successful wastewater treatment process. Apart from the aeration of the biomass, air can be injected at the membrane bottom in order to limit fouling of the membrane surface or clogging of the bundle. Oxygen transfer and longitudinal dispersion of liquid in aeration system depends on specific hydrodynamic and physico-biochemical variables.[5] Aeration also ensures the process of bulk mixing in the bioreactor, which then influences the contact between the wastewater and the microbial population, and in the end has the effect on the efficiency of the bioreactor.[6] High concentration of activated sludge biomass makes the mixing difficult, and may occur that some parts of the bioreactor volume may act as dead zones or as short circuiting liquid zones. Many authors[7–9] determined the flow pattern in bioreactors by quantitative analysis of RTD curves and by determination of plug flow (PF) index, dead volume (DV) index and short circuiting (SC) index. These phenomena influence the differences in the designed HRT compared to mean residence time of the ideal CSTR reactor. The determination of residence time is thus of major interest in the design and characterisation of MBR, where a proper and homogeneous fluid distribution is often essential. A good knowledge of the flow, including the determination of residence time distribution (RTD), allows the optimisation of the mass transfer or the purification of wastewater. Little attention has been paid to the aspects of reactor configuration and the operation modes in relation to the influence of the hydrodynamics of wastewater treatment system on activated sludge properties.[5]

In view of the importance of the concentration of activated sludge, as well as MLSS on hydrodynamic of HF MBR, the aim of this work is to study experimentally the average residence time and to compare it with the residence time of the ideal CSTR for different gas and liquid flow rates and MLSS concentrations.

2. Experimental

2. 1. Bioreactor Configuration

Residence time distribution was determined experimentally in Zenon submerged hollow fiber membrane bioreactor (HF MBR) with activated sludge. Microfiltration membrane module ZW-10 with pore size of 0.4 μm was placed vertically in the 40 L (useful volume) rectangular bioreactor. Reactor was fed with activated sludge from municipal wastewater treatment plant of Velika Gorica, Croatia, and continuously fed with model wastewater during experiments. Liquid was continuously drawn from the membrane at the top of the reactor. Flow rates of both permeate and feed water were maintained with laboratory pump and measured with a flow meter. Compressed air for mixing was supplied through diffuser at the base of the membrane. To investigate the effect of activated sludge on average residence time in a bioreactor, experiments were conducted at liquid flow rate q_l of 7.2, 11.5 and 16.5 L h^{-1} and air flow rate q_g of 1.7, 3.4 and 5.1 m^3 h^{-1}. MLSS concentration was determined before and after the experiments according to standard methods.[10]

2. 2. Tracer Test

For experimental determination of residence time distribution (Fig.1), concentrated solution of NaCl was applied as a tracer. Volume of 50 mL of saturated concentration w_{NaCl} = 28% as a short impulse (approximated by Dirac δ function) was injected by a needle from the top of the reactor. The changes of electrical conductivity were measured with a conductometer OAKTON CON-200 with a flow-through conductivity cell connected to the outfow as close as possible to the bioreactor exit. The data transfer measuring device was connected *on line* to the computer. The data were gathered every 10 seconds on average using Oakton Datalog Assist software. A database for each experiment was made on the computer, and *Mathematica* program was used for numerical and graphic interpretation of the results.

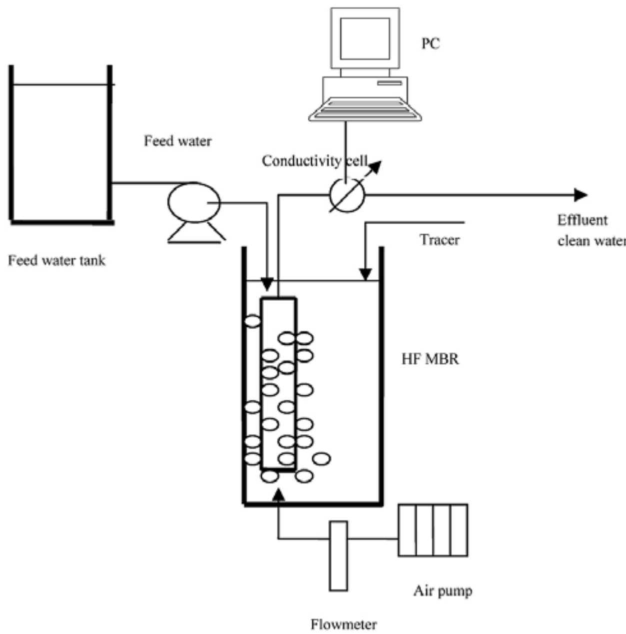

Figure 1. Schematic diagram of experimental set-up for determination of residence time distribution in a hollow-fiber membrane bioreactor (HF MBR).

2. 3. Numerical Procedures

From the tracer concentration response the mean residence time $\bar{t}$ was numerically evaluated by integration of:

$$\bar{t} = \int_0^\infty t \cdot E(t) \cdot dt \tag{1}$$

where $E(t)$ is the density of residence time distribution function called E curve.[11]

The density function (2) was obtained by the first order numerical interpolation of the tracer concentration data and subsequent area normalization to unity[12]:

$$E(t) = \frac{\lambda(t)}{\int_0^t \lambda(t) dt} \tag{2}$$

where $\lambda(t)$ is electrical condudtivity at time t.

The variance of mean residence time (second moment of RTD function) is calculated from (3):

$$\sigma^2(t) = \int_0^{\infty} \left(t - \bar{t}\right)^2 \cdot E(t) \cdot dt \quad (3)$$

All the mathematical calculations, integration of RTD curve, average residence time and variance were carried out by software system *Mathematica* 5.2.

3. Results and Discussion

From tracer experiments at liquid flow rate range of 7.2–16.5 L h^{-1} and gas flow rate range of 1.7–5.1 m^3 h^{-1}, mean residence time for ideal CSTR (τ_{id}) (which is equal to the useful volume of bioreactor V divided by the volumetric flow rate of liquid q_l) and mean residence time for hollow fiber membrane bioreactor $\tau_{MBRa.s.}$ with activated sludge and that with water $\tau_{MBRwater}$ were calculated. The comparison of mean residence times for these reactors at different liquid and gas flow rate is presented in figures 2–4. This comparison gave some information about the flow patterns such as magnitude of the dead volume (DV) or short circuiting (SC). The existence of a dead volume is indicated by τ/τ_{id} <1.[8]

Differences in mean residence time compared to the ideal CSTR at all gas flow rates are observed in membrane bioreactor. The differences are more pronounced at lower gas flow rates in activated sludge bioreactor, and less pronounced in the membrane bioreactor without suspended active sludge. At the lowest gas flow rate, liquid flow has a dominant influence on the mixing process in the reactor, and thus on the mean residence time. Contrary to the expectations, mean residence time of the activated sludge bioreactor is lower than of the bioreactor with water. The reason for this is higher density of the activated sludge, which is more difficult to mix at low gas flow rate, so we suppose that sedimentation of activated sludge occurs and concentration zones are created across the bioreactor volume. Due to less effective mixing, the injected tracer does not cover the entire bioreactor volume, and parts of the reactor work as dead zones. These assumptions were confirmed by calculation DV index shown in Table 1.

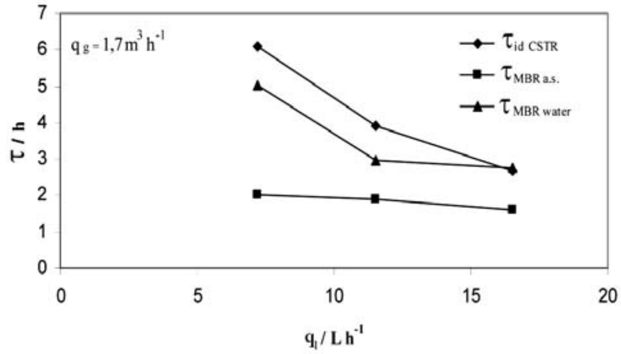

Figure 2. Comparison of the mean residence time for ideal CSTR, HF MBR with activated sludge and HF MBR without sludge at different liquid flow rates and constant gas flow rate of 1.7 m^3 h^{-1}.

Based on low values of DV index (Table 1), it could be concluded that dead zones are present in bioreactors with activated sludge, while in bioreactors without suspended sludge the values of DV are close to 1 (0.9), which indicates that the dead zones do not exist when the membrane bioreactor operates as a two-phase system.

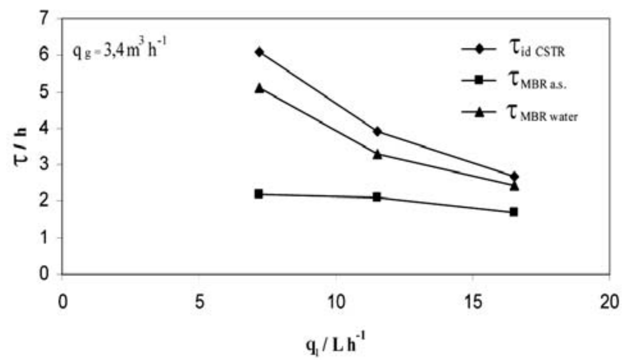

Figure 3. Comparison of the mean residence time for ideal CSTR, HF MBR with activated sludge and HF MBR without sludge at different liquid flow rate and gas flow rate of 3.4 m^3 h^{-1}.

At the highest gas flow rate of 5.1 m^3 h^{-1} (Fig. 4), the aberrations from the ideal reactor are approximately the same at all three liquid flows, which indicates that at

Table 1. Quantitative RTD properties

q_l	q_g	τ_{id}	$\tau_{MBRa.s.}$	$DV_{MBRa.s.}$	$SC_{MBRa.s.}$	$\tau_{MBRwater}$	$DV_{MBRwater}$	$SC_{MBRwater}$	MLSS
7.2	1.7	6.11	2.02	0.331	0.907	5.04	0.825	0.960	7.3712
7.2	3.4	6.11	2.19	0.358	0.908	5.09	0.833	0.977	7.1698
7.2	5.1	6.11	2.91	0.476	0.943	5.62	0.920	0.977	5.0812
11.3	1.7	3.91	1.91	0.488	0.930	2.97	0.760	0.938	4.9106
11.3	3.4	3.91	2.1	0.537	0.942	3.29	0.841	0.975	4.7106
11.3	5.1	3.91	1.69	0.432	0.944	3.55	0.908	0.971	6.6976
16.5	1.7	2.66	1.62	0.609	0.941	2.77	1.041	0.977	4.6532
16.5	3.4	2.66	1.68	0.632	0.952	2.42	0.910	0.963	4.5416
16.5	5.1	2.66	1.28	0.481	0.939	2.22	0.835	0.966	5.894

the highest flow rates, liquid and gas flow rates have about the same influence on the mean residence time.

The shortest average residence time ($\tau_{MBRa.s.}$ = 1.28 h; $\tau_{MBRwater}$ = 2.22 h) was achieved at the highest liquid flow of 16.51 Lh^{-1} and the highest gas flow rate of 5.1 $m^3 h^{-1}$, while the longest ($\tau_{MBRa.s.}$ = 2.91 h; $\tau_{MBRwater}$ = 5.62 h) was achieved at the lowest liquid flow of 7.2 Lh^{-1} and the highest gas flow rate.

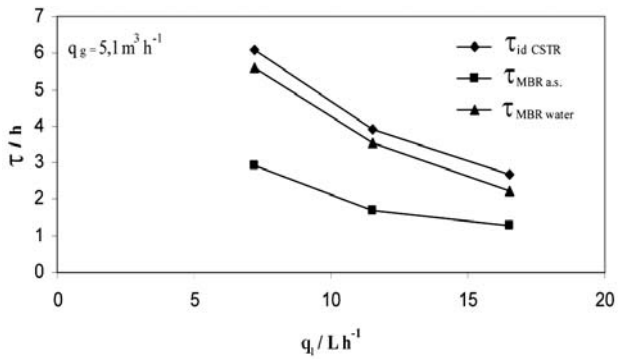

Figure 4. Comparison of the mean residence time for ideal CSTR, HF MBR with activated sludge and HF MBR without sludge at different liquid flow rate and air flow rate of 5.1 $m^3 h^{-1}$.

In the experiments performed at the lowest liquid flow of 7.2 L/h, in the both bioreactors the average residence time was shorter at lower gas flow rates than at the highest gas flow rate. Also, at the lowest gas flow rate, the obtained average residence times were lower than at the medium gas flow rate in all three cases of liquid flow. Shorter residence times could be the result of insufficient mixing, because the aerator is placed under the membrane and does not reach the entire bioreactor volume. Fouling of the membrane also needs to be considered, because it has an important influence on the dispersion of the flow, expressed with a dispersion coefficient, and can be determined by the analysis of the RTD response curve during the measurement of residence time distribution. Apart from increasing the dispersion coefficient, fouling of the membrane influences the formation of dead zones.[13] Data obtained by measuring with clean membranes showed that theoretic mean residence time, which is equal to the ratio of volume and speed of liquid flow, always matches that obtained in the experiment. However, when membranes were clogged, the mean residence time values were significantly lower than the theoretical ones, which indicates the existence of dead zones. Dead zones can also indicate membrane fouling, because the experiments were performed at the lowest liquid flow rate and lower gas flow rates, as well as at the highest concentrations of biomass (MLSS), which had already been proven to influence the fouling of the membrane.[3] Sediment causes fouling of the large part of the membrane surface, so filtration is performed through a smaller surface, which as a consequence increases the speed of the filtration.

The condition of the membrane regarding its age, permeability and applicability should also be taken into consideration. Intensive use of the membrane could cause increase of the pore size; also the permeability of the tracers and solvents has been proven. Degradation of membrane and sediment formed on its surface are reasons why RTD curves obtained by using used membranes are different from the curves obtained by using new membranes.[14] Experimentally determined mean residence time was much shorter when old membranes were used than when new ones were used, which indicates the modification of the membrane structure regarding its degradation, i.e. weakening of its filtration capability.

In this work, hydrodynamics of the entire volume of the reactor was observed, which in hollow fibre membrane module could be significantly different from that within the membrane module itself. The flow system within the membrane module depends on the density of the module packaging . At higher densities of module packaging, the flow system is significantly different from the ideal one, while at the lower densities it is almost equal to the ideal flow.[15]

Gas flow rate, i.e. aeration, has a significant influence on the mixing process. The importance of the selection of a mixing system in a three-phase MBR is essential for successful process of wastewater treatment.[16] With regulation of the liquid and gas flow rate, it is possible to obtain suitable residence time necessary for achieving optimal productivity of the wastewater treatment process in membrane bioreactor.

Because of the differences in mean residence times obtained when the MBR system operates as a two-phase system (MBR water) and as a three-phase system (MBR a. s.), it is important to define the influence of biomass on the obtained mean residence time and on the existence of dead zones. Concentration of activated sludge biomass was the highest in the experiment performed on the first day (MLSS = 7.979 g L^{-1}), and it continuously decreased throughout the days that followed, and it was the lowest

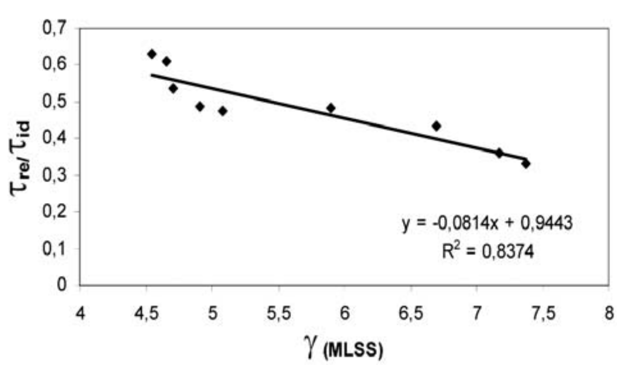

Figure 5. Linear regression model of the relative residence time with MLSS concentration

on the last day (MLSS = 4.5416 g L^{-1}). Dying of biomass occurred since the biomass did not go through the phase of adjustment to the new conditions in the membrane bioreactor after it had been taken from the secondary settler system for wastewater treatment in the town of Velika Gorica. Higer aberrations of the experimentally obtained average residence times from the ideal ones, which diminished with the decrease of MLSS, were observed at higher concentrations of activated sludge biomass.

A linear regression model of the relative residence time with MLSS concentration is determined with the correlation $R^2 = 0.8374$ (Fig 5). The influence of each liquid and gas flow rate cannot be defined, since the experiments were performed random order.

At higher MLSS values, the existence of dead volume is significant (Table 1), so for the MBR system that works under high biomass concentrations, the design of a mixing system is essential in order to achieve a better contact of water with activated sludge and thus obtain a better efficiency of the process.

4. Conclusion

In this work two average residence times were compared, i.e. for ideal CSTR and HF MBR without suspended sludge, and HF MBR with activated sludge. Also, from the experiment tracer test DV and SC indices were determined, which indicate the flow properties in the bioreactor. A linear regression model of the relative residence time with MLSS concentration was determined with the correlation $R^2 = 0.8374$.

The obtained results confirm that the selection of gas flow rate and liquid flow rate is essential, because they serve for mixing in the bioreactor. HRT in bioreactor can be influenced by the adjustment of the liquid and gas/air flow rates, which in a real three-phase system is significantly different from the ideal model. The time of contact between the wastewater and the activated sludge is very important for the efficiency of the wastewater treatment process. Depending on the concentration of the activated sludge, relative relations between the mean residence time for ideal and for real reactor change. The obtained results are applicable in development and design of a large scale membrane bioreactor.

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Povzetek

Potopljeni membranski modul z votlimi vlakni se pogosto uporablja kot membranski bioreaktor za odpadne vode. Membranski bioreaktor s potopljeno membrano (HF MBR) je kompleksni večfazni fizikalno-kemijsko-biološki sistem z internimi interakcijami med procesnimi spremenljivkami in dinamičnimi spremembami v fazah plin-tekoče-trdno. Študij hidrodinamike v laboratorijskem biorekatorju pri realnih delovnih pogojih je ključnega pomena za načrtovanje in dimenzioniranje bioreaktorja za obdelavo odpadnih vod. Akumulacija visokih koncentracij biomase povzroča pojav heterogenih območij v bioreaktorju. V prispevku je poudarjeno proučevanje vpliva aktivne brozge na povprečni zadrževalni čas, ki se pogosto razlikuje od idealno dimenzioniranega hidravličnega zadževalnega časa (HRT) v proučevanem reaktorju. Opisani so poiskusi z uporabo Dirac δ impulzov nasičene raztopine NaCl in spremljanje električne prevodnosti v območju pretoka tekočine od 7.2–16.5 L h^{-1}, pretoka zraka od 1.7–5.1 m^3 h^{-1}, in koncentracije aktivne brozge MLSS od 4.5–7.4 g L^{-1}. Izračunani so verjetnostna funkcija porazdelitve zadrževalnega časa (RTD) in povprečni zadrževalni časi τ_{MBR}. Relativni zadrževalni čas, definiran kot razmerje HF MBR τ_{MBR} in CSTR τ_{id}, je izračunan kot funkcija koncentracije MLSS. Predlagan je linearni regresijski model za relativni zadrževalni čas s koncentracijo MLSS. Model ima negativni koeficient k = –0.0814 g MLSS /L zaradi zmanšanja relativnega zadrževalnega časa z naraščanjem koncentracije aktivne brozge. S statistično evaluacijo modela dobimo korelacijski koeficient R^2 = 0.837. Diskutirano je zmanšanje povprečnega zadrževalnega časa z naraščanjem MLSS z vidika ne-enakomerno zamašene membrane.