Waste Water Treatment using MBR

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Membrane Bioreactor combines membranes with Biological processes for treatment of waste water. Presently more than 500 MBR units have been commissioned and many more are in the process of installation and commissioning around the globe. These MBR's treat both industrial and municipal waste water as well as, for in building treatment & use of grey water. Combining Membrane technology with biological processes has led to the development of three generic membrane bioreactors - separation and retention of solids, bubble – less aeration within the bioreactor (Still in R & D stage), extraction of priority organic pollutants from industrial wastewaters (Still in R & D stage). Membranes coupled to biological processes often used as replacement of sedimentation. i.e. separation of biomass. The very high quality of the treated water from an MBR process is common to all commercial aerobic systems. Complete solids removal a significant disinfection capability, high rate and high efficiency organic and nutrient removal and a small footprint are all characteristics of the MBR, regardless of the wastewater type to be treated or the commercial process used. The quality of treated water from these processes is so high that the recycling and reuse is often a viable option. The waste water treated to reuse standards, includes black water and as well as grey water. From large shopping malls, housing societies, large hotels, commercial buildings etc, commercial MBR's are providing high performance, low maintenance, small footprint on site process capable of a high quality treated water suitable for reuse. As the cost of the membrane modules reduces, combined with extended life expectancy of membranes, acceptance of the processes capabilities, advances in process design and operation have all resulted in MBR treating large volumes, low strength municipal waste water. Thus in the near future MBR provides a viable solution to the water shortage problems faced by our cities year after year.

The advantages/ disadvantages of membrane bioreactor –high quality of treated water from MBR process, complete solid removal, disinfection capability, combined high rate and efficiency of organic and nutrient removal in one unit, small foot print, high performance and low maintenance, high loading rate capability, low zero sludge production, rapid start up, sludge bulking is not a problem, modular and retrofit. The disadvantages of membrane bioreactor –

aeration limitation, membrane fouling, membrane costs. To make MBR technology as economically viable option, it becomes imperative to examine and optimize the design conditions of MBR. By operating the membranes on critical flux regimes fouling of membranes can be prevented or reduced to quite an extent.

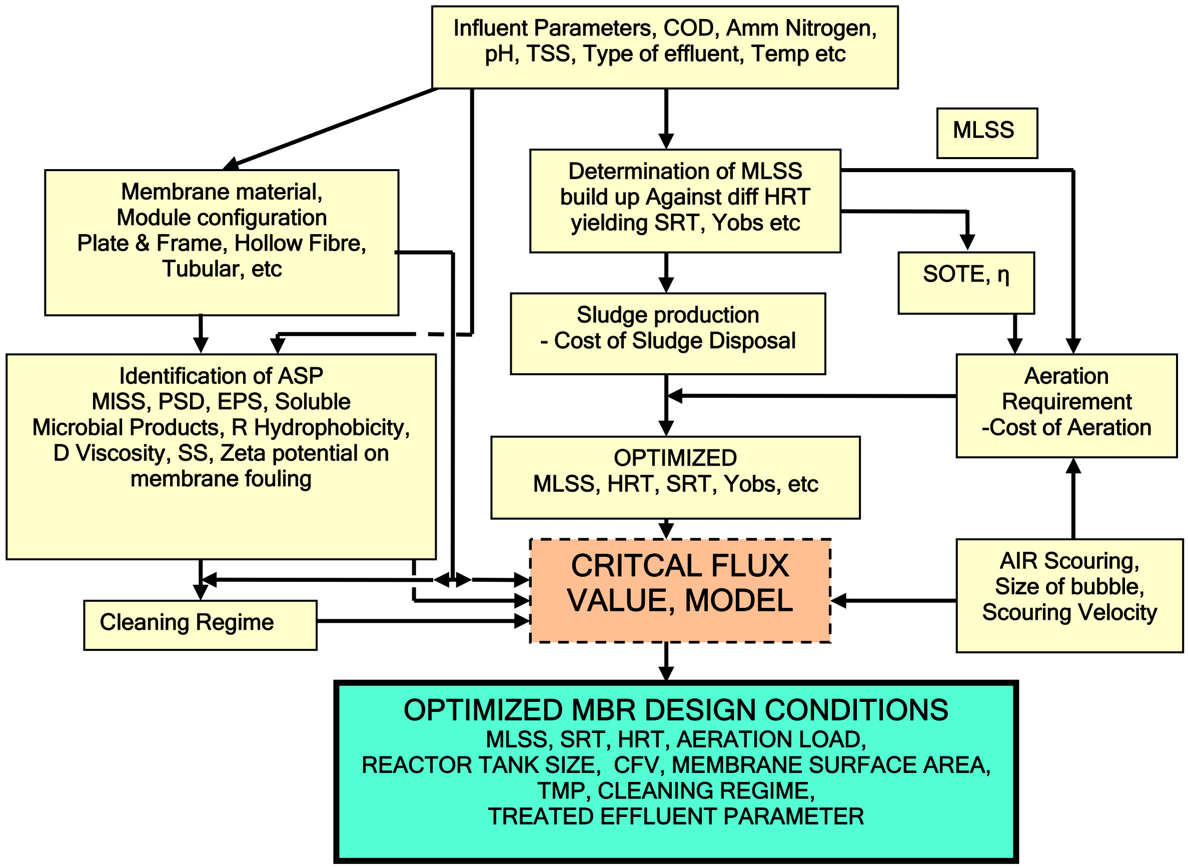
Feasibility of using MBR -

In activated sludge process, microorganisms in bioreactor are growing with the consumption of organic substrate contained in wastewater. In addition, the microorganisms are doing endogenous respiration consuming themselves. These phenomena can be described by Eq. (1), where the microbial growth is expressed by Monod equation, and the endogenous respiration, by first-order kinetic equation

$$dx/dt = ((\mu_m S_e) / (K_s + S_e))\, x \quad - \quad k.dx \qquad (1)$$

In MBR, complete retention of sludge by membrane process makes it possible to maintain high MLSS in bioreactor, which causes long sludge retention time (SRT) and low food-to-microorganism (F=M) ratio. The long SRT also causes less sludge production while low F=M ratio gives a chance to reduce hydraulic retention time (HRT). But there has to be some minimum COD available for high MLSS to survive. The minimum biodegradable COD should at least be 150 ppm.

Algorithm for optimization of design conditions of MBR:



Optimization of operational condition of MBR: Considering sludge treatment and aeration costs.

It has been known that less sludge production can be achieved while short HRT is applied in MBR process. However, sludge production is obviously inversely proportional to HRT when MLSS is fixed. Therefore, the shortest HRT and the minimum sludge production cannot be achieved simultaneously. When sludge production is minimized, aeration cost would be maximized and vice versa. Therefore, there exists an optimum point between the two extreme cases, in which total operational cost is minimized.

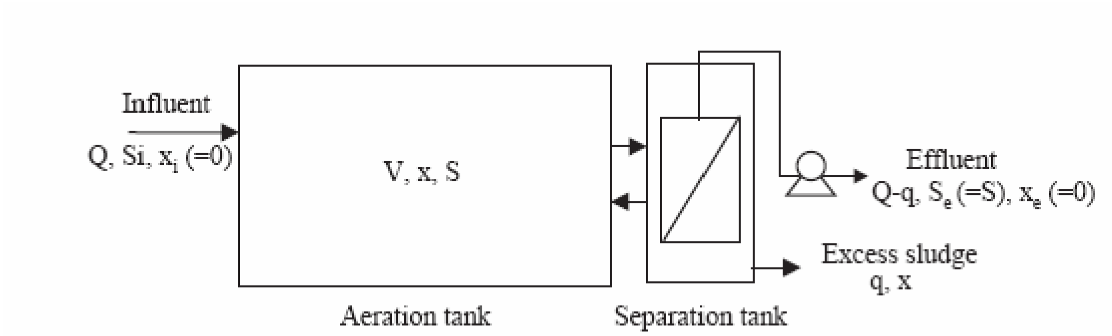


Fig. 1 - Schematic of typical membrane bioreactor (MBR) process, where influent and effluent SS are zero.

Sludge production in MBR

Fig. 1 shows a schematic of separated type MBR in which separation tank is installed separately. Here, soluble COD in mixed liquor (S) is assumed to be equal to the effluent COD (Se) because the submerged membranes used in MBR are mostly micro- or ultra filters which rarely remove dissolved materials. Additionally, all organic material in feed solution was assumed to be soluble.

While microorganisms are growing, majority of the substrate (organic pollutant in influent) is consumed by microorganisms and some substrate is discharged with effluent. This balance can be described by Eq. (2) where the first term on the right side expresses the COD balance between influent and effluent and the second term expresses the substrate consumption by microorganisms:

$$dS_e /dt = (Q/V)(S_i - S_e) - (1/Y)(\mu_m . S_e/(K_s + S_e)) . x \qquad (2)$$

Here, μ_m is a maximum specific growth rate (day^{-1}), K_s is a half saturation constant (mgL^{-1}), k_d is a endogenous decay constant (day^{-1}), S_e is a substrate constant in mixed liquor (mgL^{-1}), x is an MLSS in bioreactor (mgL^{-1}) and t is a time (days). Here, Q is an influent flow rate ($m^3\ day^{-1}$) and Y is a yield coefficient (kg MLSS $kgCOD^{-1}$).

sludge production

The MLSS increasing rate can be obtained using the time derivative of MLSS (x) as shown in Eq. (1). By the way, the sludge production rate at a certain MLSS can also be calculated by multiplication of reactor volume (V) with the MLSS increasing rate. Assuming the water content in cake is ϵ; total cake production rate (X) is calculated below when MLSS in bioreactor is controlled to a target value as follows:

$$X = [V / ((1 - \epsilon) * 10^9))]*(dx / dt)_{x= x_{target}} \qquad (3)$$

Inserting Eq. (1) into Eq. (3) following equation is obtained:

$$X = (V / ((1 - \epsilon) * 10^9) * ((\mu_m . S_e / (K_s + S_e)) - k_d)\, x_{target} \quad (4)$$

In real MBR, however, increased sludge viscosity at high MLSS boosts up the membrane fouling. The high limit of target MLSS in bioreactor has been generally set to be 15,000 mg/L. The HRT corresponding to the target MLSS 15,000 mg L^{-1} while cake production is zero is 11.4 h. This means this is the minimum HRT to obtain zero sludge.

Sludge production can be reduced significantly by increasing HRT and/ or target MLSS. If either HRT or MLSS increases, more sludge will be retained in bioreactor and this increases SRT. The SRT and the observed yield coefficient, Y_{obs} are expressed as in the following equations:

$$SRT = x / (dx/dt)_{x= x_{target}} \quad (5)$$

$$Y_{obs} = (V (dx/dt)_{x= x_{target}}) / (Q.S_i) \quad (6)$$

Thus SRT and observed yield coefficient, Y_{obs} are functions of HRT and target MLSS in bioreactor. Assuming the target MLSS of 10,000–15,000 mgL^{-1} and HRT 6 h, SRT is expected to be 20–40 days. This SRT is much longer than that in conventional activated system, i.e. mostly less than 6 days. Consequently observed yield coefficient, Y_{obs}; also is expected to be as low as 0.23–0.32 kg MLSS kg COD^{-1} while Y_{obs} in activated sludge process is 0.4– 0.5 kg MLSS kg COD^{-1} .In case HRT is more than 12 h and MLSS is 14,000 mg L^{-1}, SRT would be over 1000 days and Y_{obs} approaches to zero.

Aeration requirement

In biological wastewater treatment, organic materials contained in influent are converted into new biomass while some of them are converted to carbon dioxide with the consumption of oxygen. Therefore, the oxygen requirement can be calculated by subtracting the amount of COD converted to biomass from the total COD removed. The total oxygen consumption rate O_2 can be expressed as follows, where the first term on the right side describes the COD balance between influent and effluent and the second term describes the amount of COD converted to biomass:

$$\dot{O}_2 = d\, O_2 / dt = (Q/V) .(S_i - S_e) - \beta.(dx/dt) \quad (7)$$

Where β is a conversion factor of biomass to COD.

Aeration requirement (Q_{air}) is calculated from the oxygen consumption rate O_2 considering the specific oxygen transfer efficiency (η) and reactor depth as (m).

$$Q_{air} = \dot{O}_2 / (4.0 * \eta.m) \quad (8)$$

Aeration tank requires minimum aeration for mixing. This minimum requirement, which depends only on reactor volume, can be calculated as

$$Q_{min} = (V\,\Pi_{L,\,Q}) / 1000 \quad (9)$$

Where $\Pi_{L,\,Q}$ is a minimum air input rate having unit as $m^3 min^{-1} 1000 m^{-3}$. If Q_{min} (L day^1) exceeds Q_{air}; Q_{min} needs to be adapted as an aeration rate. The power requirement, P is directly obtained by multiplication of conversion factor with the aeration rate as shown in Eq. (10):

$$P = 0.7 * (Q_{air} \text{ or } Q_{min}) \quad (10)$$

In MBR process, sludge production is suppressed by long HRT and/or high MLSS. Along the sludge reduction, more oxygen is needed to oxidize the organic materials contained in wastewater, otherwise it turns into sludge. The oxygen requirement as functions of HRT and target MLSS can be calculated with Eq. (4). Solving Eq. (4) simultaneously with Eq. (1) and (2), oxygen requirement during the biodegradation can be calculated.

When MLSS increases from 6000 to 10,000 mg/L, oxygen requirement increases as much as 90 kg/day for the HRT of 16 h while it increases only by 13 kg/day for the HRT of 2 h, where higher oxygen requirement indicates lower sludge production. The aeration requirement can be calculated with Eqs. (5) and (6), which are based on oxygen requirement and oxygen transfer efficiency. oxygen transfer efficiency, η is highly dependent on MLSS. Specific oxygen transfer efficiency (SOTE) as a function of MLSS, which means an oxygen transfer efficiency per unit depth of aeration tank. The oxygen transfer efficiency is 9% m^{-1} in pure water but it decreases to 2% m^{-1} when MLSS increases to 17,000 mgL^{-1}. Thus there is relationship between MLSS and SOTE

Critical Flux aspect of, membrane material and module configuration, air sparging, MLSS sludge concentration and sludge properties.

Critical Flux

Approach to the fouling problem is operation below what is termed as "critical flux". Critical Flux is flux, where there is no further flux decline over time periods of several hours of operations, if the flux is defined as a combination of driving force (TMP) and hydrodynamics, does not exceed threshold values. This critical flux is by definition the flux below which no particle accumulation on the membrane surface occurs.

Critical flux must be distinguished from the limiting flux, which is the maximum flux possible by incrementally increasing the trans membrane pressure. Under certain conditions the critical flux is 2/3 of the limiting flux. Since the limiting flux increases at higher cross flow velocities (CFV) according to the film theory model, the CFV significantly impacts the level of critical flux as well. Subsequently higher trans membrane pressures can be applied with less particle deposition, which results in higher critical fluxes. Sufficient shear stress, achieved at sub- turbulent or turbulent flow conditions and indicated by dimensionless parameters such as Reynolds, shear stress or fouling numbers, prevent particles deposition on the membrane surface and, ultimately external fouling.

A simple model proposed to clarify the development of the fouling process despite the choice of sub-critical conditions. It is based on the following idea: during the first period, solute-membrane interactions provoke a reduction in the number of pores open to the filtrate flow (Fig. 2). As the permeate flow is held constant during the experimental run, this reduction of the area open to the flow is expressed as a gradual increase in circulation rate, or local flux Jp, in the pores remaining open. In the absence of regular membrane regeneration, the increase slowly intensifies as the pores close, and may lead to the local flux reaching a level equal to the critical flux value. A deposit then forms on the membrane, translating to very high hydraulic resistance: this marks the onset of the second filtration period, the modeling for which (cake filtration) has been widely developed in the literature. The following hypotheses have been put forward to develop the equations representing the changes in trans membrane pressure and local flux during the first period.

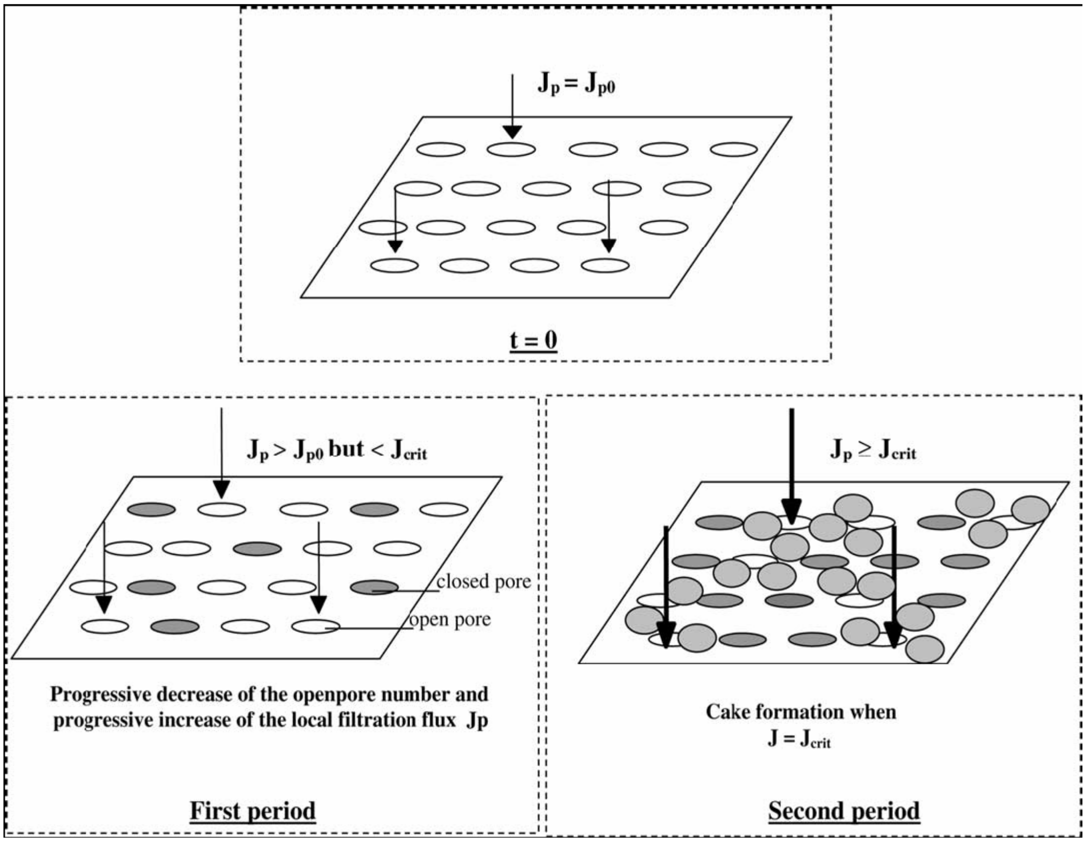


Fig. 2. Changes of filtration area and permeate local flux and consequences on fouling mechanism.

MBR Membrane material and configurations –

The development or selection of membrane materials is governed by the need to suppress membrane fouling or ameliorate the problems associated with it. To optimize the design conditions of MBR selection of membrane and the type of module is very important. The principal objective in membrane manufacture is to produce a material of reasonable mechanical strength and which can maintain a high throughput of a desired permeate with a high degree of selectivity. These two parameters are mutually counteractive, since high degree of selectivity is normally only achievable using a membrane having small pores and thus an inherently high hydraulic resistance (or low permeability). The permeability increases with increasing density of pores, implying that a high material porosity is desirable. The overall membrane resistance is directly proportional to its thickness. Therefore the optimum physical structure for any membrane material is based on a thin layer of material with a narrow range of pore size and high surface porosity. Membrane are categorized according to the material composition, which is generally either organic (polymeric) or inorganic (ceramic or metallic). The physical structure of the membrane based on these materials can vary according to the nature of the material / or the way in which it is processed. Various membranes materials could be titanium dioxide/ Zirconium dioxide cellulose acetate, polysulphone, polypropylene, PTFE, polyamide etc.

The geometry of the membrane, i.e. the way it is shaped is crucial in determining the overall process performance. The optimum geometry, or configurations, for an individual membrane element is one having characteristics like – high membrane area to module bulk volume ratio, high degree of turbulence for mass transfer promotion on the feed side., low energy expenditure per unit product volume, low cost per unit membrane area, a design that facilitates cleaning and a design that permits modularization. Some of these characteristics are mutually exclusive. For example for promoting turbulence results in an increase in the energy expense. Direct Mechanical cleaning of membrane is only possible on comparatively low area: volume units where membrane is accessible. It is not possible to produce a high-membrane area to module bulk volume ratio without producing a unit having narrow feed channels, which adversely affect cleaning regime and turbulence promotion. There are five principal configurations currently employed in membrane processes have various practical benefits and limitations. The configurations are based on either a planar or cylindrical geometry and compromise – pleated filter cartridge, plate and frame, spiral wound, tubular, hollow fine fiber. Fig (3) shows types of various module configurations.

Hollow fiber membrane elements though are less expensive to produce and are back flushable too but, on the other hand, because the hydrodynamic is less readily controlled in such systems, they are more prone to fouling than either plate or tubular modules and so require more frequent washing and cleaning. The flat plate membranes cannot, in fact be back flushed thus they have to be operated at a low flux below, that at which fouling becomes significant, the so called critical flux. In fact to completely prevent irreversible fouling (that is adsorbing solutes and colloidal materials which can only be removed chemically), but fouling rates can be reduced significantly by adopting the appropriate conditions. By able to provide rotation to the module made up of Plate and Frame membranes, cross flow filtration, like conditions are created. This effect results in minimizing fouling of membrane in such a module. **Presently only one company, in the world, M/s HUBER TECHNOLOGY, manufactures such a module.**

Fig. 3 – Various membrane module configurations

Hollow Fiber membranes

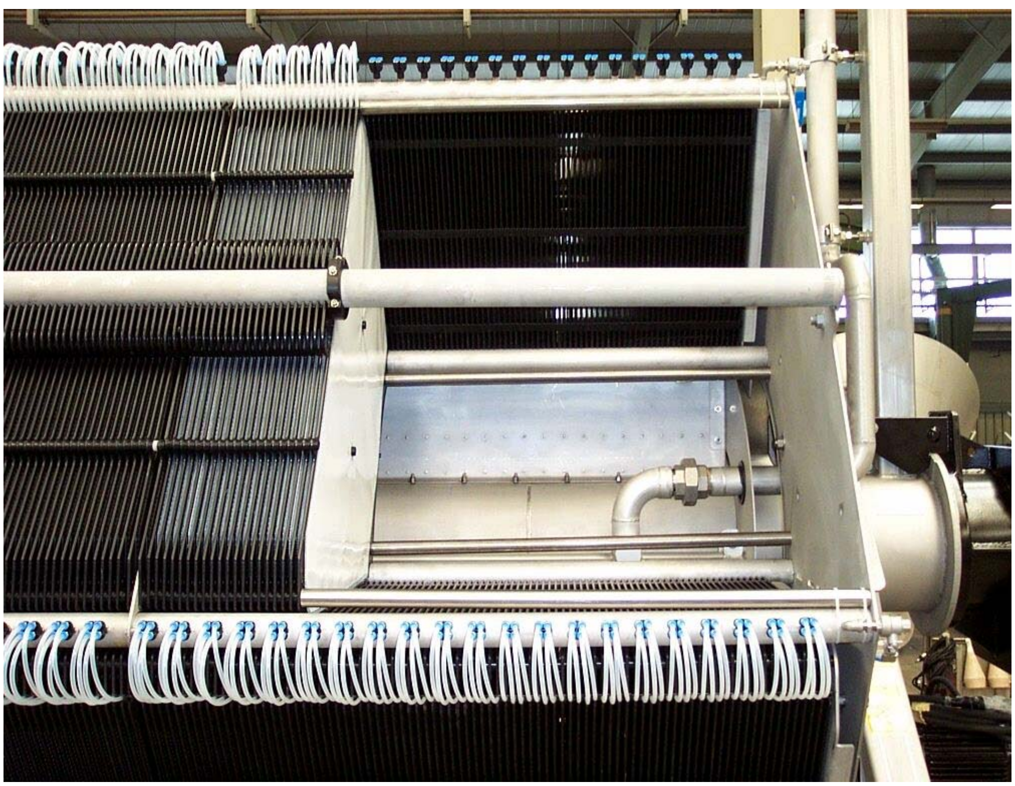


Plate and Frame membranes with rotating module, courtesy Huber Technology

Aeration device influences cross flow velocities. Cross flow velocities arising from fine and coarse bubble diffusers are different. Higher values of cross flow velocities are obtained using fine air bubbling. The smaller bubble size might have induced less uplift resistance and the lower resistance allowed for higher uplift velocities. This is, however, true only up to a point. Thereafter, cross flow velocities would decline. Bubble collision resulting in larger bubbles, diminishing gas hold-up and/or the onset of circulation patterns could be the reason and consequences of the phenomenon. As aeration intensity increased, the rate of increase in gas hold-up declined, resulting eventually in cross flow velocities plateauing. For the fine bubble diffuser, cross flow velocity virtually attains plateau level (0.69 m/s) at an aeration intensity of 0.017 $m^3/m^2.s$. Further increase in cross flow velocity (0.005 m/s) obtainable by operating at an aeration intensity of 0.021 $m^3/m^2.s$ was indeed insignificant. However, the situation is rather different for the coarse bubble diffuser. It requires higher range of aeration intensity applied, for the cross flow velocities to reach to plateau. The approaching plateau in cross flow velocity for fine bubble diffuser indicated that there was a critical aeration intensity following which further increases in aeration intensity would not further increase the cross flow velocity. The implications of aeration intensity on capital and operating costs could be roughly assessed by using Eq. 21 and Eq. 22, respectively.

$$\text{Capital cost} = 8590 * OC^{0.433} \qquad (11)$$

$$\text{Operating cost} = f\,(Q_{air}) \qquad (12)$$

Where, OC is the oxygen capacity and Q_{air} , is the air flow rate.

It is noted that the capital and operating costs will increase by 10% and 25%, respectively, if the aeration intensity were increased from 0.017 $m^3/m^2.s$ to 0.021 $m^3/m^2.s$. In contrast, increasing aeration intensity from 0.0 17 $m^3/m^2.s$ to 0.021 $m^3/m^2.s$ could only improve cross flow velocity by less than 0.005 m/s, which is indeed very insignificant. This observation suggests that it is not cost-effective to operate the reactor at aeration intensity above 0.017 $m^3/m^2.s$.

The cross flow velocity can be estimated with Eq. 23.

$$U_{Lr} = [\,(\,2gh_D*(\epsilon_r - \epsilon_d))\,/\,(K_B(A_r/A_d)^2\,)*\,(1/\,(1-\epsilon_d)^2)]^{0.5} \qquad (13)$$

where U_{Lr} is the superficial liquid velocity in the riser, g is the gravitational acceleration, h_D is the height of the gas-liquid dispersion, A_r, and A_d, are the cross-sectional areas of the riser and down comer, respectively, ϵ_r and ϵ_d are the gas hold-up in the riser and down comer, respectively, and K_B is the frictional loss coefficient for the bottom zone of the membrane unit.

Properties of activated sludge affecting membrane fouling

Membrane fouling is influenced by the activated sludge properties such as the mixed liquid of suspended solids (MLSS) concentration, sludge particle size distribution (PSD), extra cellular polymeric substances (EPS), soluble microbial products (SMP), suspended solids in supernatant (SS_s), dynamic viscosity (μ), relative hydrophobicity (RH), and zeta potential. Activated sludge properties also varies with different types of substrates present in the effluent.

Membrane fouling resistance has an exponential relationship with MLSS concentration. There are more membrane foulants in the mixed liquor as MLSS concentration increases. The sludge particle size has strong influence on membrane permeability, which shows a negative effect on fouling resistance. The sludge particle size is an important factor affecting membrane fouling. The total EPS, including protein and carbohydrate, has the strongest influence on the membrane permeability. Protein has significant contribution to membrane fouling, while carbohydrate only has moderate correlation with fouling resistance due to low amounts. The SMP and SS_s has a dramatic influence on membrane fouling, but which are induced by EPS. The increase of the total EPS will cause an increase of the dynamic viscosity of mixed liquid, and cause more polymers and sludge particles accumulate on membrane surface. The increase of RH and surface charge of activated sludge results in severe membrane fouling, and these two factors have close correlation with EPS concentration. The MLSS concentration, sludge particle size and EPS are the predominant factors affecting membrane permeability. The resistance factor is related to the MLSS, EPS and PSD.

Conclusion

Optimizing design conditions involves optimizing various dynamic variables associated with design of MBR systems, since; biomass is retained 100% in the bio reactor. Minimum biodegradable COD required for Biomass to survive is approximately 150 ppm. There is growth in MLSS in MBR till growth rate and endogenous respiration or death rate balance each other. Increase in MLSS increases the requirement of dissolved oxygen, also SOTE decreases with increase in MLSS. Thus cost of aeration, overall increases. Sludge treatment cost and aeration are inversely proportional to each other, which mean sludge treatment cost is minimized when aeration cost is maximized and vice versa. Therefore there exists an optimum point between the two extreme cases. But over a period of operation of MBR sludge treatment cost is overwhelming on aeration cost. Therefore sludge minimization should be considered to be a key for the economical operation of MBR. To predict critical flux, membrane pore size, type of membrane and membrane module configuration is important. Air sparging reduces fouling but again it has to be optimized either using coarse or fine bubble aeration. Fine bubble aeration imparts better results for control of fouling of membrane. The intensity of aeration which imparts cross flow velocity (CFV) to the air bubbles also needs to be optimized. Cross flow velocities reach maximum values on increasing aeration intensities but any further increase in aeration intensity does not increase CFV. Optimized CFV of 0.69 m/s at an aeration intensity of 0.017 $m^3/m^2.s$ for fine diffuser can be considered as fixed hydrodynamic parameter. Properties of activated sludge are another important variable parameter affecting the membrane fouling and thus critical flux. There are various parameters of activated sludge need to be considered. These involve parameters like mixed liquid of suspended solids (MLSS) concentration, sludge particle size distribution (PSD), extra cellular polymeric substances (EPS), soluble microbial products (SMP), suspended solids in supernatant (SSs), dynamic viscosity (μ), relative hydrophobicity (RH), and zeta potential. These parameters vary, if substrate is varying. Thus pilot studies of MBR, involving different kinds of effluent, play an important role in establishing activated sludge properties for different effluents. Finally to optimize design conditions of MBR and predict the operation of MBR on certain type of effluent optimization of sludge treatment cost, aeration cost, activated sludge properties for certain type of effluent and membrane module configuration needs to be done.

HUBER TECHNOLOGY, uses the algorithm and the mathematical model developed by them, as described in this paper, to design Membrane Bio Reactor systems for their clients.

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