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Moving Bed Biofilm Reactors for Wastewater Treatment: A Review of Basic Concepts

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***Abstract**:*

Moving bed biofilm reactor (MBBR) is a continuous completely mixed biofilm reactor used for various treatment purposes in both municipal and industrial wastewater. The basic principle of MBBR technology is that the biomass grows on specially designed carrier elements that move freely throughout the reactor due to aeration, liquid recirculation, or mechanical mixing. This review summarizes the structure, function, and performance characteristics of the MBBR, as well as design considerations for biofilm carriers (MBBC). It also goes on its advantages and disadvantages.

Keywords

BOD; Carriers, COD; MBBR; Nitrification; Wastewater

1. Introduction

Over the past 30 years, the moving bed biofilm reactor (MBBR) has been applied to treat a wide variety of wastewaters establishing itself as a simple, flexible and compact technology. Success has been demonstrated in treating wastewaters for the removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia and nitrogen both in municipal and industrial applications (Safwat et al., 2018). A large variety of configurations exist for the process allowing it to meet a wide range of effluent standards, including stringent nutrient limits, on a consistent basis. The main difference between MBBR technology when compared to other biofilm systems is that it combines the advantages of the traditional activated sludge system with the advantages offered by biofilm systems while minimizing the disadvantages of both (Hanafy et al. 2019). Some of the inherent advantages to using MBBR systems include 1) higher volumetric efficiencies; 2) increased process stability; 3) minimal head loss without requiring periodic backwashing; 4) flexibility and simplicity of operation; and 5) compatibility with a variety of solids separation techniques (Water Environment Federation, 2011). Much of the original research and development of the MBBR was conducted at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway in the mid-1980s. Initial research was motivated by an international effort to reduce nitrogen discharges to the North Sea. This motivated researchers to explore cost-effective upgrade options for existing wastewater treatment facilities including technologies based on compact biofilm processes (Odegaard et al., 1991). This eventually led to the development of the original Kaldnes Moving Bed process in the late 1980s where early applications of the technology were focused on the construction of smaller wastewater treatment facilities (WWTFs) across Norway (Odegaard et al., 1993, 1994; Rusten et al., 1997). Later studies eventually evaluated the applicability of the technology to a variety of different scenarios including pilot studies at existing WWTFs (Odegaard et al., 1994; Hem et al., 1994; Rusten et al., 1997), pilot studies for industrial wastewater treatment (Rusten et al., 1992, 1996, 1998, 1999; Broch-Due et al., 1994, 1997) and full scale studies on the upgrading of existing WWTFs (Rusten et al., 1994, 1996, 1998). The technology was eventually patented and commercialized in 1989. Today, there are more than 300 treatment plants based on the MBBR process (and its variants) in operation or under construction in 22 different countries the world over (Odegaard, 2006); most of the larger municipal and industrial plants are located in the Scandinavian countries, the U.K., Italy and Switzerland.

2. Structure, Function and Performance of the Moving Bed Biofilm Reactor

The basic concept behind the design of an MBBR system is to have a continuously operating biofilm reactor with low risk for clogging, low head loss and a high specific biofilm surface area (Odegaardet al., 1993; Odegaard, 2006). High specific surface area for biofilm growth is achieved by having the biofilm grow on small carrier elements that move along with the flow of the water in the reactor. This movement is typically caused by aeration in aerobic reactors and mechanical stirring in anaerobic reactors and ensures that the whole volume of the reactor is used in treatment. The most widely used biofilm carrier elements, originally developed for use in the Kaldnes Moving Bed process, are made of polyethylene (density 0.95 g/cm^3) and are shaped like small cylinders with a cross inside the carrier and fins along the outside of the carrier (Odegaard, 2006). Figure 1 illustrates an example of biofilm carrier.

Figure 1: Biofilm carrier

Filling of the reactor volume with the carrier elements may be decided on a case by case basis based on effluent standards, allowing for a good deal of flexibility in design. A maximum filling of approximately 70% (by volume) is recommended in order to allow for adequate carrier movement in suspension (Odegaard, 2006). In most operations, the maximum specific surface area achievable is approximately 350 m^2/m^3, with the biofilm growing predominantly on the protected inside of the K1 carrier (Rusten et al., 1992, 1994, 1995b). In aerobic systems, the elements are kept in suspension using aeration grids consisting of distribution piping and small-diameter diffusers with 4-mm holes positioned along the underside. In anaerobic systems, rail-mounted submersible mechanical mixers are used to circulate the carrier elements and ensure complete mixing (Water Environment Federation, 2011; Odegaard, 2006). The mixers need to be located towards the surface of the reactor with a slight negative inclination to help push the media down into the lower depths of the reactor. Horizontally configured stainless-steel wedge wire sieves are typically used to retain the media within the reactor. The position and orientation of the sieves takes advantage of the media and the process aeration grid for scouring (Water Environment Federation, 2011; Odegaard, 2006). Overall, the rugged design of MBBR systems allows them to operate virtually maintenance free for extended periods of time (Water Environment Federation, 2011; Odegaard, 2006).

3. General Design Considerations for MBBR Systems

Process design with MBBR systems is based on the concept that treatment is achieved with several reactors operating in series where each reactor serves to achieve a particular treatment objective (Rusten et al., 1995a, 1995b). This philosophy is used because each reactor promotes the development of a specialized biofilm based on the prevailing growth conditions within the reactor. Although typical biomass concentrations are similar to those in activated sludge systems, approximately 2-5 kg suspended solids (SS)/m^3, the biomass is much more viable (higher food to microorganism [F/M] ratio) leading to higher volumetric removal rates (Rusten et al., 1994, 1995b). Based on these observations, it was determined that the net effective biofilm area is the key design parameter for MBBR treatment facilities (Odegaard, 2000). As a result, performance and removal characteristics for MBBRs are typically given in terms of the surface area loading rate (SALR) and the surface area removal rate (SARR), respectively.

3.1. Carbonaceous BOD/COD Removal

Residence times in MBBR systems designed for BOD/COD removal will generally be quite low, ranging between 15-90 minutes (Odegaard, 2006). Biodegradable, soluble organic matter is quickly degraded whereas particulate organic matter may be caught by the irregularities of the attached biomass, hydrolyzed and subsequently degraded (Odegaard et al., 2000; Odegaard, 2006). In most cases, combined particulate/phosphorus removal is achieved by combining the MBBR process with a chemical treatment step (Odegaard et al., 1993; Rusten et al., 1997). Average dissolved oxygen (DO) concentrations of approximately 3 mg/L will be sufficient to achieve desired BOD/COD removal objectives whereas higher values do not tend to improve the SARR (Rusten et al., 1998; Odegaard et al., 2000). The SALR for a MBBR designed for carbonaceous BOD/COD removal will depend both on the treatment objective and the method selected for solids separation. The reactor should be designed for a low SALR when nitrification is required downstream of the reactor and at a higher SALR when only carbonaceous matter removal is required. A maximum SALR of approximately 30 g soluble COD/m^2d is achievable before inhibition of the biomass occurs (Odegaard et al., 2000; Odegaard, 2006).

A low rate MBBR design with a design SALR below 5 g BOD_7/m^2d is generally required if nitrification is required downstream (Hem et al., 1994; Rusten et al., 1994, 1995a, 1995b; Water Environment Federation, 2011). A normal rate MBBR design is typically based on two reactors operating in series to achieve basic secondary treatment objectives (Rusten et al., 1992, 1997; Odegaard et al., 1993). SALR values of 5-15 g BOD_7/m^2d are typical of normal rate designs with achievable removals of greater than 80% (Water Environment Federation, 2011). Even with annual average wastewater temperatures as low as 6°C, these normal rate designs have been shown to provide effective and reliable performance at full scale municipal WWTFs (Rusten et al., 1997). Normal rate designs have been often combined with follow-up chemical addition and flocculation for phosphorus removal and solids separation. A high rate MBBR design is typical for MBBR systems treating industrial effluents or serving as a form of biological pretreatment (Broch-Due et al., 1994, 1997; Rusten et al., 1992, 1996, 1998, 1999). The main purpose of high rate MBBR systems is to remove the soluble and easily biodegradable BOD from the influent stream. SALR values above 20 g BOD_7/m^2d are typical for high rate designs with removal rates greater than 75% being achievable (Water Environment Federation, 2011). Many high rate MBBRs have been used to upgrade or retrofit existing treatment systems treating various industrial effluents where the existing system was no longer able to handle the high and often highly variable organic loads (Rusten et al., 1992, 1996, 1998, 1999). One disadvantage with operating high rate MBBRs is that the settling character of the biofilm slough diminishes under these conditions (Rusten et al., 1992; Odegaard et al., 2000). As a result, high rate MBBR systems are often combined with chemical coagulation and flocculation, flotation or with a solids contact process step to remove solids resulting in a high-rate, compact treatment system (Odegaard, 2006).

3.2. Nitrification

The conditions and performance of a nitrification-stage MBBR unit will be impacted by several factors including 1) the organic loading; 2) the dissolved oxygen concentration; 3) the ammonia concentration; and 4) the wastewater temperature. The organic loading can significantly impact the ammonia conversion rates in MBBR systems. The growth of heterotrophic bacteria, in the presence of organic matter, will tend to dilute the density of nitrifying organisms in the aerobic portion of the biofilm; at higher organic loadings, no nitrification of importance is likely to occur within the biofilm (Harremoes, 1982; Bovendeur et al., 1990). During pilot scale studies, it was shown that an organic load of 1-2 g BOD_7/m^2d resulted in a nitrification rate of approximately double that achievable under an organic load of 2-3 g BOD_7/m^2d (Hem et al., 1994); under an organic load of approximately 5 g BOD_7/m^2d, nitrification rates close to zero were observed (Hem et al., 1994; Rusten et al., 1994, 1995a, 1995b). At full scale, average nitrification rates of between 1.01 g NH_4-N/m^2d and 1.24 g NH_4-N/m^2d were observed (Rusten et al., 1995a, 1995b). It was shown that these rates were dependent on whether the MBBR was operating in the pre-denitrification or post-denitrification mode.

The dissolved oxygen concentration and the ammonia concentration can also have a significant effect on the rate of ammonia conversion in MBBR systems. It was shown during pilot/full scale studies that the rate of ammonia conversion was dependent on the oxygen concentration below 2 g O_2/g NH_4-N and on the ammonia concentration above 5 g O_2/g NH_4-N (Hem et al., 1994; Rusten et al., 1994, 1995a, 1995b). The nitrification rate was found to be first-order dependent on oxygen (oxygen limiting conditions) and 0.57-order dependent on ammonia (ammonia limiting conditions). Transition between the two rates was found to occur between 2.7 g O_2/g NH_4-N and 3.2 g O_2/g NH_4-N (Hem et al., 1994). A disadvantage of using MBBRs for nitrification is that due to the oxygen sensitivity of nitrification, nitrifying MBBRs should be operated at relatively high oxygen concentrations to achieve high efficiencies (Hem et al., 1994; Rusten et al., 1994, 1995a, 1995b). An advantage of this oxygen dependence is that the reactor volumes may be utilized optimally by controlling the air supply according to the actual influent concentration of ammonia and the degree of nitrification desired (Rusten et al., 1994, 1995a, 1995b).

Several temperature-related factors are important in determining the achievable rate of nitrification in MBBR systems. Wastewater temperatures in an MBBR will affect the inherent nitrification kinetics of the biofilm; the rate of diffusion of substrate and oxygen across the biofilm layer; and the solubility of oxygen in the liquid (Water Environment Federation, 2011). A true temperature coefficient of θ = 1.09 was determined, considering both differences in organic loads and oxygen concentrations (Rusten et al., 1994; 1995b). Although the dependency of nitrification kinetics on temperature are apparent, they can be offset to a certain extent in MBBR systems by the combined effect of higher attached biofilm concentrations observed at colder temperatures and by the availability of a higher bulk oxygen concentration (Water Environment Federation, 2011; Rusten et al., 1994). In net, the nitrification rate observed within MBBR systems may be maintained adequately at colder operating temperatures despite a reduction in the overall nitrifying activity of the biofilm.

4. Moving Bed Biofilm Carriers (MBBC)

In a study presented by Martinez-Huerta et al. (2009), the parameters affecting MBBC performance were considered and six initial biofilm carrier designs were proposed. The parameters considered for the MBBCs were (Martinez-Huerta et al. 2009):

a) The density of material (the density of material should be close to the density of water so that they float easier)

b) Cylindrical versus complex shape of the carrier (cylindrical carriers tend to have better hydrodynamic behavior and less mechanical losses due to collisions whereas complex carriers need to be larger and harder and therefore require more energy to mix)

c) Internal and external walls of the carrier (internal walls increase surface area whereas external walls may have fins or ribs to minimize friction between other carriers and the reactor and to preserve external biofilm)

d) Area to volume ratio

e) Size of specific surface effectively used

f) Diameter of smallest cavity

g) Resistance to clustering

h) Percent of occupation

i) Manufacturing considerations such as model complexity, thickness of walls, radius and height of carriers, number of elements/m^3 and filling ratio

In an experiment conducted by Odegaard et al. (2000), the effect of the shape and size of four different biofilm carriers on the removal of organic matter was examined. All carriers were made of high-density polyethylene to avoid the influence of buoyancy on test results. The results indicated that shape and size of biofilm carriers did not have a significant effect on the removal of organic matter from municipal wastewater as long as the effective surface area was the same, and that MBBR systems should be designed based on surface area loading rate (Odegaard et al., 2000).

Because biofilm carriers should have a density close to that of water, most carriers are made of plastics such as polyethylene and polypropylene (Chen et al., 2012). Plastic carriers have low hydrophilicity and poor biological affinity; as a result, biofilms tend to grow slowly and are easily detached (Chen et al., 2012). In an attempt to correct for these limitations, roughness and biological compatibility of biofilm carriers can be increased by chemical or physical surface modifications (Chen et al., 2012). In an experiment performed by Chen et al. (2012), the surface of polyethylene carriers were modified using two combinations of chemical modifications: chemical oxidation – surface covered with ferric ion (CO-SCFe) and chemical oxidation – surface grafting of gelatin (CO-SGG). As a result of surface modifications, the surface roughness and oxygen-containing groups on the carriers increased, and the iron and gelatin-based groups created a positively charged surface (Chen et al., 2012). This improved microbial affinity, promoted biofilm formation, increased bacteria concentration, and enhanced wastewater treatment efficiency (Chen et al., 2012). Also, the introduction of iron ions by CO-SCFe method and cell recognition sites by CO-SGG method increased the content of extracellular polysaccharides and proteins in extracellular polymeric substances (EPS), which can accelerate microbial adhesion and promote pollutant biodegradation (Chen et al., 2012).

As MBBR technology has advanced, further research has been conducted to find carriers that have a low cost, long operational lifespan, and surface that is conducive to attached-growth biomass (Zhao et al., 2006). Many studies and experimental works have been conducted to examine the performance of a number of possible biofilm carriers including granular activated carbon, anthracite, zeolite (Zhao et al., 2006), pumice stone, porous glass beads, , giant reed, cotton, straw, and sisal fiber waste (Sabzali et al., 2012). Biofilm carriers are being developed to maximize the bacteria-fluid interface using minimum energy (Martinez-Huerta et al.2009).

In a study presented by Zhao et al. (2006), the application of diatomaceous earth (DE) as a biofilm carrier for the treatment of municipal wastewater was evaluated. DE is a powdery, nonmetallic mineral composed the fossilized remains of diatoms and is light weight, multi-shaped, rigid, and inert, with a high porosity, absorptivity, and purity (Zhao et al., 2006). DE has been used as filter for a variety of purposes, as well as an adsorbent for metal ions and dyes (Zhao et al., 2006). It was selected as a biofilm carrier due to its high porosity and surface area, which are important parameters for the adsorption of pollutants and promotion of biofilm growth (Zhao et al., 2006). Due to the physical-chemical properties of DE, such as coagulation, adsorption, uniformity, and high surface area, Zhao et al. (2006) found that using DE as a biofilm carrier can produce desired water quality with low construction and operation costs, simple operation, and low maintenance (Zhao et al., 2006).

5. Conclusions

Over the past 30 years, the moving bed biofilm reactor (MBBR) has been applied to treat a wide variety of wastewaters. Success has been demonstrated in treating wastewaters for the removal of biochemical oxygen demand (BOD)/chemical oxygen demand (COD), ammonia and nitrogen both in municipal and industrial applications. MBBR technology combines the advantages of the traditional activated sludge system with the advantages offered by biofilm systems while minimizing the disadvantages of both. Some of the inherent advantages to using MBBR systems include 1) higher volumetric efficiencies; 2) increased process stability; 3) minimal head loss without requiring periodic backwashing; 4) flexibility and simplicity of operation; and 5) compatibility with a variety of solids separation techniques (Water Environment Federation, 2011). Due to the flexible nature of the process, several different treatment objectives can be met, including stringent nutrient limits, on a consistent basis. The moving bed biofilm reactor has been applied to treat a wide variety of wastewaters. It has been established as a simple, flexible and compact technology in the removal of BOD/COD, ammonia and nitrogen from both municipal and industrial wastewater streams. Table 1 presents a summary of the advantages and disadvantages of MBBR technology based on the discussion presented in the previous sections.

Table 1: Advantages and disadvantages of the MBBR process

Advantages	Disadvantages
• Simple, flexible and compact design • High volumetric removal rates are achievable • Performance independent of solids return • Simpler design based on several reactors operating in series • Can be operated over a range of loadings (e.g. for BOD/COD removal, less than 5 mg BOD_7/L to more than 20 g BOD_7/L) • Nitrification rates can be controlled by varying aeration rates (linear relationship) • All processes can operate efficiently over a range of temperatures (as low as 6°C)	• Aeration grids and propellers prone to excessive wear due to collisions with biofilm carrier material • Relocation of the carrier material required prior to maintenance within the reactors • High BOD/COD loadings lead to poor settling conditions (e.g. use of coagulants/flocculants in clarifier) • Nitrification requires high oxygen inputs at high ammonia loads (under oxygen limited conditions)

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