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Scope of microbial desalination for removal of chlorides from brackish water

Antara Das[a], Supriyo Goswami[b] and Debabrata Mazumder*[b]

[a]Asutosh College, Kolkata-700 026, India

E-mail : tukaiantara18@gmail.com

[b]Department of Civil Engineering, Indian Institute of Engineering Science and Technology, Shibpur, Howrah-711 103, West Bengal, India

E-mail : supriyogoswami.ju@gmail.com, debabrata@civil.iiests.ac.in

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Abstract : Since the past few years, scientists are concerned on desalination of seawater and brackish water to increase the amount of drinking water. Microbial Desalination Cell (MDC) is a promising bioelectrochemical technology of near future in the area of water treatment. Being a renewable energy method, it is well known for simultaneous wastewater treatment and desalination of brackish water. MDC does not require any external energy source while desalinating water, thus it tries to mitigate the scarcity of drinking water. Microbial Desalination Cell is actually a combination of a Microbial Fuel Cell (MFC) and electrodialysis (ED). This is a very novel concept for sustainable development and should be well reared up. This paper provides an all over idea regarding the scope and use of MDC process in chloride removal from brackish water. The origin of MDC, various configurations and their applications are discussed along with their advantages and disadvantages.

Keywords : Microbial desalination, brackish water, chloride removal, wastewater treatment, scope of application.

I. Introduction

Water is a profuse natural resource of the world. But people can't use it completely as maximum portion of it is covered by the sea. About 97% of the earth's water can be found in the seas and oceans and about 2% is frozen up in glaciers and ice caps. Hence, more and more fresh water is needed for drinking and domestic purposes. Over the last fifty years, the demand for fresh water has increased by three times[1]. Ground water table is also declining due to over exploitation by the industries and agricultural irrigation. Therefore, to increase the amount of potable water, scientists are concerned on seawater and brackish water desalination[2]. It has been noticed that since 1980, there is a large increase in number of desalination plants[3]. The traditional methods for desalination are electrodialysis, thermal based distillation, reverse osmosis etc. which all are energy intensive process and hence not economical[4].

In search of some energy efficient as well as low capital cost desalination technology, MDC appeared as a viable alternative for the traditional ones. Microbial Desalination Cell (MDC) is a green technology which is very promising in the near future. It is a combined process of Microbial Fuel Cell (MFC) and electrodialysis (ED). MDC is appreciated for desalinating water with simultaneous treatment of wastewater and current generation by itself[5]. Here, the innovation is only addition of an extra unit in the middle of the microbial fuel cell filled with saline water. The first small cubic shaped MDC was proposed in 2009[6], which was successful in the lab using ferricyanide catholyte and acetate anolyte.

With time, scientists worked on the shape, designs of MDCs to increase the performance of desalination. The components of MDC like cathode, electrolyte solution were changed in different MDC configurations. Air cathode was used in a MDC[7]. Sustainable biocathode was used in another MDC[8]. The electrolytes of two terminal units were re-circulated for pH maintenance[9,10]. Capacitor was added in the electrode surface to enhance ion adsorption[11,12]. The chambers were decoupled for better flexibility of reactor[13]. The desalination chambers were increased in number[14]. Stacked MDCs were operated to increase charge transfer efficiency[15,16]. Apart from the batch study, MDC was run in continuous mode by an up-flow MDC[17,18]. Osmotic MDC was constructed by change of membrane and desalination performance was enhanced[19–21]. The effect of increasing the inter-membrane distance on MDC performance was also studied[22]. The orientation of traditionally settled membranes was inter-changed and the performance was checked[14]. The desalination unit was packed with ion exchange resin and the enhanced desalination rate was measured by another MDC[23].

By increasing the number of cell pairs, charge transfer efficiency was increased noticeably but the current generation was decreased by the MDC[24]. They had varied the salt concentration in the middle chamber also. During desalination, a MDC can produce high amount of energy (of about 180–231%) in form of hydrogen using 5 to 30 g/L NaCl salt solution[25]. The removal of ions is about 99% and a good amount of energy was generated by a general MDC[11]. Not only the Na^+ and Cl^- ions, the other ions in the saline water affect the MDC performance and is studied elaborately[26,27]. The transport phenomenon of different ions in a MDC is also reported[28]. This gives an idea that the sparingly soluble ions reduce the performance of MDC by membrane fouling.

II. Background of MDC

Concept of Microbial Desalination Cell (MDC) comes from the theory of bio-electrochemical systems. The main advantage of a MDC unit is that it can generate electricity within the cell. MDCs produce up to 231% more energy in form of hydrogen gas than other desalination processes using NaCl solutions ranging from 30 g/L to 5 g/L. The first basic study on MDC has reported that the salt removal rate was nearly 90% on one desalination cycle from 35 g/L salt water[6].

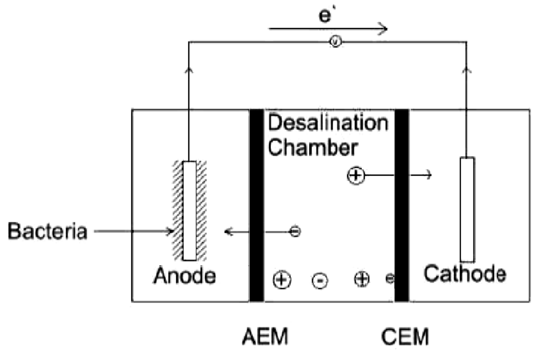

Fig. 1. Schematic diagram of a Microbial Desalination Cell.

A typical microbial desalination cell generally consists of three chambers namely anode chamber, cathode chamber and a desalination chamber in the middle. The anode and saline water chamber are separated by an AEM i.e. anion exchange membrane. Similarly the cathode chamber and the desalination chamber are separated by a CEM (cation exchange membrane). The two electrodes are connected through an external wire. The cathode chamber is either filled with aerobic water or exposed to air. The anode chamber is filled up with wastewater which is the source of the organic matter. Some exoelectrogenic bacteria are employed here which anaerobically oxidize the stored organic matter in the waste water and converts it into electrical power. These microorganisms release electrons which are the main source of current generation. The electrons produced, are transported from anode to cathode via the external circuit creating an electrical field. This potential difference between the two electrodes makes the cations and anions separate in the saline water. The cations pass through the CEM and the anions migrate through the AEM respectively.

The basic reaction occurs in a MDC is the following :

Anode : $(CH_2O)_n \longrightarrow ne^- + nH^+ + nCO_2$

Cathode : $O_2 + ne^- + nH^+ \longrightarrow nH_2O$

III. Performance of MDC in chloride removal

Theoretically, studies have shown that due to low energy demand, MDC is more efficient for seawater and brackish water desalination where the saltwater is highly concentrated. It has been showed that pure NaCl solution was more efficient in comparison to synthetic sea water[17,18]. They operated the up-flow MDC for continuous 4 months. They had seen that the electrons produced by the bacteria in the anode chamber, were completely used for desalination. In an UMDC the desalination rate is dependent on the volume of the salt solution and HRT. At HRT of 4 day, UMDC removed about 99% of salt from the solution of 30 g/L TDS concentration.

For desalination, acetate was used as feed solution of two different concentrations (5 g/L and 20 g/L)[7] and the NaCl concentration was also varied. Using air cathode at higher substrate concentration, the desalination was more at low salt concentration.

In case of real wastewater as the anolyte, 66% desalination was seen on a single desalination cycle. This was because the conductivity of the wastewater was low and passive ion transfer in the anode chamber from the middle chamber enhanced the desalination rate by 1.5 times. But it was clearly noticed that due to complex ionic composition in wastewater or real seawater, MDC faced some problems like imbalance in anolyte pH. This happens within the cell through the redox reactions i.e. protons are released in the anolyte and can't go to the catholyte, so acidity increases. Similarly in the cathode chamber through the reduction reaction hydroxyl ions are produced causing alkalinity[6,9,10]. Performance was checked when real seawater was used instead of synthetic seawater. MDC efficiency was decreased by 22% when artificial seawater was used replacing NaCl solution[17]. At high salt concentration desalination rate had to increase theoretically because of lowering internal resistance. The performance of MDCs was enhanced when buffer was added in the anode solution as well as the electrolytes were re-circulated. Recirculation helped in better desalination performance by 48% on using 25 mM phosphate buffer solution. Some scientists showed that a recirculation MDC improves desalination on low concentration of buffer. It reduced salt concentration by 34% of a 20 g/L solution using 50 mM PBS solution and when 25 mM PBS was used, it was 37%[9].

When the MDCs were connected in series and operated longer than one month in continuous mode, about 98% salt was efficiently removed by the first cell at an HRT of 2 days. Desalination rate decreased with decreasing HRT. But the total desalination rate decreased on increase of retention time[29]. This discrepancy was because the conductivity decreased in the middle chamber causing increased internal resistance.

In the multi desalination cells like stacked MDCs, the result was something different. Synthetic seawater was constantly desalinated in the dilute cells and the effluent from these cells entered in the concentrated cells. Both flow rates were maintained in opposite directions. It was seen that for a single MDC, in a dilute cell the conductivity was reduced by 85%. After one single treatment by the 4 MDCs attached in series, the concentrate conductivity increased by 27% and dilute one decreased by 44%. After the three stage process, the total salinity was reduced by 98%. In comparison to multi cell stack MDC, single cell stack MDC has more internal resistance because in the dilute cell, the low salinity water increases internal resistance due to low conductivity[16]. Hence, when more cell pairs were introduced or thin membranes were used, this resistance was reduced[15,24].

The traditional MDC generally is good for desalination of low concentration of salt water like 5 g/L. It is proved that for brackish water or estuarine water MDC is more efficient than seawater desalination[11,29].

It was observed that at the higher salt concentrated solution (35 g/L), the decoupled MDC significantly removed salt at higher rate (0.070 g/d) than lower concentration solution (1 g/L)[13]. Some of the researches showed that desalination performance was affected with inter membrane distance[22]. Six different distances (from 0.3 to 2.5 cm) were studied at same influent flow rate. Desalination efficiency decreased with decreasing inter-membrane distance and increasing salt concentration. At 0.5 cm distance between the membranes, when the HRT was 10 h, the desalination efficiency was highest (40%) and with increasing HRT (50 h), increasing inter-membrane distance (2.5 cm), desalination efficiency decreased by 10%. It was also seen that for high salt concentration solution, desalination efficiency increased with increasing inter-membrane distance. But at the same inter-membrane distance, desalination performance increased by 1.1–2.3 times for high concentration salt solution. These data helped to understand that HRT has bigger effect on desalination at high concentration salt.

A conventional MDC constantly faces the problem of increasing salinity in anolyte as the ions migrate from the middle chamber and pass through the AEM. This affects the microorganisms' growth followed by the MDC performance. This problem was avoided by the capacitive MDC where a low concentration salt solution was desalinated up to 70% in a single run[11]. This is advantageous because the ions when migrate through the membranes, get adsorbed in the surface of the electrodes, and when the potential difference was nullified, the ions go back to the solution. Thus the anode and cathode solutions do not get contaminated as well as avoid pH problem[19].

IV. Drawbacks of MDC

MDC is a novel approach to reach the required drinking water level but it has some difficulties for practical applications. Apart from the important advantages like simultaneous wastewater treatment and desalination of water, the biggest drawback is that the both property does not work with the same efficacy when scaling up largely. One affects the other process. In order to be cost effective, the ion exchange membranes and electrodes are to be chosen properly. Most importantly if an MDC works for a long term it should be checked that the membrane fouling is negligible[13]. The very first work on MDC was done using ferricyanide catholyte and acetate anolyte. But use of the chemical solution is not an environment friendly approach as well as not a sustainable way for treatment. In addition, the rapid decrease in COD level in the feed solution made to change the anode solution many times, which was not practically feasible[6]. To avoid this problem some scientists used air cathode along with a Pt catalyst. Here the problem is that for maintenance of an air cathode, high energy is needed and the expense of the catalysts is high enough[7]. To have good environmental applications, some researches were done using biocathode. A biocathode is actually a biofilm generation on the surface of the cathode to catalyze the reduction in cathode chamber. It is actually a very good idea because it is environment friendly, cost beneficiary as well as self-generating[8]. It is also noticed that the start-up time of a MDC reactor is reduced on use of these types of cathodes[30]. But the one and only limitation is that the whole process is complex and time consuming[31]. In the next few studies, to have more practical experience, scientists avoided acetate anolyte and used real wastewater in the anode. Major problem arose when the separation of ions occur, these ions enter into the anode and cathode chambers. This imbalances the pH level of the wastewater followed by improper environment for the growth of microorganisms. The large changes of pH were controlled by the new type of MDC called recirculation MDC or rMDC and it also helped to get better desalination efficiency[9,10]. Here comes the need of a buffer solution. To improve charge transfer efficiency some researchers used a more number of ion exchange membranes or made the desalination chambers more in number. Somehow it increases the desalination rate than the regular MDC but the physical handling becomes tougher. Stacked MDCs successfully showed that optimizing the external resistance, it increased the desalination rate as a whole[16]. In addition to this, in recovery of more energy, stacked MDCs are more beneficial and cost effective also[32]. The current generation is though reduced by increased cell pairs method[24].

Multiple MDCs when connected in series and operated in continuous mode, desalination rate was increased but decrease in coulombic efficiency was observed[29]. The problem of entering salt ions into the anode and cathode was avoided by innovation of another MDC called capacitive microbial desalination cell (cMDC). This cell absorbs salts on electrode surfaces and restricts them to go into the electrolyte solutions. But after one desalination cycle, the electrodes are to be cleared manually which is not system efficient[11]. At a very low initial salt concentration, the distance between the two electrodes was also varied. Variation in the liquid volume in the respective chambers was studied in the decoupling MDC[13], which provided more flexibility to handle an MDC. Variation in the distance of ion exchange membranes also matters in the rate of desalination i.e. when the distance between the membranes was low, the system achieved high desalination[14]. While original wastewater is used in the anode chamber, the maximum cases showed that the anolyte had to be replaced multiple times. When the desalination starts to taking place, the conductivity decreases which forces to drop the voltage. It proves that MDC operation is better as a pre-treatment of RO than a stand-alone process of desalination.

V. Future scope

MDC is promising concept to work out for simultaneous wastewater treatment and desalination of water. The largest MDC reactor so far is a 105 L volume MDC[33], which achieved a desalination rate of 9.2 kg/m^3/d. But currently it is not so in use. From low to high, different concentrations of salt waters has been studied for desalination. Synthetic seawater, real brackish water all have been tested by various MDCs. For wastewater treatment, in maximum cases, synthetic acetate fed water or domestic wastewater has been used. MDC can work as an individual process for desalination or better can be used with reverse osmosis technology[34]. MDC also can work when coupled with FO cells and apparently perform well. The coupled MDC-FO system removes COD by 50% which is higher than an individual FO cell[35]. Further research has to be done for better result and how a MDC can be applied in large or industrial scale to mitigate the water crisis. If a MDC is applied in a desalination plant, it should be cost effective and feasible to handle. Therefore, optimization of internal resistance and lessening membrane fouling are the necessary parameters for a good MDC operation. The volume ratio is an important factor which needs to be studied.

VI. Conclusion

Microbial Desalination Cell is a unique process which can lower both the energy consumption and the capital cost for use in a desalination unit. They can generate electricity by itself. It works on wastewater treatment and desalination simultaneously. Henceforth, the wastewater plants and desalination plants both can install a MDC unit to save power. MDC can be used a pre-treatment of reverse osmosis or in small case as a stand-alone desalination process. More development on MDC has to be done for its larger application in industry scale. The size of MDC has to be enlarged from ml to lit keeping the performance unhampered. Hence the scaling up is the main upcoming challenge. The treated wastewater can be reused and the desalinated water can meet the demand of potable water. For sustainable development, if MDC can be used broadly, it will be a novel step in future growth having multiple benefits.

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