THE DESEL SYSTEM – CAPACITIVE DEIONIZATION FOR THE REMOVAL OF IONS FROM WATER

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ABSTRACT

Capacitive deionization (CDI) represents a new approach to the treatment of a variety of water/wastewater streams contaminated with inorganic compounds. ENPAR Technologies Inc. of Canada has developed its DesEL System, which combines high water recoveries with high ion removal efficiencies. The system operates on the principle of capacitive deionization to remove ionic compounds referred to as total dissolved solids (TDS). The results of several bench and pilot tests of capacitive deionization systems are presented. In addition to the removal of general TDS, the system can be configured to preferentially remove monovalent ions. This alternative approach has been used to selectively remove nitrate from groundwater with only minor reductions in overall TDS. Pilot testing of the DesEL system has been conducted on groundwater containing high arsenic levels (0.210 to 0.820 mg/L). The DesEL system was effective at removing the As from the groundwater stream to less than the detection limit of 0.005 mg/L. The DesEL system has proven to be an effective technology for a variety of water and wastewater treatment applications.

KEY WORDS

Capacitive deionization, total dissolved solids, groundwater, water treatment, wastewater, arsenic.

INTRODUCTION

Capacitive deionization (CDI) technology is a relatively new and emerging technology for the removal of ionic compounds or total dissolved solids (TDS) from various water streams. The purpose of this paper is to provide an introduction to ENPAR's CDI technology, the DesEL System, and to present the results of bench and pilot-scale testing on various water streams.

CDI Technology – The DesEL System

The main component of the DesEL System is a novel, electrostatic charging system comprised of inexpensive carbon electrodes which behaves as a capacitor. The capacitor is energized using direct current, creating positive and negatively charged surfaces. Ionic compounds such as iron, chloride, arsenic and nitrate are attracted to and adsorbed onto the surface of the electrodes, via an electrostatic charge (Figure 1).

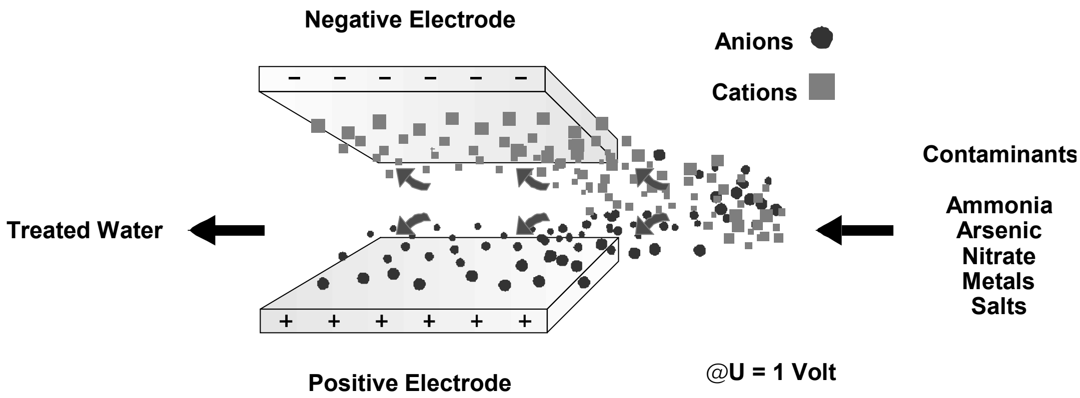

Figure 1. Capacitive deionization.

To regenerate the system, the polarity of the cell is reversed causing the capacitor to release the contaminants into the cell channels. The contaminants are removed from the cell by flushing with a small quantity of liquid, thereby, forming a concentrated solution.

The operating potential is relatively low (approximately 1.2V) such that no electrolysis reactions occur, precluding breakdown of the capacitor material and the formation of secondary solid phases.

Previous designs of CDI systems were limited to the treatment of relatively low ionic strength solutions (TDS < 3000 mg/L). The reason for its limited application has been identified as the high pore volume to surface area characteristic of the carbon electrode material. The high pore volume of the material traps salts like a sponge resulting in coulombic inefficiencies.

In order to overcome this limitation, the DesEL unit employs the "Charge Barrier" innovation consisting of ion selective layers. This innovation enables the treatment of high TDS water streams and allows for water recoveries >90%.

Lifetime testing has been demonstrated treating hard water with minimal pretreatment (15 µm cloth filter) at 80% water recovery for extended periods with insignificant reductions in efficiency (Bino *et al*., 2003).

The main advantages of the DesEL System over conventional water treatment technologies are:
1. Minimal pretreatment required.
2. Extremely high water recoveries coupled with high ion removal efficiencies.
3. Low maintenance.
4. No addition of salts or chemicals to treated water.
5. Readily removes problem contaminants such as nitrate, perchlorate and arsenic.
6. Can be designed to preferentially remove contaminants without complete deionization of the water stream.
7. Can be operated at various levels of ion removal and water recovery efficiencies.

DESCRIPTION OF TEST SYSTEMS

Bench-Scale Systems

Testing of streams and contaminants is initially conducted using a laboratory scale unit (Figure 2). The bench system consists of a single CDI cell with a total electrode surface area of 0.7 m^2. The system is typically operated at flow rates ranging from 300 to 400 mL/min. Purification cycles typically range from 120 to 600 s, while recharge cycles are between 90 to 120 s. A conductivity probe is used to monitor the treated stream and, in combination with a PLC, is used to control operation of the system. Conductivity criteria are used to set the desired level of treatment and water recovery. Thus, the system can be configured for a wide variety of water streams and treatment criteria.

Figure 2. Bench-Scale CDI System – DesEL 400

An alternative cell design has been developed for the preferential removal of monovalent ions and has been tested using the bench-scale system. The main application for this alternative cell design is for the selective removal of nitrate from groundwater.

Pilot-Scale Systems

The design of pilot and commercial systems is based on a standard size CDI cell with an electrode surface area of 10 m^2 (Figure 3). Pilot systems consisting of 2, 4 and 10 cell groups have been constructed and are currently in operation. The multiple cells are operated hydraulically in parallel but are connected electrically in series.

The pilot systems are typically operated at a flow rate range of 3 to 5 L/min per cell. The pilot systems are configured with similar control systems to that of the bench-scale units and, therefore, can be configured for a variety of applications.

Figure 3. Pilot 2-cell system - DesEL 4K

BENCH-SCALE TESTING

TDS Removal from Process Water

Tests using the DesEL system were conducted using surface water from Hamilton Harbour located in the eastern part of Lake Ontario, Ontario, Canada. This water source is often used for process water by local industries.

In collaboration with a steel company, a study was initiated to test the use of the DesEL system to treat this water source for use in the plant. The targets for treatment were to reduce the concentrations of calcium and chloride to 40 mg/L and to 60 mg/L, respectively, in the treated water stream. The DesEL system was configured to provide a TDS removal of approximately 80%, based on conductivity.

The results of the test are presented in Table 1. The TDS of the water stream decreased by >80% compared to the input water. The concentration of Ca was reduced by 90%, from 55 mg/L to 5.4 mg/L. The concentration of Cl^- was reduced by more than 80% from 121 mg/L to 21 mg/L. The unit was operated at a water recovery of approximately 95% during the treatment test. The treatment targets were readily achieved using the DesEL System. Power consumption for the CDI cell was estimated at 0.7 kWh/m^3 of water treated.

Table 1. Hamilton Water Test Results

Parameter (unit)	Input Sample	Treated Water	Waste Stream
pH	7.6	6.7	8.3
Conductivity (µS/cm)	757	117	13,450
TDS (mg/L)	462	77	Approx. 8200
Na (mg/L)	66	11	2000
Ca (mg/L)	55	5.4	208
Mg (mg/L)	15	1.6	71
Fe (mg/L)	0.37	0.12	NA
Cl^- (mg/L)	121	21	>3900
SO_4^{2-} (mg/L)	57	6.3	628

Preferential Removal of Nitrate from Groundwater

Background
In previous studies, the DesEL technology has been shown to be effective at removing ions (total dissolved solids) from water and wastewater (Shelp *et al.*, 2004). However, in several drinking water sources, nitrate is the only contaminant of concern. An alternate cell design for the DesEL system was tested to target the removal of nitrate while minimizing the removal of multivalent ions.

A problematic ground water source was identified and selected for testing. The groundwater was contaminated with nitrate-N up to 34 mg/L and had an overall TDS concentration of 790 mg/L. The treatment goal was to reduce the nitrate-N down to less than 10 mg/L while minimizing overall TDS removal.

Results
Preliminary results indicated that a conductivity set point of 0.9 mS/cm was sufficient to achieve the target nitrate removal. A conductivity of 0.9 mS/cm of the treated water corresponded to an overall TDS removal of only 31% (based on an inlet conductivity of 1.3 mS/cm).

Inlet and treated nitrate-N levels for several test runs are presented in Figure 4. The results clearly show that the DesEL system was effective at removing nitrate from the groundwater. Water recoveries of up to 95% were attained during the study.

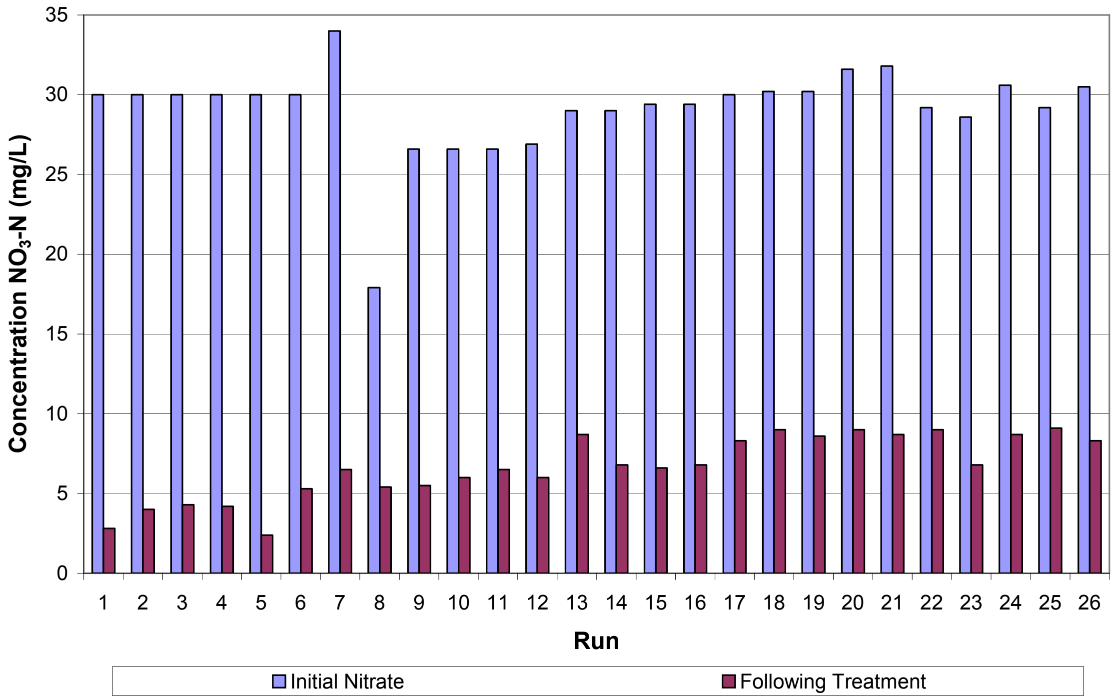

Figure 4. Nitrate removal using modified DesEL bench system.

The water chemistry for one of the test runs is presented in Table 2. As expected, greater removal of the monovalent ions was observed compared with the multivalent ions. Excellent selectivity for nitrate removal was achieved with 69% removal of the nitrate compared with an overall TDS removal of 35%.

Power consumption for the CDI cell was found to be relatively low at 0.33 kWh/m^3 water treated.

Table 2. Water Chemistry Results – Nitrate Removal

Element	Symbol	Input Water (mg/L)	Cleaned Water (mg/L)	Waste Water (mg/L)
Calcium	Ca	69	68	170
Magnesium	Mg	17	17	31
Sodium	Na	127	59	770
Potassium	K	56	23	510
Nitrate Nitrogen	NO_3-N	31	9.6	270
Chloride	Cl^-	130	72	940
Sulfate	SO_4^{2-}	130	120	270
pH		8.15	7.93	7.85
Alkalinity (as $CaCO_3$)	$CaCO_3$	200	180	370
Total Dissolved Solids	TDS	787	512	4110
Conductivity (mS/cm)	E.C.	1.3	0.87	6.8
Percent of Input (Recovery)		100%	92%	8%

The modified DesEL reactor readily removed nitrate to less than the target level. The modified cell design was successful at preferential removal of the nitrate from the water stream.

PILOT TESTING

Removal of As from Groundwater

A 2-cell pilot system was used to examine the removal of As from groundwater sources. The study was conducted by the Instituto Mexicano de Tecnologia del Agua (IMTA), in association with ENPAR (Figure 5). Dr. Garrido's research team from IMTA and ENPAR's Alberto Nieto, MSc., P.Eng., examined the efficacy of the DesEL System for the treatment of potable water sources in Mexico contaminated with arsenic. Arsenic concentrations up to 2.35 mg/L have been detected in groundwater sources, far in excess of the maximum permissible limit of 0.025 mg/L (Official Mexican Norm NOM-127-SSA1-1994). It is estimated that 500,000 people live within rural areas containing arsenic levels exceeding 0.05 mg/L.

The groundwater used for the testing was obtained from the town of Huautla, located in the state of Morelos, Mexico. The TDS of the groundwater was measured at 339 mg/L with an As concentration of 0.210 mg/L. In addition to testing the raw groundwater, As spiked groundwater containing 0.820 mg/L of As was also tested. The DesEL system was configured for a TDS removal of approximately 95% (see Garrido *et al.*, 2006 for additional details).

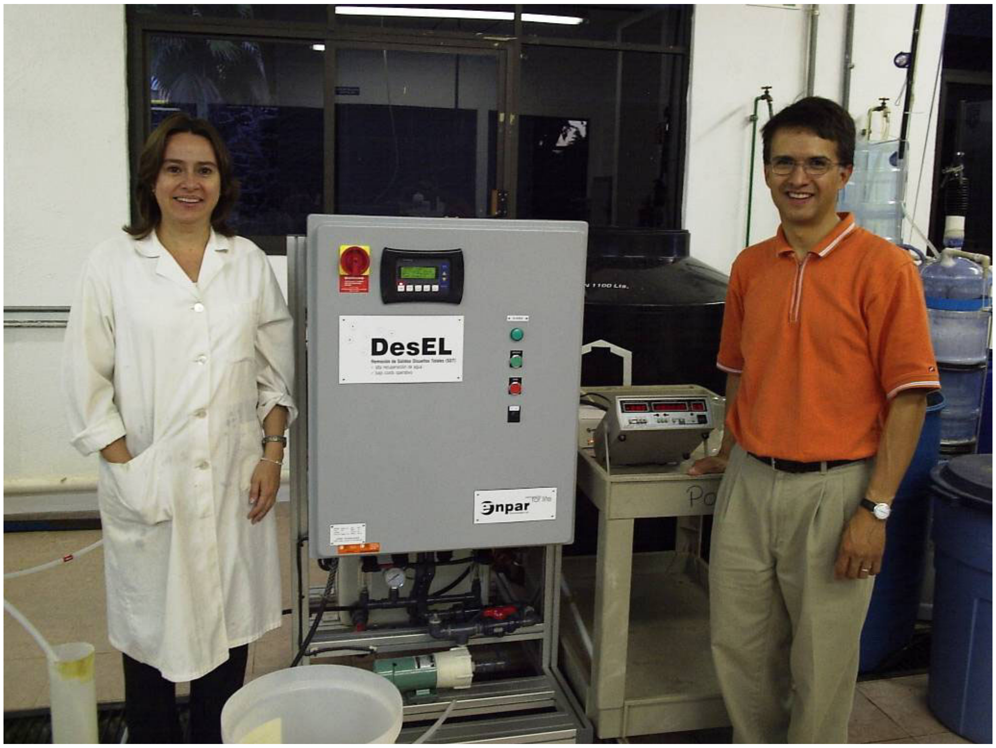

Figure 5. Arsenic removal project managed by Dr. Sofia Garrido of IMTA and assisted by ENPAR's Alberto Nieto, M.Sc., P.Eng.(DesEL-4K Unit - 4800 LPD).

The results of testing demonstrated consistent removal of As to below the detection limit of 0.005 mg/L treating both with both raw and As-spiked groundwater with up to a 99.4% removal efficiency for the As. Water recoveries of up to 97% were achieved during the trials.

Power consumption for the CDI cells was found to be 0.80 kWh/m^3. Total power consumption for the system, including cells, pump and controls was measured at 1.37 kWh/m^3.

The results indicated that the DesEL system was a cost-effective method of removing As from contaminated groundwater sources.

SUMMARY

There is a current need for reliable, high efficiency, low maintenance technologies for the treatment of drinking water, wastewater and industrial process waters. Furthermore, these technologies should be efficient at addressing problem contaminants such as arsenic and nitrate.

The DesEL System has proven to be a promising new technology for the treatment of a wide variety of water and wastewater streams. The system has been demonstrated to provide high contaminant removal efficiencies while achieving high water recoveries (producing minimal concentrate volumes). In addition to general TDS removal, preferential removal of nitrate, a common groundwater contaminant has been demonstrated using a modified cell design.

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