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Electromagnetic–mechanical desalination: Mathematical modeling

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HIGHLIGHTS

- Novel separation method for salt removal from a moving fluid is developed.
- Charged particle separation using electrical and magnetic fields is simulated.
- The effects of different operating parameters on the separation are examined.
- Lower fluid velocity increases the separation efficiency.

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ABSTRACT

A theoretical model is developed for electromagnetic–mechanical salt removal (EMSR) process and solved numerically to investigate the optimum operating parameters for separation. The fluid flow and charged particle motion under hydrodynamics, and electrostatic and magnetic forces are modeled using the CFD software ANSYS FLUENT. The Navier–Stokes equations are solved using Eulerian approach, while the discrete phase is modeled using a Lagrangian approach. A source term is added to the Navier–Stokes equation to account for the effect of electric and magnetic fields. The developed model is validated using results in the literature. Different important operating parameters, i.e. electrical and magnetic forces, charged particle diameter, and fluid velocity affecting separation process are examined using the developed model. It is shown that operating at a lower fluid velocity increases the residence time and increases the separation efficiency. Operating at a lower charged particle velocity in the axial direction is recommended even though it decreases the induced magnetic force. Doubling the induced electrical and magnetic forces increased the transverse velocity and decreased the capture time each by about 2 times. However, doubling the axial flow velocity increased the transverse velocity 25% only. It is clearly demonstrated that combining electrical and magnetic forces together can effectively be used to separate dissolved salts from seawater.

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1. Introduction

For many years, efforts have been made to develop efficient desalination technologies for obtaining potable water from saline water. Some of the earliest desalination technologies were developed centuries ago and they were powered by solar energy. There is an increasing demand for advancing conventional desalination technologies. The increasing demand for efficient desalination systems is driven by the increasing cost of fossil fuels for thermal and electrical energy generation. Desalination of seawater or brackish water is generally accomplished using water evaporation (phase change), or by using a semi-permeable membrane to separate fresh water from concentrated saline water, or by a combination of the two as in membrane distillation.

There is a growing demand for an efficient separation technique of salts from seawater using electrical or magnetic means. The most classical industries where magnetic fields are used to attain the separation and filtration goals are the mineral processing industries. However, the practical and industrial applications of magnetic separation are still very limited. Magnetic separation can be applied to separate magnetic and non-magnetic charged particles in different proportions via utilizing the magnetic behavior of charged particles or by using coated magnetic charged particles to enhance the separation. The electro-magnetic separators should be operated continuously so that the dissolved charged particles, i.e. ions, can be diverted by the electrical and magnetic fields while moving in the stream so it can be separated from seawater. The structural design of the electro-magnetic separator is important due to the limitation of the low residence time of moving particles.

Electro dialysis (ED) is an electrochemical process for separation of ions across charged membranes from one solution to another under the influence of an electrical potential difference used as a driving force. ED was developed in the 1950s for desalting water. ED process is based on the principal that most dissolved salts are positively or negatively charged and they will migrate to electrodes with an opposite

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charge. The electrodes exert a force on dissolved charged particles (ions), attracting or repelling them depending on their electrical charge. This process has been widely used for desalination of sea or brackish water, treatment of industrial effluents, recovery of useful materials from effluents and salt production. The basic principles and applications of ED were reviewed in the literature [1–3]. In order to reduce membrane scaling and fouling, electro dialysis reversal (EDR) process is introduced, where the voltage is reversed at periodic time intervals [4].

The use of magnets for salt separation of sea water has been proposed by a number of studies and patents [5–15]. Magnetic separation is considered a simple technique in the mining industry for various applications. It has been used for separation of magnetic from non-magnetic waste, or for separation of gangue from ore to increase the concentration of ore [16,17]. Some research work on magnetic separation has also been used in the waste water treatment [18,19].

Magnetic separation in fluidic system is used in bioseparation applications to facilitate the analysis of biomaterials in microscale system. Magnetic particles, typically made from magnetite (Fe_3O_4) are increasingly used in different fields of microbiology and biotechnology. Magnetic nanoparticles with a diameter of 1–100 nm are currently used for biological and chemical separation.

The magnetic separation force can be applied via a passive (soft or hard) magnetic element in which a bias field is applied. Soft passive magnetic element can be integrated into a fluidic system via deposition on the separation cell, and an external bias field is used to magnetize the soft element [20–26]. An advantage to this method is ability to switch on/off the magnetic field by applying or removing the external bias field. In contrast, hard permanent magnet cannot be switched on and off. In addition, the magnetic force can also be applied via an active magnetic element in which voltage is driven in coils or conductors. The active magnetic element can be switched on and off as needed by supplying the voltage to the coils or conductors [20,22].

Several researchers have studied magnetic separation in micro fluid system [20–26,35–36]. Choi et al. studied the capture of magnetic beads in micro fluid system via an active magnet for bioseparation applications [20,21]. Kong et al. [22] studied the separation of magnetic beads using an active magnetic field in which the beads are directed to one outlet. Smistrup et al. used an electromagnet element to investigate separation in microfluidic system [23–25].

Mikkelsen et al. [27] have studied theoretically the motion of magnetic beads in fluidic system, and they used Greens's function approach to model the movements of beads within the fluid. Nandy et al. [28] investigated the capture efficiency of magnetic particles in fluidic system as a function of physical properties. The performance of magnetic separation in continuous flow microsystems is studied by Pamme et al. [29,30]; Lehman et al. [31]; and Shikida et al. [32]; Wang et al. [33]; Tsuchiya et al. [34].

In this paper, electrical and magnetic forces are combined together to separate dissolved salts from seawater. The system considered in this study consists of a small rectangular channel with 1-inlet and 3-outlets. The magnetic element used is a magnet placed at the surface of the channel and produces a constant magnetic force. The electrical force is applied via metallic conductor plates (electrode) placed on the channel internal surface and connected to an electrical power source. The dissolved charged ions are directed and captured by the applied magnetic and electrostatic forces in the flow channel.

A mathematical model of the process is developed to examine the different design and operational parameters. This study is accomplished via developing a Computational Fluid Dynamics (CFD) model for ion separation in the electromagnetic–mechanical salt removal (EMSR) from seawater. The fluid flow and ion motion under electrostatic and magnetic forces are modeled using a user-defined function integrated to FLUENT. A source term is added to the Navier–Stokes equation to account for the driving forces effect resulting from the induced electrical and magnetic fields. This source term is obtained by solving the electric field and charge transport equations. The results of the simulation are presented to track **ions** motion in the EMSR. Numerical calculations for the fluid flow and ions motion are carried out by solving the Reynolds-averaged Navier–Stokes equations. In the development of the model, two parameters, namely residence time and capture time are introduced to quantify the separation efficiency of electrical and magnetic systems. These parameters are useful to predict separation efficiency for different operating parameters such as flow rate, channel length and height, and electrical and magnetic forces. The different important operating parameters that affect separation process are investigated in this paper using the developed model.

To the best of the author's knowledge, there was no prior attempt to combine electrical and magnetic forces to separate dissolved salts from seawater. The developed model is useful to gain insight into the separation efficiency of dissolved salts in the EMSR process. The computational model can be applied to any geometrical configuration of electrical and magnetic desalination processes.

2. Process description

The proposed separator utilizes magnetic and electrical forces for achieving the separation as shown in Fig 1. The system consists of a small rectangular channel with 1-inlet and 3-outlets. A barrier is used to split the flow to separate the concentrated streams from the clean solution. The magnetic element used is a hard magnet placed at the surface of the channel and produces a constant magnetic force as shown in Fig. 1. The electrical force is applied via metallic conductor plates (electrode) placed on the channel internal surface and connected to an electrical power source. The current system utilizes continuous flow separation has advantage over patch operating mode. Continuous separation mode enables higher separation output.

In this separator configuration, the separation mechanism used is primarily based on electrical and magnetic forces acting on a specific direction within the flow channel. The dissolved salt (ions) are pushed via the induced electrical and magnetic forces in a specified direction, (−ve ions move to the upper wall, and +ve ions move to lower wall). The concentration of the −ve ions in the upper part of the channel increases as the fluid moves in the axial direction, and the concentration of the +ve ions in the lower part of the channel decreases in the axial direction. A barrier is installed at the end of the flow channel to separate the −ve and +ve charged outlets from the clean solution as shown in Fig. 1.

Electrodes are used to move the ions in the desired direction for separation. A negative voltage is applied at the electrodes to generate the electrical field. It is assumed that the dissolved ions in seawater can be dealt with as dissolved charged particles; thus the two terms, particle and ions, are used interchangeably in this paper.

The flow channel structure material, as shown in Fig. 1, is selected such that it has a very low electrical conductivity and it does not have any magnetic behavior. Possible material for the channel is polypropylene or acrylic plastic with its low electrical conductivity.

3. Mathematical modeling

The mathematical approach is based on modeling the fluid flow and the movement of multiple charged particles, i.e. ions suspended as shown in Fig. 1. Fluid flows in the z-direction due to the pressure difference between the upstream and downstream of the duct. The electrical and magnetic forces affect the dissolved charged particle (**ion**) motion and push it to move in the transverse (y-direction). These combined electrical and magnetic forces [37], F_{EM}, are given as,

$$F_{EM} = F_E + F_M = q[E + (v_z \times B)], \quad (1)$$

where $F_E = q\,E$ is the electrical forces imposed by the electrical filed, and $F_M = q(v_z \times B)$ is the magnetic field force imposed on the dissolved charged particles and known as Lorentz force. Where E is the electric

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