



Historical perspective

## Fouling on ion-exchange membranes: Classification, characterization and strategies of prevention and control



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## ABSTRACT

The environmentally friendly ion-exchange membrane (IEM) processes find more and more applications in the modern industries in order to demineralize, concentrate and modify products. Moreover, these processes may be applied for the energy conversion and storage. However, the main drawback of the IEM processes is a formation of fouling, which significantly decreases the process efficiency and increases the process cost. The present review is dedicated to the problematic of IEM fouling phenomena. Firstly, the major types of IEM fouling such as colloidal fouling, organic fouling, scaling and biofouling are discussed along with consideration of the main factors affecting fouling formation and development. Secondly, the review of the possible methods of IEM fouling characterization is provided. This section includes the methods of fouling visualization and characterization as well as methods allowing investigations of characteristics of the fouled IEMs. Eventually, the reader will find the conventional and modern strategies of prevention and control of different fouling types.

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**Abbreviations:** AAS, atomic absorption spectrometry; AEMs, anion-exchange membranes; AFM, atomic force microscopy; ATR-FTIR, Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy; CEMs, cation-exchange membranes; CHP, chronopotentiogram; CLSM, confocal laser scanning microscopy; CVC, current-voltage curve; DGGE, denaturing gradient gel electrophoresis; EDS, energy dispersive X-ray spectroscopy; EIS, electrical impedance spectroscopy; ED, electrodialysis; GC, gas chromatography; HPLC, high-performance liquid chromatography; IR, infrared; IEM, ion-exchange membrane; LCD, limiting current density; MS, mass spectrometry; MF, microfiltration; NF, nanofiltration; OES, optical emission spectrometry; PCR, polymerase chain reaction; PEF, pulsed electric field; RO, reverse osmosis; SDBS, sodium dodecylbenzenesulfonate; SEM, scanning electron microscopy; SEC, size exclusion; UF, ultrafiltration; UV/vis, ultraviolet-visible spectroscopy; XRD, X-ray diffraction analysis.

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## 1. Introduction

Fouling is the phenomenon of undesirable attachment of certain species (living organisms or non-living substances) to the surface or inside the material. This phenomenon is one of the key problems for the modern chemical, agricultural, food, pharmaceutical processing and water treatment. The cost of cleaning procedures and membrane replacement may vary from 20 to 30% [1] for the pressure-driven membrane processes to 40–50% for the electromembrane processes [2]. In the scope of the present review, we will consider only the fouling on ion-exchange membranes (IEMs), which are applied in electrodialysis (ED), electrolysis, diffusion dialysis, Donnan dialysis, fuel cells etc. IEMs are a special membrane type providing ionic selectivity since they carry electrical charges. This particular type of selectivity leads to separation of ionic species from the neutral media allowing demineralization, concentration and modification of products. Moreover, IEMs are involved in the energy conversion and storage processes. However, the formation of deposit may occur on the IEM surface and/or inside the membrane causing an increase in electrical resistance, a decrease in permselectivity and membrane alteration [3,4]. Thus, the industrial application of IEM based processes is hampered due to fouling problems. Therefore, the aim of the present paper is to describe the fouling types occurring during processes using IEMs, the methods for fouling detection and characterization, and the ways of fouling prevention and control. The main emphasis will be put on the ED processes since they are the most widespread processes using IEMs.

## 2. Classification of IEM fouling

### 2.1. Colloidal fouling

Colloids are non-dissolved suspended solids, which are presented in natural and processed waters and many effluent streams in forms of clay minerals, colloidal silica, iron oxide, aluminium oxide, manganese

oxide, organic colloids etc. [5,6]. The size of colloid particles may vary from 10 Å to 2 µm in diameter. For instance, the majority of colloidal particles found in natural waters are small aluminium silicate clays. These clays are in the 0.3 to 1.0 µm diameter size range. The main feature of colloids is an excessive charge on the surface (net charge), which leads to adsorption of ions from the surrounding solution. Fig. 1 represents a general model of the colloid structure which was developed by Gouy [7] and Chapman [8] and later by Stern [9]. The solid in this model has an excessive positive surface charge, which attracts negatively charged molecules from the solution. The Stern layer is tightly adjusted to the solid due to electrostatic forces compensating most part of excessive positive charge. The ions from diffusion layer neutralize the rest of excessive charge. The diffusion layer acts as a caution preventing colloids coming in contact with one another and coagulating [6].

Thereafter, colloid particles have a net charge, which plays an important role in terms of colloid stability (according to the theory of Derjaguin, Landau, Verwey and Overbeek (DLVO) [10,11]) and also may lead to the attachment of colloid to the membrane surface. Numerous works are dedicated to the investigation of nature, structure and stability of colloidal fouling as well as to the mechanisms of its formation on the membrane surface. Most of these investigations are related to membrane filtration processes [6,12–20]. In electrodialytic processes, the attention usually focuses on the anion-exchange membrane (AEM) colloidal deposits since most part of colloids treated by ED is negatively charged, which leads to interactions with positively charged ion-exchange groups of AEMs [5,21–24]. For instance, Lee et al. [25] studied the formation of a special colloidal fouling such as fouling by a surfactant agent (sodium dodecylbenzenesulfonate (SDBS)). These authors developed a mechanism of fouling formation where SDBS micelles formed the fouling layer on the membrane surface due to increased molecular size and highly negative charges. Ghalloussi et al. reported the sorption of organic colloids inside the IEMs during their use in food industrial processes [26,27]. The factors affecting colloidal fouling are concentration of fouling particles as well as dissolved salt concentration, pH, temperature, membrane properties, mode of operation and hydrodynamic conditions.

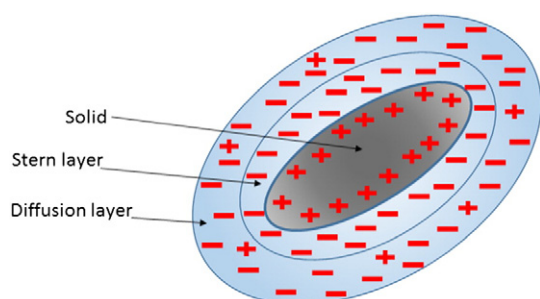


Fig. 1. Model of positively charged colloidal particle.

### 2.2. Organic fouling

Organic fouling is similar to organic colloidal fouling except for the fact that organic foulants are initially dissolved in the solution treated by ED. Additionally, the colloidal state of organic molecules is maintained by weak, long-range van der Waals forces of attraction and electrostatic forces of repulsion, in contrast to ordinary organic molecules, which predominantly have covalent bonds [28]. Organic fouling occurs when a treated solution contains organic substances such as oil, carbohydrates, proteins, aromatic substances, humic acid and anti-foaming agents [4,29–45]. These organic substances stick to the surface of the membrane and/or lodge themselves inside the membrane. This

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