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Cost evaluation of large-scale membrane capacitive deionization for biomass hydrolysate desalination

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ABSTRACT

The bio-based industry is striving to replace refined sugars by much cheaper secondary feedstocks for the production of bio-fuels and chemicals. However, due to their higher complexity, a number of technological challenges need to be overcome. One example are the high concentrations of sodium and potassium present in the biomass hydrolysates that inhibit fermentation and hence need to be reduced. Previous research demonstrated the technical feasibility of membrane capacitive deionization (MCDI) for biomass hydrolysate desalination as a chemical/waste free alternative compared to the commonly used ion-exchange process (IEX). In this paper, the economic viability of MCDI was investigated for a production capacity of 500 ton sugar day^{-1} and a target Na removal from 3 to 0.1 g kg^{-1} hydrolysate. Although capital costs were higher for MCDI than for IEX due to the expensive MCDI cells and power supplies, operating costs were lower because less water and chemicals are used and less wastewater is generated. Cost calculations for different initial feed concentrations indicated that IEX was only preferential over MCDI when the feed Na$^+$ concentration was below 0.4 g kg^{-1} hydrolysate. Then the higher chemical, water and wastewater treatment costs for IEX no longer outweighed the higher cost of MCDI cells compared to IEX resins.

1. Introduction

Cheap raw materials are essential for the economical production of biofuels and chemicals like ethanol, butanol, organic acids and acetone through fermentation processes [1–3]. Instead of high cost substrates like glucose or starch, cellulosic or lignocellulosic materials from agriculture, agro-industry or forestry should therefore be used. Apart from their low cost, these biomass hydrolysates have also gained increasing interest due to their abundance, renewability and sustainability (no food-feed competition) [1,4–6]. The downside is that they contain a much larger number of impurities present in larger quantities and hence require extensive pretreatment [2,3,7–9]. High concentrations of salts such as sodium and potassium, for example, need to be removed from the hydrolysates before they can be fed to the fermentation process, because they can act toxic to the microorganisms and lower biochemical productivity [3,10,11]. Ion-exchange (IEX) processes are used for this purpose nowadays [12,13], but the chemicals used for resin regeneration entail high operational costs and the generation of a secondary waste stream [14,15].

In our previous study [16], membrane capacitive deionization (MCDI) was demonstrated as a chemical-free alternative for biomass hydrolysate desalination, with Na$^+$ removal efficiencies over 90%. MCDI uses an electric field generated by pairs of oppositely charged porous carbon electrodes to remove ions from a feed stream flowing through a spacer channel sandwiched in between these electrodes. Ion-exchange membranes inserted in front of the electrodes increase the efficiency of the process. Upon saturation of the electrodes, the electric field is reversed, so that the ions are repelled from the electrodes, after which they are flushed from the cell in a small but highly concentrated waste stream [17–21]. Such an approach is considered more sustainable compared to ion exchange (IEX), in which the waste not only contains feed ions, but also a considerable amount of regeneration chemicals.

However, like for electrodialysis, the capital costs for MCDI could potentially constitute a bottleneck for larger-scale applications, such as in biorefinery. Hence, the objective of this study was to deepen the economic evaluation of MCDI for biomass

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hydrolysate desalination and to benchmark it against the currently applied IEX process for different feed salt concentrations. Cost calculations were based on experiences from lab-scale MCDI tests for biomass hydrolysates [16] as well as real industrial and economical data. To the authors' knowledge, such a detailed cost estimation for MCDI has not yet been reported in literature. In the end, this cost evaluation can assist decision makers to choose the most cost effective and sustainable desalination method between IEX and MCDI and potentially accelerate the large-scale industrial application of MCDI technology for specific streams.

2. Experimental

The economic evaluation is carried out for a production capacity of 500 ton sugar day^{-1} at 30% (w/w) sugar concentration. A 99% sugar recovery is targeted, so this means that 505 ton sugar or 1496 m^3 hydrolysate is fed to the plant per day. The Na^+ concentration in the hydrolysate is 3 g kg^{-1} hydrolysate (or 3.4 g l^{-1} hydrolysate), while the target concentration after desalination is 0.1 g kg^{-1} hydrolysate (or 0.1 g l^{-1} hydrolysate). Both the MCDI and IEX installations are designed for continuous operation with 8000 operating hours per year.

Subsequently, the sensitivity towards the feed salt concentration is evaluated by performing cost calculations for both MCDI and IEX at different feed Na^+ concentrations ranging between 0.2 and 3 g kg^{-1} hydrolysate, targeting the same product Na^+ concentration of 0.1 g kg^{-1} hydrolysate.

2.1. Membrane capacitive deionization

2.1.1. Description of the installation

A schematic of the proposed MCDI plant is shown in Fig. 1. This plant is designed as a modular system of which the basic building block (Fig. 2) is a pair of electrodes deposited on graphite foil current collectors with a central flow hole, placed at either side of a spacer channel. During desalination, the biomass hydrolysate flows through the spacer channel and the ions are attracted and stored in the electrodes under the influence of an electric field (typically 0.8–1.5 V), so that a desalinated effluent is produced. Ion-exchange membranes positioned in front of the electrodes improve the efficiency of this desalination process. When the electrodes get saturated with ions, they are regenerated by reversing polarity, so that the ions are repelled from the electrodes and flushed from the cell in a highly concentrated waste stream. Up to a hundred of such electrode pairs can be stacked together in one MCDI cell, with a typical total electrode surface area of 10 m^2 [22,23].

The design of the MCDI plant starts with the number of cells (N_{cell}) required to achieve the desired desalination. This number is dependent on many parameters, such as the Na^+ concentration in the feed and the target Na^+ concentration for the product, the desalination cycle duration and the cell sorption capacity. The number of cells required can be calculated with Eqs. (1)–(3).

$$N_{Na} = \frac{Q * c_{feed} - Q * \frac{\eta_{sugar}}{100} * c_{product}}{n_{des}} \tag{1}$$

$$n_{des} = \frac{T}{t_{des}} \tag{2}$$

$$N_{cell} = \frac{N_{Na}}{C_s} * 3 \tag{3}$$

with N_{Na} the amount of Na^+ that needs to be removed per cycle (kg), η_{sugar} the desired sugar recovery (%), c_{feed} and $c_{product}$ the feed and the desired product Na^+ concentration respectively (kg m^{-3}), Q the influent flow rate (m^3 d^{-1}), n_{des} the total number of desalination cycles per day (d^{-1}), T the total daily operating time, t_{des} the duration of one desalination cycle and C_s the cell sorption capacity (kg $cell^{-1}$).

It should be noted that MCDI is inherently a discontinuous process. To ensure a continuous sugar production, at least two parallel loops of MCDI cells thus need to be present, so that one loop of cells can be regenerated while the other one continues running. In this case, it was even decided to include three parallel loops (Fig. 1), alternating between desalination, regeneration and standby mode (to cope with process disturbances and periodic cell cleanings). Therefore, the total number of cells required is multiplied by a factor 3, as can be seen in Equation (3). Within each loop, the MCDI cells are further arranged in modules comprising 40 cells, connected hydraulically in parallel and electrically in series [23]. This design is chosen as the 'golden mean' between maximal operational control and minimal costs. A parallel arrangement of the cells would be beneficial in terms of voltage control, but the number of cells per module would then be much lower to limit

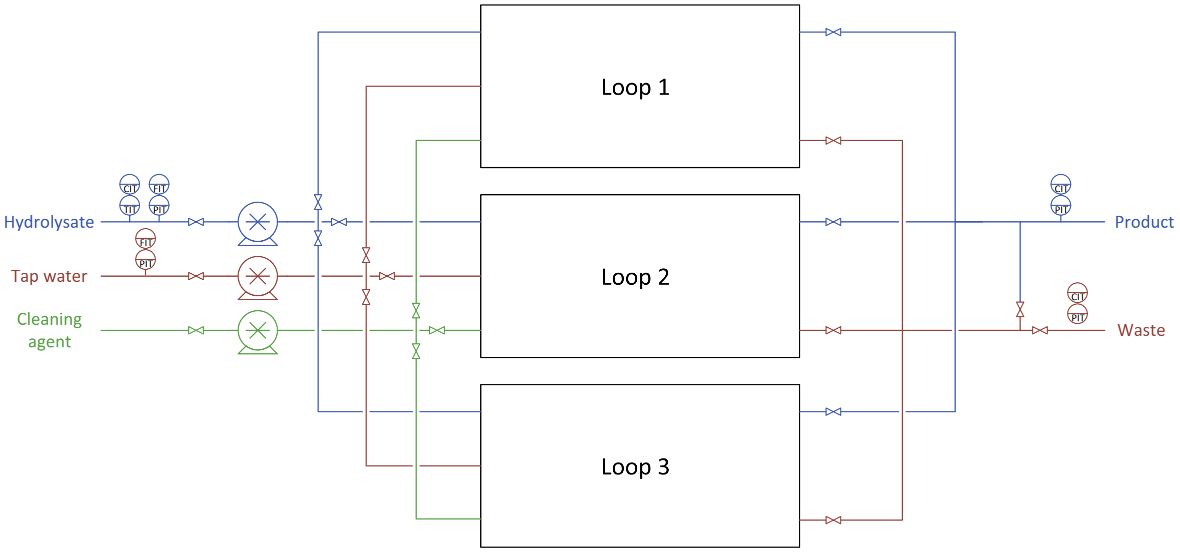

Fig. 1. Schematical representation of the MCDI plant. Each loop is operated alternately (desalination, regeneration and standby) and comprises 64 modules of 40 CDI cells (10 m^2).