Sustainable Water Desalination Using Waste Heat: Optimisation Of A Liquid-Liquid Extraction Process

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Abstract

In this paper, a waste heat utilisation based liquid-liquid extraction method is considered for the desalination of seawater. Mass and energy balances, phase behaviour and salt distribution in the two phases constitute the mathematical model. A sensitivity analysis of the main design variables was performed and results indicate their impact on the final product quality and the total energy consumption.

Keywords: water desalination, liquid-liquid extraction, low-temperature extraction.

1. Introduction

Although water covers 75% of earth’s surface being an abundant natural resource, only 3% of it is potable. Increasing world population stresses the reality of water shortage and increases the need for technologies that can provide potable water. Seawater desalination can embody the solution of this problem. There are two main categories of desalination methods that have been extensively used: thermal methods and membrane methods. Thermal methods such as multi-stage flash distillation (MSF), multi-effect distillation (MED) and vapour compression (VC) require high energy inputs, hence are costly and unsustainable processes. Membrane methods include mainly reverse osmosis (RO) and although they do not require high energy inputs, they are not cost effective mainly because of the cost of membrane replacement. Using low grade energy not only reduces the cost of the process but also constitutes it as a sustainable one. Liquid-liquid extraction (LLE) has been explored in the past, and is currently used in various industrial applications (I. C. Karagiannis and P. Soldatos 2008). The main solvents used are amines (C. N. Kimberlin et al, 1965) and polymers (L. Lazare, 1992) but no solvent extraction desalination plants are currently commercially available. Amines have been rejected as potential solvents due to their presence in the final product. A specially tailored polymer, however, can give a lot of impetus to the potential of this technology. The objective of this work is to study an LLE based process for water desalination. This process also known as the Puraq method is an LLE process that uses a liquid polymer to extract salt out of seawater at temperatures that do not surpass 60°C. These specially tailored polymers when mixed with water can pass from regions of complete miscibility into two phase separation, within the temperature range of interest. Low solubility in water satisfies a final aqueous phase containing virtually no polymer. Using optimisation-based techniques the Puraq method is assessed in order to check the potential of this process (K. Thanapalan and V. Dua, 2011). To achieve this, a mathematical model is developed for the description of the process with sensitivity
2. Process modeling

The process consists of a heat transfer contractor (HTC), a wash contractor (WC) and heat exchangers (HE). A detailed description of the overall flowsheet can be found in Lazare (1992). In this paper, the HTC is modelled using phase equilibrium as well as salt distribution correlations. In Figure 1, the part of the flowsheet around the HTC is presented.

In Figure 1 seawater enters through stream 5 and mixes with the polymer stream that enters the LLE system through stream 4. During this step water and salt distribute to the polymeric phase. This distribution depends on the salt distribution coefficient that was first described in Lazare (1992) and is given in equation 1.

\[ K_s = 1.5e^{0.0000691k^3 - 0.01278x^2 + 0.84114x - 18.133} \]  

Equation 1

Lazare (1992) also addressed the requirement for phase equilibrium. Since the distribution coefficient and the phase equilibrium correlations are highly non-linear constraints and can cause computational difficulties, in this paper a linear phase equilibrium equation is used, as presented in equation 2.

\[ x = 0.017T + 0.4 \]  

Equation 2
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In both equations 1 and 2, \( x \) represents the mass fraction of the polymer in the solvent phase. In addition to these two equations, mass and energy balances for the presented flowsheets are also considered. Finally, the objective function is set to minimising the energy consumption of the heat exchanger and the relevant constraint is given in equation 3.

\[
Q = \sum_i (F_i \cdot C_{pi}) T_2 - \sum_i (F_i \cdot C_{pi}) T_1
\]

Equation 3

where \( i \) refers to components: water, salt and polymer.

3. Problem Statement

Given:
- The seawater feed in terms of water and salt concentration
- Feed temperature
- Specific heat capacities
- Phase equilibrium correlation
- Salt distribution correlation
- Minimum percentage of salt in the product

Minimise:
- Energy consumption

4. Results and Discussion

After implementing the model in GAMS (A. Brooke et al. 1998), a sensitivity analysis was performed. The objective function was always set as the minimisation of energy consumption. The objective was to investigate the impact of the feed temperature and the salt content in the feed. A decrease of 30\%, and a respective increase were imposed in these two design variables. Flowrate of water was kept constant at 23696000 kg/hr for both cases and the temperature was set at 28.67\(^\circ\)C when investigating the impact of salt content. The results are presented in Figures 2 and 3. In Figure 2, it is shown that the impact of the feed temperature on stream 7 is shown to be very small. The value of \( m_{SA} \) which is defined as the flowrate of salt in stream 8 remains practically identical in a wide range of temperatures. This means that the location from where seawater is collected has a small impact in the HTC.
In Figure 3, the impact of the salt content in the feed is investigated. As expected, while the salt flowrate in the feed (stream 5) increases the salt flowrate in stream 8 also increases.

Finally, the impact of the final salt concentration in the water was investigated in order to determine how the energy consumption changes. As expected, to achieve the least percentage of salt in the final product more energy had to be consumed.
In summary, the impact of the feed temperature was found not to have an impact in the HTC operation. Moreover, the impact of the salt content in the feed stream was investigated and as expected while the salt feed increases the blowdown salt content also increases. Finally, the energy consumption was investigated as a function of the final product quality and more energy was necessary for cleaner water.

5. Concluding Remarks

In this paper, an optimisation-based approach for investigating the impact of few key variables in an LLE water desalination process is presented. This specific process uses waste heat for extraction of salt from seawater and has a great advantage over traditional desalination processes. Current works involve implementing the same procedure for the overall flowsheet in order to determine how energy consumption can be further reduced.

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References

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