Using Low-Grade Heat for Solvent Extraction based Efficient Water Desalination

Kary Thanapalan and Vivek Dua*

Centre for Process Systems Engineering, Department of Chemical Engineering,
University College London, London WC1E 7JE

Abstract

In this paper, a systematic approach for analyzing the energy consumption of solvent extraction based desalination systems is studied. This approach involves developing a mathematical model, incorporating mass and energy balances and phase relationships, of the desalination system and then using the model to optimize energy consumption. Model based optimization is used to explore the possibility of using low grade heat for desalination.

Keywords: Solvent extraction, Desalination systems, Mathematical model

1. Introduction

The global aspiration to increased affluence, welfare and consumerism, while accommodating increased populations, will almost certainly result in increased global water demand. Unless this demand can be met, the number of people who will be affected by water shortage is likely to increase several folds. Economically viable methods for desalination can reverse this trend and ensure continuous supply of good quality water. Two technologies, thermal and membrane, dominate the water desalination outlook; thermal method is energy intensive and membrane separation is expensive to install, operate and maintain. The objective of this work is to investigate solvent extraction based desalination systems which are energy efficient and less expensive to operate, so that can be used as an alternative to thermal and membrane technologies. There are many desalination methods that are used to produce potable water from seawater (Thanapalan and Dua, 2010). The oldest and still common process used is distillation. The dominant desalination processes using distillation method are called the Multiple Effect Distillation, the Multi-Stage Flash (MSF) distillation, and Vapour Compression (VC). These three methods utilize the principle of evaporation of the seawater by adding heat and/or lowering the pressure (thermal methods). Membrane separation processes, such as reverse osmosis (RO) is also widely used method. The solvent extraction based process studied in this work can use low-grade heat or waste energy for desalination, which is not readily possible for other traditional desalination technologies. The utilization of low-grade heat makes the process more attractive from energy efficiency point of view. Model-based optimisation can assist in making such assessment and exploring further option for energy efficiency. Two types of solvents, amines and polymers have been suggested to extract water from salt. In this paper a polymer solvent is considered for carrying out Solvent Extraction based Efficient Desalination (SEED). These polymers form a homogeneous solution with water at particular temperatures and also separate into two phases when the temperature is increased. Another unique property of these polymers is their very low solubility in

*Corresponding author, e-mail: v.dua@ucl.ac.uk
Thanapalan and Dua

water. Therefore, when the homogeneous solution of polymer-water separates, the aqueous phase practically contains no polymer.

2. Mathematical model of SEED system

The system model contains four interacting subsystems; deaerator, heat exchangers, wash contractors (WC) and heat transfer contractors (HTC). Each one is defined as a unique system involving a given number of operating variables which are linked by equations. Detailed description of the desalination system can be found in Genin (2009) and Lazare (1992). In this paper, detailed operation of only WC and HTC are presented focussing on the stage-wise operations in WC and HTC.

2.1. Wash contractors

This unit is used to wash the polymeric solvent in order to remove the salt dissolved in it. In order to write the mass and energy balances on this unit, it is assumed that the salt is diluted and transferred from one phase to the other and the unit has 3 stages (see Fig. 1). For the mass balance the stage-wise operation can be represented as follows;

\[ U_1: F_r + F_{a1} = F_{o1} + F_{o2}, \]
\[ U_2: F_{a2} + F_{a3} = F_{o2} + F_{o3}, \] and
\[ U_3: F_{o3} + F_{o4} = F_r + F_{a5} \]

Similarly energy balance can be written for each stage. So for the whole unit energy balance and mass balance can be written as follows.

Mass balances on Water (W), Salt (S) and Polymer (P): \[ W_{o1} + W_{o2} + W_{o3} = W_r + W_{a1}, \]
\[ S_{o1} + S_{o2} + S_{o3} = S_r + S_{a1}, \] and
\[ P_{o1} + P_{o2} + P_{o3} = P_r + P_{a1} \]

2.2. Heat transfer contractors

To investigate its operation the HTC’s are assumed to have 5 stages and each stage divided into two zones. In the first zone the pure polymer-rich solvent is enriched with water and salt by contacting with the deaerated seawater. A rich solvent \((F_r)\) and an impoverished stream of seawater \((F_s)\) leave the unit. The carrier or raffinate phase is the water from stream \(F_s\) and the pure solvent or extract phase is the polymer-rich phase. During this step, water and salt are transferred from the carrier to the solvent. The zone 1, is assumed to be in closed form and in this zone, water and salt are transferred from a phase to another. Adopting a similar approach stage-wise equations for this zone have been derived. Here the equations for the whole unit is presented.

Mass balance on W and S : \[ F_{o4} + F_{a5} = F_{o3} + F_{o5}, \]
\[ F_{o4} = F_{a4} + F_{a5} \]
Using Low-Grade Heat for Solvent Extraction based Efficient Water Desalination

Energy balance:

\[
F_t^r C_t^r (T_t - T_c^r) + F_t^p C_t^p (T_t - T_c^p) = F_i^r C_i^r (T_i - T_c^r) + F_i^p C_i^p (T_i - T_c^p)
\]

The second zone consists of a centrifugal separation of the two-phase mixture of the stream \( F_i \). The purpose of this step is to retrieve the gross product ( \( F_i \)), in order to obtain the potable water product of the process. The following equation governs the centrifugal separation process for the system described here. \( F_i^r = w_p (F_i^r + F_i^p) \).

\( w_p \) is the weight fraction of the polymer in the polymer rich phase of the process. Again for zone 2, stage-wise operations are conducted by using similar approach as described in WC. In zone 2, for the whole unit mass balance on \( W, S \) and \( P \) are given as follows:

\[
F_i^n = F_i^n + F_i^p, \quad F_i^p = F_i^p, \quad \text{and} \quad F_i^p = F_i^p
\]

Phase relationship and distribution coefficient of salt between phases are two key underpinning issues for WC and HTC. Lazare (1992) conducted an experimental study to show that the phase relationship follows the Flory-Huggins equations for polymer solution. These results are used to develop a phase relationship for the SEED system.

In Fig. 2 the phase relationship between the water and polymer phases is presented. The figure also shows the distribution of sodium chloride as a function of polymer content of the aqueous phase. From Fig. 2 it is clear, when the temperature is increased, the weight percent of polymer in the polymer-rich phase also increases. Therefore, to remove water from the polymeric phase, temperature should be increased. This is done when the solvent passes through the series of heat exchanger before centrifugation in the process. The equations describing the phase relationship are:

\[
F_i^r = w_p (F_i^r + F_i^p) \quad (1)
\]

\[
w_p = \delta_p B \quad (2)
\]

\[
\frac{-pB}{1 + \frac{C_1 (1 - S)}{C_2 S}} \ln \left( 1 - \varphi_p \right) + \left( 1 - \frac{1}{M} \right) \varphi_p + \left( \frac{Z_s + Z_T}{T} \right) \varphi_p^2 \quad (3)
\]

where, \( w_p \) is the weight fraction of the polymer in the polymer rich phase, \( \varphi_p \) is the volume fraction of polymer, \( M \) is the ratio of the molecular volume of polymer to that of water, \( S \) is the weight fraction of salt in the aqueous phase, and \( \left( \frac{Z_s + Z_T}{T} \right) \) is the solubility parameter with temperature dependence, \( \delta_p B, C_1 \) and \( C_2 \) are constant parameters. Fig. 3 describes the relationship between distribution coefficient against
Thanapalan and Dua

polymer content in the polymer rich phase. Fig. 3 was constructed by using the experimental results presented in Lazare (1982). The equation obtained for the relationship between the distribution coefficient and the polymer-rich phase weight percent polymer is:

\[ K_s = \xi \exp \left( a \phi_s^b + b \phi_s^c + c \phi_s + d \right) \]  \hspace{1cm} (4)

and the equilibrium for salt content:

\[ F_s' F_s = K_s F_{s'} F_{s} \]  \hspace{1cm} (5)

where, \( K_s \), \( \xi \), \( a, b, c, \) and \( d \) are the constant parameters. An interplay between phase relationship, (1) – (3), and distribution coefficient relationship, (4) – (5), can be used to optimally design and operate the desalination system, and possibility of using low-grade or waste heat for desalination can be explored.

3. Energy consumption and cost analysis

Recently there has been growing interest and pressure on reducing energy consumption (Georgiadis et al., 2008). The energy required in any given desalination system depends on the system’s design and operation characteristics and the quantity and type of losses encountered during separation. In this section the energy requirement for the SEED system is analyzed with reference to the popular desalination processes such as MSF, VC and RO. The SEED process uses the principle of solvent extraction techniques, where solvent is used to separate water from salt in seawater. This process is designed to work on lower operating temperature, thus it is of interest from sustainability point of view (Thanapalan and Dua, 2010). However, it should be noted that currently no solvent extraction based desalination plants are commercially available. This is due to the popularity, maturity and reliability of old techniques such as MSF, VC, and RO. It is therefore, essential to search for design and operating conditions which lead to reduction of energy dissipation and consequently lower water production cost to promote the SEED technology. To this end, we used the systematic approach to model the system and adopt the example presented in Lazare (1992) to show the improvements of the energy consumption via the optimisation. SEED plant’s requirement of energy consumption is in the range of \( 4 - 8 \) kWh/m\(^3\). This is less than the other popular desalination methods requirements. The energy consumption in desalting water processes is one of the important parameters that dictate the choice of the desalination method. In addition to the energy consumption the cost of the technology and the final unit cost of the desalted water determine the choice of the desalting system.
4. Optimization of SEED process

The optimization of the SEED process is with the objectives of meeting the production rate and purity with minimum energy consumption. To do these analysis the model described in section 2, is implemented in GAMS software (Brooke et al., 1998). Consider the general formulation of the optimization problem where the optimal values of variables \( \mathbf{x} \), representing flowrates, temperatures etc., is computed by minimizing the objective function \( f(\mathbf{x}) \) subject to equality constraints \( \mathbf{h}(\mathbf{x}) = 0 \) and inequality constraints \( \mathbf{g}(\mathbf{x}) \leq 0 \). The equality conditions are governed by each of the subsystem (unit) models equations and the inequality constrains are the specifications of the operation of the system, which are presented below. Inequality constrains \( \mathbf{g}(\mathbf{x}) \):

\[
F_1^w : 9534 \text{ m}^3/\text{hr} \leq F_1^w \leq 13166 \text{ m}^3/\text{hr},
F_1^t : 45.4 \text{ kg/hr} \leq F_1^t \leq 177 \text{ kg/hr},
F_1^s : 0.038 \text{ kg/hr} \leq F_1^s \leq 0.043 \text{ kg/hr},
F_1^p : 10109 \text{ m}^3/\text{hr} \leq F_1^p \leq 10350 \text{ m}^3/\text{hr}
\]

Where, \( F_1^w \) and \( F_1^p \) are the feed flow rates of the species and solvent input flow rate respectively. The optimization of the energy consumption of the SEED process is carried out with respect to the base case of the process presented in Lazare (1982, 1992), by setting the same inlet seawater feed temperature and flowrates for the base case. Results similar to those reported in Lazare (1982, 1992) were obtained and thus the model developed in this work can now be used to explore new process synthesis and design options and further reduce the energy consumption. The energy used is in this process is the low grade heat or waste energy, and even that energy can be used more efficiently by developing model-based design and optimization.

5. Concluding Remarks

In this paper, a systematic and model-based approach for investigating the energy consumption of solvent extraction based desalination systems is presented. The solvent extraction based process studied in this work can use low-grade heat or waste energy for desalination, which is not readily possible for other traditional desalination technologies. Current work involves using model-based optimization techniques for process synthesis and design of solvent extraction based desalination systems by using low-grade heat.

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