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Thermodynamic analysis on the theoretical energy consumption of seawater desalination

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HIGHLIGHTS

- A novel model is proposed for calculating the TEC of seawater desalination.
- Activity coefficient and osmotic coefficient are considered in the model.
- Seawater is assumed to be NaCl–MgCl2–MgSO4 rather than aqueous NaCl solution.

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ABSTRACT

It's well known that there are various methods being used in seawater desalination, which lead to different energy consumptions. However, the theory of thermodynamics reveals that the theoretical energy consumption (TEC, equivalent to the minimum work W_{min}) of seawater desalination is only related to the initial and final state. Thermodynamic analysis of the TEC can contribute to the energy-saving of seawater desalination. In this paper, a novel mathematical model is proposed to calculate the TEC of seawater desalination concerning the recovery ratio, by assuming seawater to be aqueous NaCl–$MgCl_2$–$MgSO_4$ solution rather than aqueous NaCl solution. The activity coefficients of salts and the osmotic coefficients of water are calculated by the Pitzer model. The effect of ionic strength, recovery ratio, the activity coefficients of salts and the osmotic coefficients of water, seawater substitution on the TEC are also discussed. It is shown that ionic strength, recovery ratio, activity coefficients of salts and osmotic coefficients of water, seawater substitution have their different effects.

1. Introduction

Seawater desalination is an energy-consuming process. Therefore, the fundamental way of reducing its cost is to minimize the total energy consumption of seawater desalination process. This is one of the most challenging issues during the past decades of research and development on this topic [1,2]. The second law of thermodynamics, able to tell us a quantity of energy inefficiencies in each part of the process, is particularly useful in optimizing the design and operation of seawater desalination and promoting the plant performance [3]. The first step in such an analysis is the determination of the theoretical energy consumption (TEC).

Dodge [4] considered all desalination techniques as a simple separation process and obtained a general minimum work for the separations. The minimum separation work given in the tables is calculated by extracting pure water from a 3.5% NaCl solution (mass fraction) at different recovery ratios. Gao [5] regarded seawater as an ideal solution of aqueous NaCl, and proposed a simplified model to calculate the TEC, whose results showed that the separation of 34,000 mg/L aqueous NaCl solution to obtain 500 mg/L potable and 136,000 mg/L concentrated seawater at 25 °C, the cost of which is 1.41 kW h t^{-1}. In the above studies, seawater is represented by aqueous NaCl solution. Cerci [6] considered the saline water as an ideal solution, obeying Rault's law. In his research, the solution was assumed as a dilute solution for the mole fraction of salt in the 3.5% NaCl solution (mass fraction) is about 0.011. The enthalpy of the solution was considered as the sum of the enthalpies of pure components in the solution. So the activity coefficients of salts and the osmotic coefficients of water were not taken into account. The other studies [7–14] using ideal mixture model of pure water and sodium chloride salt have the similar hypothesis.

The present work will propose a novel mathematical model to calculate the TEC of seawater desalination concerning the recovery

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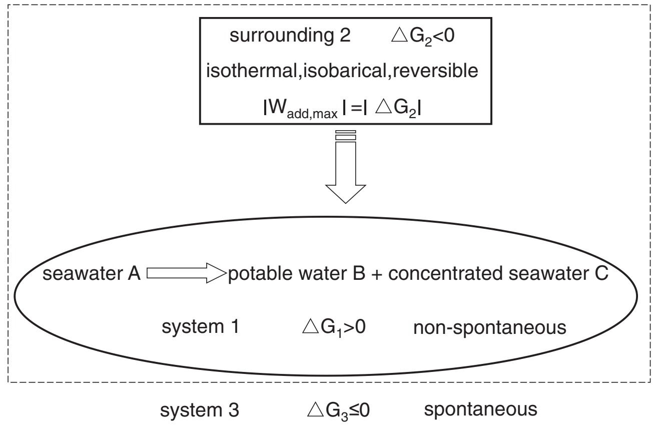

Fig. 1. The thermodynamic analysis on the energy-saving for seawater desalination process.

ratio, by assuming seawater to be an aqueous solution of NaCl–$MgCl_2$–$MgSO_4$ [15] rather than that of NaCl. The activity coefficients of salts and the osmotic coefficients of water are calculated by the Pitzer model. The effect of ionic strength, recovery ratio, the activity coefficients of salts and the osmotic coefficients of water, seawater sample on the TEC are also discussed, respectively.

2. Calculation method

2.1. Thermodynamic analysis of the energy-saving for seawater desalination

Ji [16], who made an analogy between the emission of pollution and the operation process of the heat engines, has proposed the Carnot efficiency and the efficiency of heat engines for different physical waste-removal processes and established the thermodynamic framework of the energy-saving for a waste-removal process. Based on the work of Ji, the thermodynamic framework of the energy-saving for seawater desalination process can be illustrated in Fig. 1. The Carnot efficiency indicates the maximum thermal efficiency of heat engine, which converts heat into work. The Carnot efficiency does not take working medium into account, while the efficiency of heat engines considers working medium. Therefore the analogy between the efficiency of heat engines or Carnot efficiency for heat engines and that for seawater desalination process is made as working medium is considered or not. The TEC Q_1 for seawater desalination by physical methods means that the working medium is not considered, only considering the separation of potable water from seawater, the process is reversible. The TEC Q_2 and the actual energy consumption Q_3 for seawater desalination by different techniques mean that the working medium is considered, so the process is irreversible. For instance, in thermal seawater desalination, evaporation process is an irreversible process, and much energy must be lost. Thus, for different seawater desalination processes, the Carnot efficiency and the efficiency of heat engines can be defined by $\eta_1 = Q_1/Q_2$ and $\eta_2 = Q_2/Q_3$, respectively. η_1 is the maximum of η_2 but can not approach η_2 practically. An appropriate seawater desalination process can be selected according to the Carnot efficiency. The energy conservation potential of different seawater desalination processes can also be determined by the efficiency of heat engines. It is seen that the value of the TEC Q_1 is a crucial data in any investigation of the energy conservation potential and the mechanisms for seawater desalination processes.

The TEC Q_1 is also the basis of calculating the efficiency of the second law of thermodynamics ($\eta_{II} = Q_1/Q_3$ *or* $\eta_{II} = Q_1/(Q_1 + \int_0^t \Theta dt)$. where Θ is entropy production rate [17], which is particularly useful to the energy-saving analysis of seawater desalination process.

2.2. Thermodynamic analysis on the TEC of seawater desalination

2.2.1. Thermodynamic analysis method

As we all know that mixing processes occur spontaneously in nature, and they are highly irreversible. The reverse process of separation of a mixture into its components spontaneously is impossible. As shown in Fig. 2, system 1 represents a physical separation process to obtain potable water B and concentrated seawater C by desalinating seawater A,

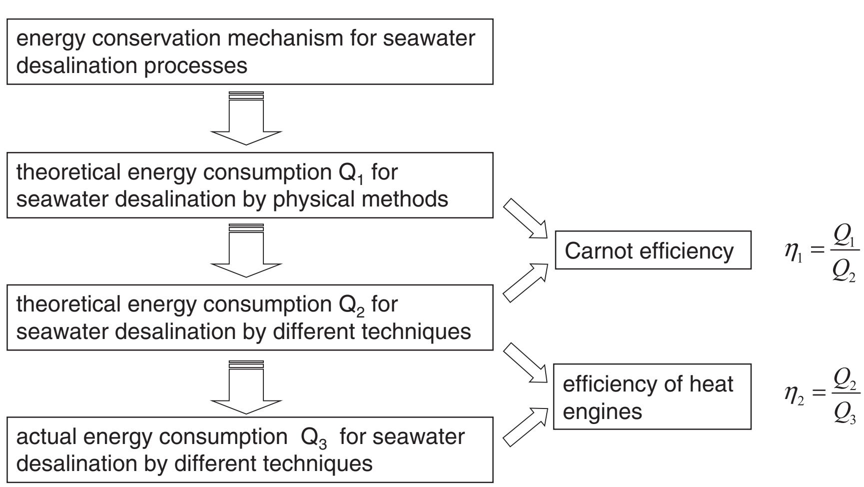

Fig. 2. Thermodynamic analysis method for the TEC of seawater desalination.