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Minimizing the total cost of multi effect evaporation systems for seawater desalination

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HIGHLIGHTS

- An optimization mathematical model of MEE is presented.
- Investment and operating costs are minimized for a nominal water demand.
- A sensitivity analysis of the main parameters and variables is presented.
- Detailed solutions and a complete discussion of the results are presented.

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ABSTRACT

A mathematical model developed recently by the authors is extended into a non linear mathematical programming problem to determine the nominal optimal sizing of equipment (heat transfer area) and optimal operation conditions that satisfy a fixed nominal production of fresh water at minimum total annual cost. Relative marginal values computed from the optimized results and a global sensitivity analysis are then used to rank the process parameters according to their influences on the total cost. Once the nominal design and operating conditions are determined, a new optimization problem is stated: Is it possible to increase (using the nominal optimal design) the water production over the nominal capacity of production? Thus, the new optimization problem consists of the maximization of the distillate production. Optimization results for both design problems are presented and discussed in detail. One of the obtained results reveals that the increase of the distillate production in 20% over the nominal capacity (200 kg/s), leads to increases in the total operating cost from 10.8 to 11.4 million US$/yr while the seawater flow rate and the steam temperature increase about 23 and 5%, respectively.

1. Introduction

Despite the significant progress on the desalination processes made since the 1960s to overcome the problem of fresh water supply [1], technological and research efforts are still required to improve the system's efficiency and to reduce the water production cost. The major challenge is to reduce the energy cost by improving the steam economy or performance ratio PR (kg of fresh water produced by kg of steam used) [2–4]. For the MEE system, there exist strong trade-offs between the steam used in the first effect as heating utility, the total heat transfer area for evaporation and pre-heating and production level. For a desired production of distillate, the reduction of the steam consumption increases the required total heat transfer area and vice versa. Several methodologies based on energy and/or exergy analysis have been applied to study the performance of MEE systems [5–7].

Several papers have been published over the last years, dealing with the thermo-economic analysis of different MEE systems. Instead of simultaneous and rigorous optimization methods, most of the authors applied parametric optimization and used several simulation software to study the influence of the operation conditions and the size of the evaporation effects on the performance of the MEE unit [8–10].

In contrast to these articles, the main contribution of this paper is that the operating conditions and size of each effect are optimized simultaneously instead of a parametric way. In addition, local and global sensitivity analyses for all model parameters, which are useful for both practical and mathematical modeling point of views, are also presented.

The application of the mathematical programming approach for the optimal design of desalination processes is receiving a renovated interest due to the fact that the performance of solvers handling non-linear constraints for simultaneous optimization was largely improved.

Recently, Druetta el at. [11] successfully applied the mathematical programming approach to optimize the MEE system from an efficiency

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point of view and to study different arrangement configurations. In this paper, the model presented in [11] is properly extended in order to include a complete and detailed cost model to determine the optimal size of equipment and optimal operation conditions that satisfy a given nominal production of fresh water at minimum total annual cost. After that, a second optimization problem is solved in order to identify the operating conditions that should be modified in order to increase the distillate production over the nominal capacity production. The results obtained for both optimization problems are discussed and compared in detail. In addition, for both optimization problems, local and global sensitivity analyses are also performed in order to evaluate the relative importance of each one of the model parameters. Qualitative and quantitative results obtained from the analyses will provide valuable insights for the design of new MEE plants or, if the case, for the identification of alternative operating modes in existing plants with the main aim to improve the process efficiency. To the knowledge of the authors, no articles addressing local and global sensitivity analyses of all process parameters have been published.

The parameters to be analyzed are defined in several sets, as follows.

a) Sea water conditions. The sea water salinity and temperature vary with the plant location and the season of the year. From a thermal integration point of view a sensitivity analysis on these parameters may be valuable because it may identify several hybrid desalination systems. In other words, it may indicate the convenience (or not) to integrate the seawater incoming with other processes.
b) Physical–chemical properties and design specification. Usually, most of the hypotheses used to derive simplified mathematical models consider that several physical–chemical properties do not significantly vary with temperature, composition and/or pressure and therefore they are considered as model parameters (fixed and known values). Similarly, a given value is usually assumed for overall heat transfer coefficients to compute the heat transfer areas. However, in some cases, it may not be appropriate. A sensitivity analysis on these parameters will determine the correctness of the hypothesis. Thus, it will provide useful insights about the convenience of use of correlations instead of a fixed and known value.
c) Operating conditions. A sensitivity analysis will allow us to identify the operating conditions that may improve the process efficiency or may minimize the total cost. For instance, it is important to know, for an existing MEE unit, the operating variables that must be modified to increase the distillate production.
d) Specific costs. The specific costs used to compute investment and operating costs may vary significantly with place and time. Therefore, it is also essential to know how they affect the total annual cost.

The paper is outlined as follows. Section 2 briefly describes the MEE process and presents the problem formulation. Section 3 summarizes the assumptions and describes the mathematical model. Section 4 discusses the simulated and optimized results obtained from the model. Finally, Section 5 summarizes the conclusions of the paper.

2. Process description

Fig. 1 shows a schematic diagram of the MEE forward feed scheme which will be studied in this paper. As shown, the brine stream (B) and the distillate (D) flow in the same direction but opposite to the feed stream (F). The first effect is characterized by the least salinity and the highest temperature. The feed stream (F) is heated in preheaters by the condensation of vapor produced in each one of the effects. Then, F enters into the first evaporation effect and a part of the produced vapor (V^p_1) is used for pre-heating in the pre-heater 1 and the remaining vapor (V_2) is used for evaporation in the Effect 2. Then the condensate coming from the preheater 1 and the evaporation effect 2 are flashed into the flashing box 2. The process is repeated along the remaining effects.

There exist several trade-offs among the total heat transfer area, heating utility demand (steam), mass flow rates, production level and electric power consumption. Then, the main objective of this paper is to minimize the total annual cost of the MEE unit (investment and operating costs) but considering all the trade-offs simultaneously.

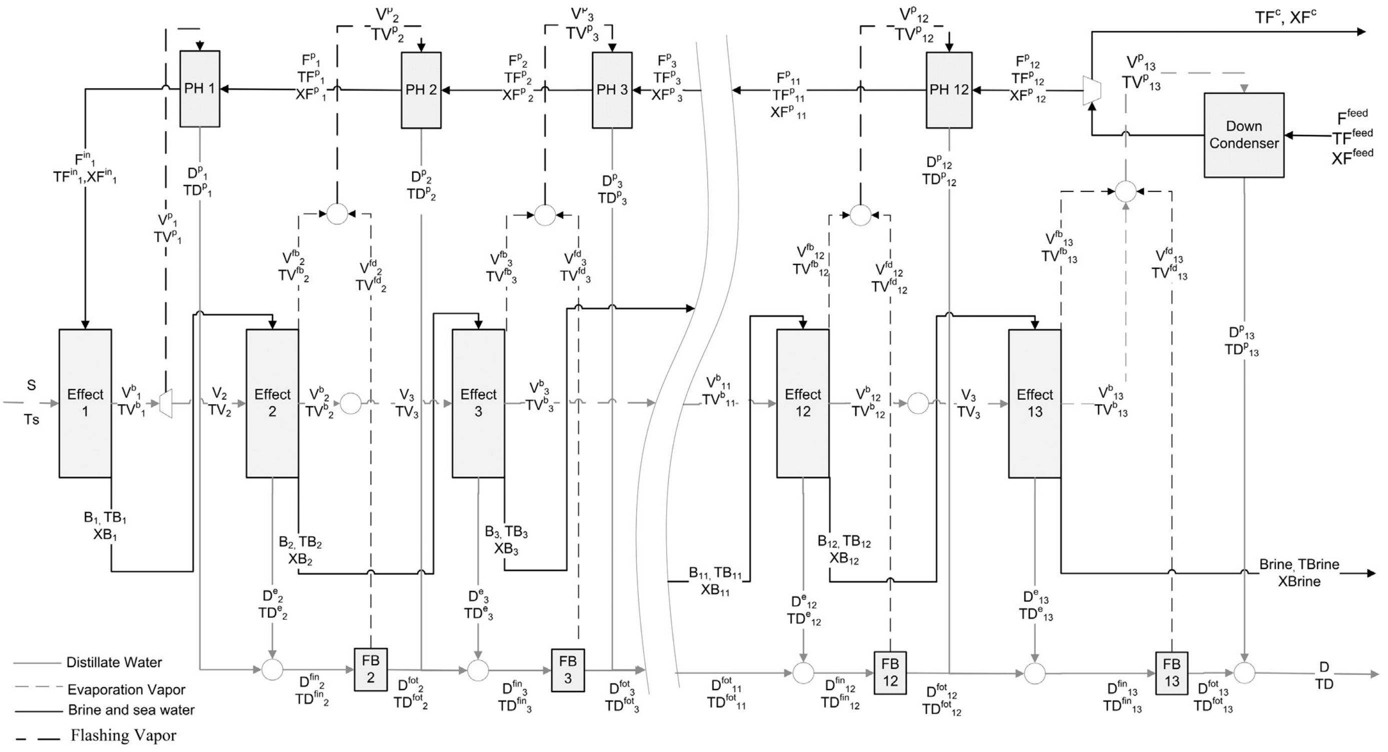

Fig. 1. Conventional multi-effect evaporation (MEE) process (forward feed configuration).