Desalination 447 (2018) 74–83

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Correlations for estimating the specific capital cost of multi-effect distillation plants considering the main design trends and operating conditions

George Kosmadakis[a], Michael Papapetrou[a,b,*], Bartolomé Ortega-Delgado[b], Andrea Cipollina[b], Diego-César Alarcón-Padilla[c]

[a] Wirtschaft und Infrastruktur GmbH & Co Planungs-KG (WIP), Sylvensteinstr. 2, 81369 Munich, Germany
[b] Dipartimento dell'Innovazione Industriale e Digitale, Università degli Studi di Palermo, Viale delle Scienze, Ed.6., 90128 Palermo, Italy
[c] CIEMAT, Plataforma Solar de Almería, Ctra. de Senés km 4.5, 04200 Tabernas, Spain

ARTICLE INFO

Keywords:
Multi-effect distillation (MED)
Desalination
Capital cost
Correlation
Plant capacity
Distillate flow rate
Heat exchanger area
Number of effects
Heat source temperature

ABSTRACT

This work proposes a correlation for the specific capital cost of multi-effect distillation (MED) plants, considering their main design options and parameters, such as the number of effects, size/capacity, and heat source temperature. These parameters are varied within a large range to cover as many different cases as possible. The cost correlation decouples the evaporator cost and includes in the expression the ratio of the heat exchanger area to a reference one. This area is calculated using a validated MED numerical model, with the results then processed to produce fitted expressions. Two versions of this correlation with different levels of complexity are proposed, which provide similar results. The results of the improved correlation have been compared with the actual specific cost of a limited number of MED plants for validation purposes. It has been shown that this correlation provides more accurate results in most of the cases, although the sample is small due to limited availability of data from other plants. The specific capital cost of typical MED plants is then examined, presenting the cost when the number of effects and heat source temperature change. These calculations capture the expected trend of the plant cost under different main design options.

1. Introduction

The most common method of estimating the capital cost of a MED plant is to correlate the specific cost with the plant capacity. This approach has been followed by many groups, in order to estimate the specific cost [1]. For that purpose, a conservative correlation has been proposed in Ref. [2], which is the outcome of processing the costs of many MED plants (in \$) and is expressed as a function of the plant capacity, equal to the distillate flow rate (D). This correlation, is given in Eq. (1) valid for a plant capacity up to 10,000 m^3/day.

$$C_{MED}(\$/m^3/day) = 3054D^{-0.0249} \tag{1}$$

The MED specific cost as a function of plant capacity is shown in Fig. 1 for the range of validity of Eq. (1). When applying this correlation for plants of higher capacity, this specific cost never moves to values below 2400 \$/(m^3/day), even for very large ones. Evidence shows that this is an overestimated value [3–5].

Eq. (1) has some other limitations, especially when the MED plant design deviates from the norm (recent designs introduce higher number of effects and/or higher temperatures of heat supply [6], as well as application of MED in fields other than seawater desalination [7]). The most important design parameters with a high contribution on the MED capital cost are the number of effects and the heat exchanger (HEX) area [8], which also define the top brine temperature (TBT).

There are various approaches in this field found in the literature. Some of them consider a constant specific capital cost [9], while others correlate this cost with the plant capacity [1]. The more advanced ones express the cost of the main components as a function of their design specifications [10,11], always requiring to simulate the process for concluding to these specifications.

The current work introduces additional elements in the correlation that take into account design characteristics of MED plants, aiming to increase the accuracy of the MED capital cost estimation, and at the same time make it possible to greatly simplify this process, without the need to use any thermodynamic model for simulating the system. The first step of the methodology was to apply a detailed MED model that

* Corresponding author at: Wirtschaft und Infrastruktur GmbH & Co Planungs-KG (WIP), Sylvensteinstr. 2, 81369 Munich, Germany.
E-mail address: michael.papapetrou@wip-munich.de (M. Papapetrou).

https://doi.org/10.1016/j.desal.2018.09.011
Received 4 May 2018; Received in revised form 14 September 2018; Accepted 15 September 2018

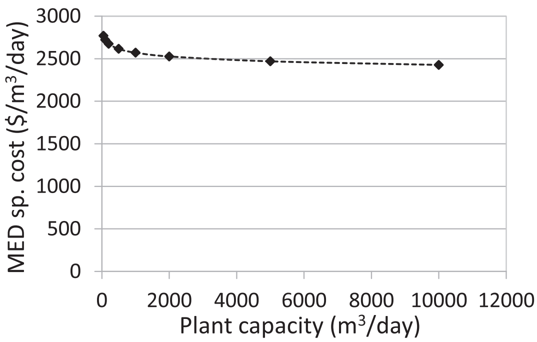

Fig. 1. Specific MED cost as a function of plant capacity up to 10,000 m^3/day.

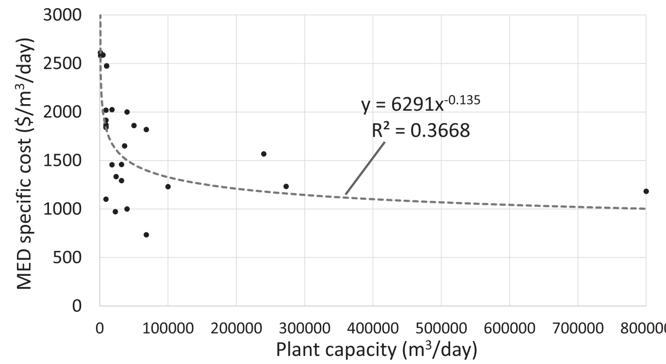

Fig. 2. MED specific costs and their fitting as a function of plant capacity.

correlates the following parameters with each other:

- Number of effects
- HEX area
- Distillate flow rate
- Heat source temperature

A regression analysis has been then conducted to correlate the HEX area and distillate flow rate with the number of effects, and heat source temperature. Polynomials of up to 4th order have been fitted with accuracy almost 100%. These can be then used for comparative analysis based on a typical reference case.

The next step was to introduce the HEX cost fraction in a similar expression as Eq. (1) and use the above polynomials to examine the MED capital cost, when varying the main parameters. This allowed deriving a cost correlation as a function of both distillate flow rate and HEX area, using polynomial fitting.

The final step was to further simplify the cost correlation for quick and reliable estimations of the MED capital cost. The overall result is a general-purpose correlation that includes the impact of the factors having the highest contribution on the MED capital cost, and could be valuable for evaluating the cost of new MED designs and concepts [12,13] under a large range of operating conditions, as well as hybridization approaches including MED [14].

2. Assessing the MED capital cost

2.1. New MED capital cost correlation as a function of plant capacity

Initially, the validity range of Eq. (1) is expanded to a higher plant capacity and approach the average values instead of the conservative ones. Therefore, a detailed literature review has been conducted that gathered various reported MED capital costs, supplemented by data from Desaldata database [1,2,4,15–21]. The available values have been processed and then grouped according to the plant capacity, in order to conclude to a numerical correlation of the MED specific cost similar to Eq. (1). The plants that are used only for municipal fresh water supply are considered (not for power plants or industry). Also, the ones used for dual-purpose have been excluded. The outcome of this analysis is shown in Fig. 2 with a sample of 28 plants.

A fitting has been implemented from the data of Fig. 2 with a rather low accuracy (R^2 of about 0.37) that captures the trend of the varying capacity. The fitted correlation is given by Eq. (2), in $/($m^3$/day), being valid from 500 up to 800,000 m^3/day.

$$C_{MED,fit} = 6291D^{-0.135} \quad (2)$$

The outcome of this analysis and the fitted correlation of Eq. (2) reveals that for capacity over 4000 m^3/day, corresponding to a small MED plant, the specific cost can be below 2000 $/($m^3$/day). On the other hand, for very large MED plants with capacity over 200,000 m^3/day, the specific cost approaches the value of 1000 $/($m^3$/day), which is in accordance to recently reported data [4].

2.2. The need for improving the MED capital cost correlation and evaporator cost fraction

As shown in Fig. 2, there is a large variation of the MED specific cost even for the same plant capacity. This variation reaches even a factor of 2 in extreme cases (1000 to 2000 $/($m^3$/day) for about 30,000 m^3/day capacity), causing the low accuracy of the fitting. Site-specific reasons contribute to these reasons, such as the plant location (different country with different market conditions), local labour cost, and feed water characteristics. Other reasons may vary to some extent over time, such as the material cost of the heat exchangers, and the operating/steam costs.

However, one main parameter affecting the cost that can be accounted for is the plant design [22], and especially the different number of effects and temperature of heat input, which bring a large variation of the evaporator's heat exchanger surface area [8].

In an effort to improve the accuracy of the correlation results, especially for cases deviating from the average (in terms of number of effects and heat source temperature), we propose to follow a similar methodology also adopted in Refs. [19, 23]. In those studies, the cost correlation has been broken down, introducing weighing factors, to take into account the cost variation of the components with the higher contribution to the capital cost. This method has proved its reliability to estimate the specific cost for various conditions and new designs/concepts [24,25], and is also followed here. The aim is to decouple the evaporator cost from the other parts of a MED plant, since the evaporator accounts for the highest percentage of the MED capital costs, equal to 40% [26]. The cost break-down of the other MED parts are not of interest for this work, and not further elaborated.

For this purpose, a validated numerical model has been applied for various operating and design conditions [27]. The results of this model are necessary, in order to identify how the number of effects and heat source temperature affect the HEX area and distillate flow rate, and finally conclude to correlations that introduce the effect of the design parameters to the MED capital cost. This procedure is presented in the next section, with the improved cost correlation further elaborated in Section 4.

3. MED numerical model

A mathematical steady-state MED model has been used [27], with the purpose to conduct multi-parametric studies of the main variables of MED plants. The parameters that are primarily examined are: