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

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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.

Keywords: multi-effect distillation (MED), desalination, capital cost, correlation, plant capacity, distillate flow rate, heat exchanger area, number of effects, temperature.

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.

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

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].

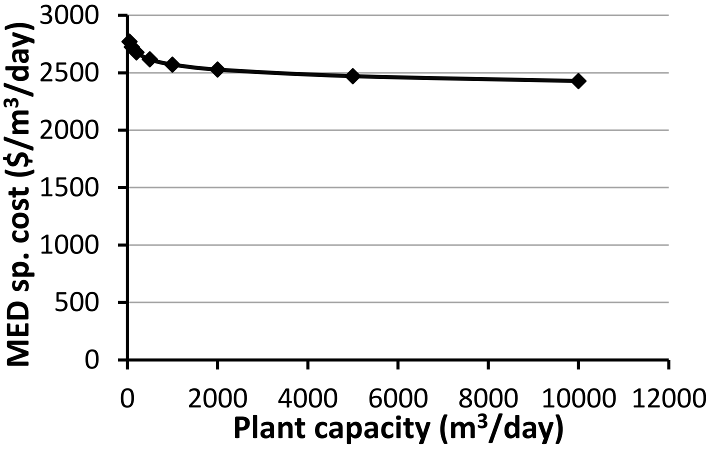

Fig. 1. Specific MED cost as a function of plant capacity up to 10,000 m^3/day

Equation 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).

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. The first step was to apply a detailed MED model that 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 to derive 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 under a large range of operating conditions.

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 [1,2,4,9–15]. 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.

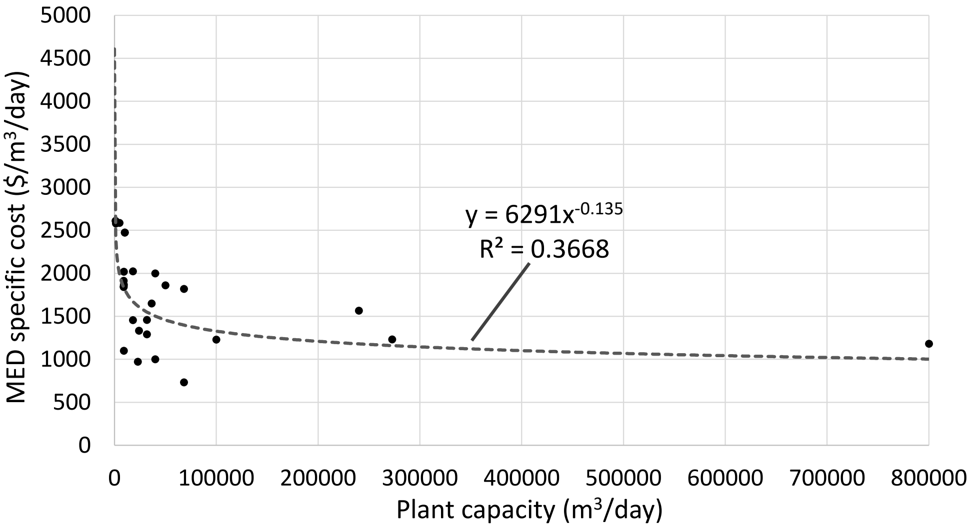

Fig. 2. MED specific costs and their fitting as a function of plant capacity

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.

$$C_{MED,fit} = 6291 D^{-0.135} \tag{2}$$

The outcome of this analysis and the fitted correlation of Eq. (2) reveals that for capacity over 4,000 m^3/day, corresponding to a small MED plant, the specific cost can be below 2,000 \$/(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 1,000 \$/(m^3/day), which is in accordance to recently reported data [4].

2.2 The need for improving the MED capital cost correlation and cost break-down

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 (1,000 to 2,000 \$/(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 [16], 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. [13,17]. 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 [18,19], 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% [20].

For this purpose, a validated numerical model has been applied for various operating and design conditions [21]. 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 [21], with the purpose to conduct multi-parametric studies of the main variables of MED plants. The parameters that are primarily examined are:

1. Number of effects, ranging from 3 up to 30. The maximum number is reduced where necessary to ensure that the temperature difference between effects is always over 2.5 °C. The number of effects reaches 30, in order to cover any possible future design option.
2. Heat exchanger area of each effect.
3. Distillate flow rate of each effect.
4. Temperature difference of each effect, according to the heat source temperature and the number of effects.
5. Feed water salinity and temperature.
6. Heat input and its temperature.

This model follows the standard approach for forward-feed MED plants and is already described with detail in Ref. [6]. The model considers feed preheaters and distillate flashing boxes and is based on mass and energy balances applied on each component of the plant. Besides, the model relies on the heat transfer equations of the heat exchangers and incorporates theoretical correlations for determining the boiling point elevation and non-equilibrium allowance. The heat source is assumed to be saturated steam at the defined temperature. Other features of the model are:

- Equal heat transfer areas of evaporators and preheaters. This approach is done based on typical industrial MED schemes. The introduction of this constraint leads to varying temperature difference between effects (and preheaters).
- Consideration of the saturation temperature losses of the vapor due to pressure drop in demisters, pipe lines and inside the evaporators. This restriction has been relaxed, when simulating high number of effects, in order to reduce the complexity of the model and improve its convergence.
- The vapor enters each evaporator at saturation conditions and exits as saturated liquid.
- The vapor produced is assumed to be free of salts.
- The effect of non-condensable gases has been neglected.
- Two plate heat exchangers have been considered at the outlet of the plant, in order to cool down the exiting brine and distillate.

The overall heat transfer coefficient of the heat exchangers is a function of temperature [22], the boiling point elevation (BPE) is a function of brine concentration and temperature [23], and the non-equilibrium allowance (NEA) is a function of the temperature difference of the boiling brine between effects [24]. The model has been implemented in Engineering Equation Solver (ESS) software environment, a simultaneous solver of non-linear equation systems, which permits to simulate different scenarios with flexibility.

The number of effects is varied up to the point that the average temperature difference between effects is at least 2.5 °C for each temperature level. For the lowest temperature of heat input considered (60 °C), this limit is reached for 8 effects, while for the case of 80 °C the limit is 15 effects. The temperature of heat input is varied in the range from 60 to 140 °C, covering the majority of MED plants, including high-temperature MED designs that have started to be examined in case adequate heat source temperature is available and solutions for scaling issues with high top brine temperature are possible [25]. The TBT values for each case are also shown in the Appendix for clarity.

Other model input and parameters that are kept the same for all cases are:

- Constant heat rate input of 10 MW in the first evaporator.
- The end condenser temperature has been fixed to 35 °C.
- The intake seawater salinity and temperature are 40,000 ppm and 22 °C respectively.
- A terminal temperature difference (TTD) of 3 °C is imposed in the preheater associated with the first effect (temperature difference between the feed at the outlet and the condensing vapor in the preheater). Similarly, a TTD of 3 °C has been assumed at the end condenser.
- The recovery ratio is 38% according to Ref. [26].
- The temperature of the brine and distillate at the outlet of the plate heat exchangers has been considered to be 25 °C.

A regression analysis has been conducted using the results of the numerical model. This analysis concluded to polynomial functions with very high accuracy for the calculation of the distillate flow rate and HEX area only as a function of the heat source temperature, and the number of effects, within the range of the parameters considered here ($60 \leq T \leq 140$ °C, $3 \leq N \leq 30$). The fitted functions are given in Eqs. (3), (4) for the distillate mass flow rate and HEX area respectively with a fitting accuracy of $R^2=0.9998$ and 0.9999. The coefficients of these correlations (a_i and b_i) are given in Tables 1 and 2 respectively.

$$\dot{m}_D = a_1 + a_2T + a_3T^2 + a_4N + a_5N^2 \tag{3}$$

$$A_{HEX} = b_1 + b_2T + b_3T^2 + b_4T^3 + b_5T^4 + b_6N + b_7N^2 + b_8N^3 + b_9N^4 + b_{10}TN + b_{11}TN^2 + b_{12}TN^3 + b_{13}T^2N + b_{14}T^2N^2 + b_{15}T^2N^3 + b_{16}T^3N + b_{17}T^3N^2 + b_{18}T^3N^3 \tag{4}$$

where T is the heat source temperature in Celsius degrees and N the number of effects.

Table 1. Coefficients of Eq. (3)

a_1	2. 70073708E+00
a_2	-2.821797340E-02
a_3	1.042603040E-04
a_4	3. 72683709E+00
a_5	-3.081884220E-02

Table 2. Coefficients of Eq. (4)

b_1	2.68586297E+04	b_{10}	-1.87082017E+02
b_2	-1.33645829E+03	b_{11}	-1.29048221E+01
b_3	2.44770182E+01	b_{12}	4.48279893E-01
b_4	-1.88924088E-01	b_{13}	1.98296987E+00
b_5	5.19451891E-04	b_{14}	7.11095569E-02
b_6	5.51003331E+03	b_{15}	-3.40892197E-03
b_7	7.50418119E+02	b_{16}	-6.58456815E-03
b_8	-1.97732653E+01	b_{17}	-1.06883451E-04
b_9	9.84824917E-03	b_{18}	8.38238282E-06

It should be stressed that the purpose of this work was not to examine with high detail the design and performance of a MED plant, but rather to extract reliable trends and identify the inter-relation of its key design parameters. At the same time, other possible plant designs have been examined, such as parallel-feed MED-TVC [27], for which very similar results are obtained (heat exchanger area, distillate mass flow rate), as shown in the Appendix, making it possible to expand the analysis to various MED plant configurations (forward or parallel feed). The design results and their trend are presented and briefly discussed in the Appendix.

4. Proposed MED specific cost correlation

The methodology followed here requires the use of a reference MED plant, in order to reduce the uncertainty and possible error of the numerical results of the MED model. The main specifications and capital cost of the reference plant are presented next.

4.1 Reference MED plant design and cost

A reference MED plant is considered for the purpose of the developed methodology. Therefore, the main specifications of the reference MED plant are selected based on the most common design options: heat source temperature of 70 °C and 8 MED effects, resulting to a TBT of 65.4 °C, as shown in the Appendix. The selection of 8 effects is based on the average number of effects from the reviewed papers relevant to MED plants, and represents a typical configuration that is valid for all locations with cold and hot seawater [28]. The main design specifications for these reference conditions are shown in Table

3. It is assumed here that the reported MED cost as a function of only the plant capacity (Eq. (2)) corresponds to this reference case.

Table 3. Specifications of the reference MED plant

Heat source temperature	70 °C
Number of effects	8
TBT	65.4 °C
Heat input	10 MW
Distillate mass flow rate	29.27 kg/s
Plant capacity	2,531.46 m^3/day
HEX area	8,841.0 m^2
Specific HEX area	302.01 m^2/(kg/s)
Feed water salinity	40,000 ppm
MED specific cost (using Eq. (2))	2,185.99 \$/(m^3/day)

The specific cost of a MED plant with the reference conditions as a function of the heat input, ranging from 1 up to 300 MW, is shown in Fig. 3.

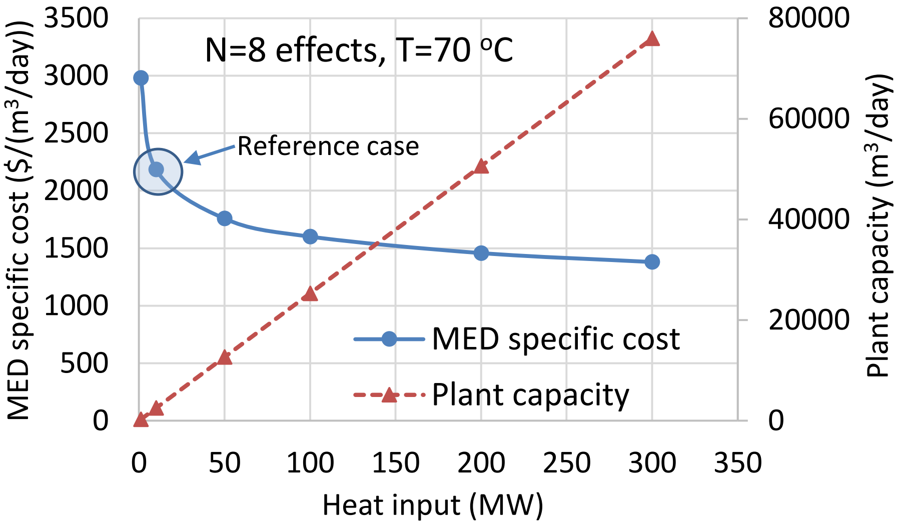

Fig. 3. MED specific cost and plant capacity as a function of the heat input amount for the reference case (8 effects, heat source temperature of 70 °C)

The heat input range covers the majority of existing and planned MED plants [1]. In Fig. 3 we see that for large plants the specific cost approaches a value of almost 1,350 \$/(m^3/day), slightly reducing for very large plants.

4.2 Improved correlation for MED specific cost

The evaporator cost represents a large fraction of the total MED capital cost and therefore, its contribution is separated. This decoupling is possible with the use of a weighting factor that represents the typical cost fraction of the evaporator. Thus, the first part of the improved correlation represents the costs of the plant components that depend only on the distillate flow rate (e.g. pumps, intake system, piping, etc.), including any other auxiliary and overhead costs, and its second part the cost of the evaporator, expressed through its HEX area. The general form of the proposed correlation is shown in Eq. (5) that includes the ratios of HEX area of the examined MED plant to the reference one, presented in section 4.1.

$$C_{MED} = 6291 D^{-0.135}\left[(1-f_{HEX}) + f_{HEX}\left(\frac{HEX\ area}{HEX\ area{,}ref}\right)^{0.8}\right] \tag{5}$$

where f_{HEX} is the cost fraction of the evaporator, and the constant of 0.8 is used to take into consideration the plant scale/capacity, as also suggested in other related works [11,29,30]. The term ($1\text{-}f_{HEX}$) expresses the cost fraction of the components that do not depend on the HEX area.

The fraction of the capital cost that corresponds to the evaporator is considered to be 40% [20], as explained previously. However, this fraction could vary when the design conditions or scale/capacity change. The use of an exponent lower than unity reduces this uncertainty. In any case, this is examined in a sensitivity analysis that is presented at the end of the results section.

The HEX area of the reference MED plant and the one under consideration (with different design and operating parameters) can be calculated based on the results of the methodology presented in the previous section. The HEX area of the reference plant is given in Table 3, while the HEX area of a different design is calculated from the polynomial function given in Eq. (4), as a function of the heat source temperature and the number of effects. It should be stressed that both HEX areas should refer to the same heat input. For a variable heat input, the reference area of Table 3 and the MED plant under investigation are adjusted, considering a linear variation (see Fig. 3).

The use of Eq. (5) allows to conduct parametric analysis for the MED specific capital cost as well, with main parameters the heat input and its temperature, by calculating the distillate flow rate based on the polynomial function given in Eq. (4) for a variable number of effects. This is very useful when the operating costs of a MED plant are also considered [31], for estimating the Levelized Cost Of Water (LCOW) [1,4,32], given in \$/m^3, which is necessary for any MED plant developer.

Finally, Eq. (5) can be simplified by replacing the HEX area ratio with a simpler function of the heat source temperature and the number of effects. In order to do so, non-linear multi-variable regression analysis in Matlab has been conducted with the same MED numerical results. This analysis concluded to a very accurate expression (R^2 equal to 0.9935) as a function of the number of effects (N) and the heat source temperature (T), shown in Eq. (6).

$$C_{MED} = 6291 D^{-0.135}\left[(1-f_{HEX}) + f_{HEX}\left(\frac{N}{N_{ref}}\right)^{1.277}\left(\frac{T_{ref}}{T}\right)^{1.048}\right] \tag{6}$$

where N_{ref} is the reference number of effects equal to 8, and T_{ref} the reference temperature of the heat source equal to 70 °C.

The expression of Eq. (6) is equivalent to Eq. (5) and shows a very small deviation, and both are derived from the processing of the same dataset. Moreover, Eq. (6) can be used for the same range of parameters

($60 \leq T \leq 140$ °C, $3 \leq N \leq 30$) and provides in a more direct way the effect of the MED specific cost with the variable number of effects and heat source temperature presented previously. Finally, from the computational point of view it is less complex to apply Eq. (6) than Eq. (5) that includes a 4th grade polynomial function.

4.2 Validation of the proposed cost correlation

The proposed cost correlation is validated here, using available data of MED plant costs and their main design parameters. This process is not extended, due to lack of available data and the difficulty to find out the number of effects for each plant. Moreover, the validation about the heat source temperature is not examined, since all commercial MED plants operate with a similar temperature, dictated by the limitation of scaling phenomena in the evaporator (TBT up to 70 °C). Therefore, the validation concerns only the variation of the number of effects.

Table 4 shows the MED plants that have been used for validation purposes. Some main specifications are also provided for these plants [8,14,33–35]. Focus is given on having a sample with large enough differences so that the conclusions are as solid as possible. A larger sample of plants would be necessary to increase the confidence of the correlation accuracy. This is left for future work with the aim to further improve this correlation.

Table 4. MED plants considered for validation purposes

Plant	**Country**	**Capacity (m^3/day)**	**Number of effects**
Al-Hidd	Bahrain	272,760	7
Trapani	Italy	18,000	12
Al-Jubail	Saudi Arabia	800,000	8
Yanbu	Saudi Arabia	68,190	9
Kalba	United Arab Emirates	9,090	4
Layyah	United Arab Emirates	36,368	5
Umm Al-Nar	United Arab Emirates	31,822	6

The specific costs of the plants of Table 4 are shown in Fig. 4. These include the actual specific cost, according to Desaldata [14], as well as the ones calculated by the standard correlation, Eq. (2), and its improvement, Eq. (6). The effect of heat source temperature is not included in this analysis, since all plants are considered to operate with the same heat source temperature of 70 °C, due to missing data.

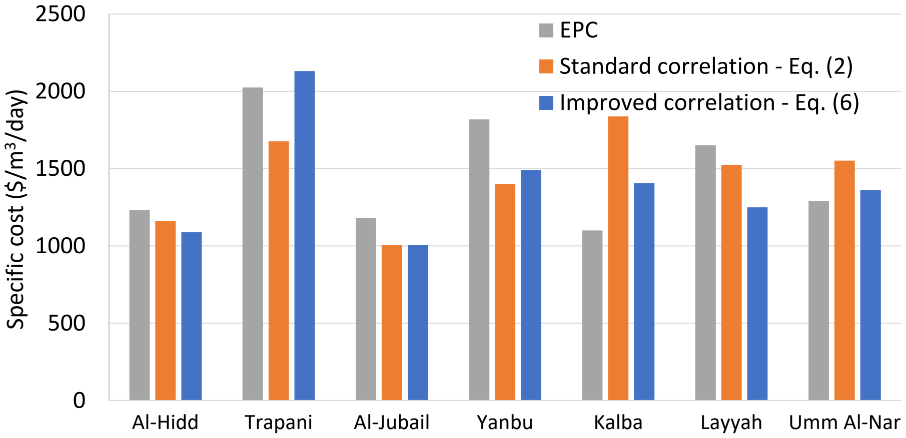

Fig. 4. Comparison of calculated MED specific capital cost with EPC costs

From this sample of MED plants, the improved correlation provides more accurate results for most of the plants. More specifically, the small cost difference in Al-Hidd is due to the use of 7 effects, which slightly decreases the specific cost calculated by the improved correlation (by 70 $/m^3$/day), but still within a 10% variation. In Trapani and Yanbu, a higher number of effects is used compared to the reference of 8 effects (12 and 9 respectively), with the improved correlation giving higher values, which are closer to the actual specific cost. The MED plant in Al-Jubail has 8 effects (equal to the reference one) and this is why both correlations give the same result, about 15% lower than the actual one. The MED plant in Kalba has just 4 effects, and the improved correlation predicts with much higher accuracy the specific cost, going from a 67% to 27% deviation from the actual specific price. The Layyah and Umm Al-Nar plants have similar plant capacity and number of effects (5 and 6 respectively), but their actual specific cost deviates by about 350 $/m^3$/day. Therefore, it was expected that the improved correlation will show a mixed behavior, approaching the actual specific cost in one case (in Umm Al-Nar) and having a larger difference in the other (in Layyah).

Overall, the improved correlation reduces the deviation with the actual specific cost, and in most of the cases provides more accurate results, with about ±20% difference compared to the actual data, whereas the standard correlation has a higher relative difference. However, many significant parameters and design conditions contribute to these deviations, such as the different top brine and heat source temperatures, any possible intermediate steam extraction (in case of TVC-MED plants) reducing the specific cost, the feed seawater temperature and salinity.

5. Results

In this section we present the results when using the improved correlation and compare them with the ones of the correlation of Eq. (2). These results concern the MED specific capital cost for various designs and conditions. These conditions cover the variation of heat source temperature from 60 to 140 °C, and of the MED effects number from 3 up to 30 (the maximum number of effects is restricted by the imposed minimum average temperature difference between effects of 2.5 °C).

5.1 Variation of heat source temperature

A constant number of effects equal to 8 is used (as in the reference case) to examine the effect of the heat source temperature on the MED specific cost. The heat input is equal to 10 MW and its temperature is varied from 60 up to 140 °C. The specific capital cost of a MED plant is shown in Fig. 5, using the standard calculation method (Eq. (2)) and the ones proposed here (Eqs. (5) and (6)).

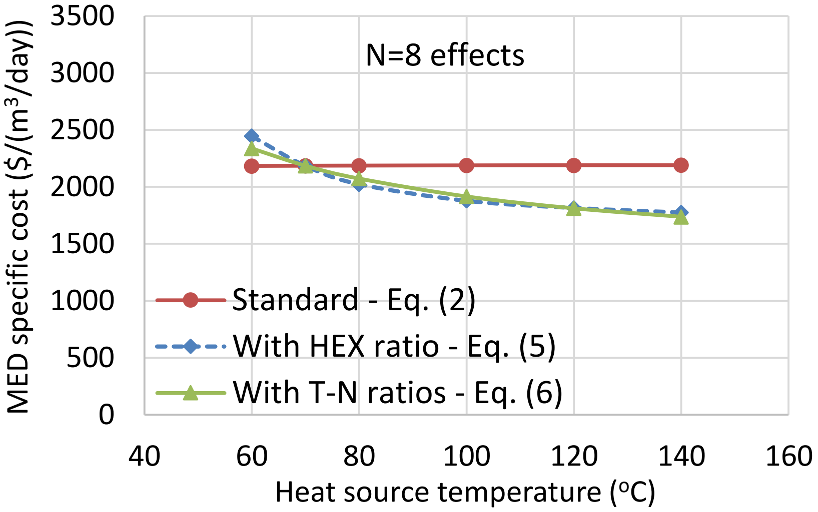

Fig. 5. MED specific cost for variable heat source temperature and 8 effects

Using a standard cost correlation, the MED specific cost is about the same for different temperatures, although the HEX area greatly decreases as temperature increases, with the plant capacity being almost the same. Specifically, the HEX area decreases from about 12,400 m^2 at 60 °C, to 9,000 m^2 at 70 °C, and to just 4,000 m^2 at 140 °C. The fact that the specific capital cost according to Eq. (2) remains almost constant for such high variation of the HEX area of about an order of magnitude (which should be accounting for about 40% of the capital cost according to Ref. [20]), highlights the limitations of the standard approach [36]. The proposed correlation effectively handles this critical drawback, showing a specific capital cost variation of about 27% between the extreme cases of 60 °C and 140 °C, obtaining a more correct trend. Moreover, the results of the two proposed correlations (Eqs. (5) and (6)) are very similar and from now on only the calculations of Eq. (5) will be shown.

The large cost decrease for higher temperatures fully justifies the recent efforts to increase the MED operation temperature to over 70 °C and reach even 100 °C or higher by avoiding scaling phenomena in the evaporator [37]. This is the reason that in the present study such large temperature range has been considered. However, when operating at higher temperature, it is a common practice to use more effects, which has been shown to increase the specific cost. This effect is presented in the next section.

5.2 Variation of the number of effects

The number of effects is examined here and how this affects the MED specific costs. For the same temperature, there is a one-way relation of number of effects with HEX area, as shown in Fig. A2 in the Appendix. In Fig. 6 is shown the MED specific cost for a variable number of effects and heat source temperatures using the standard correlation and the one proposed here.

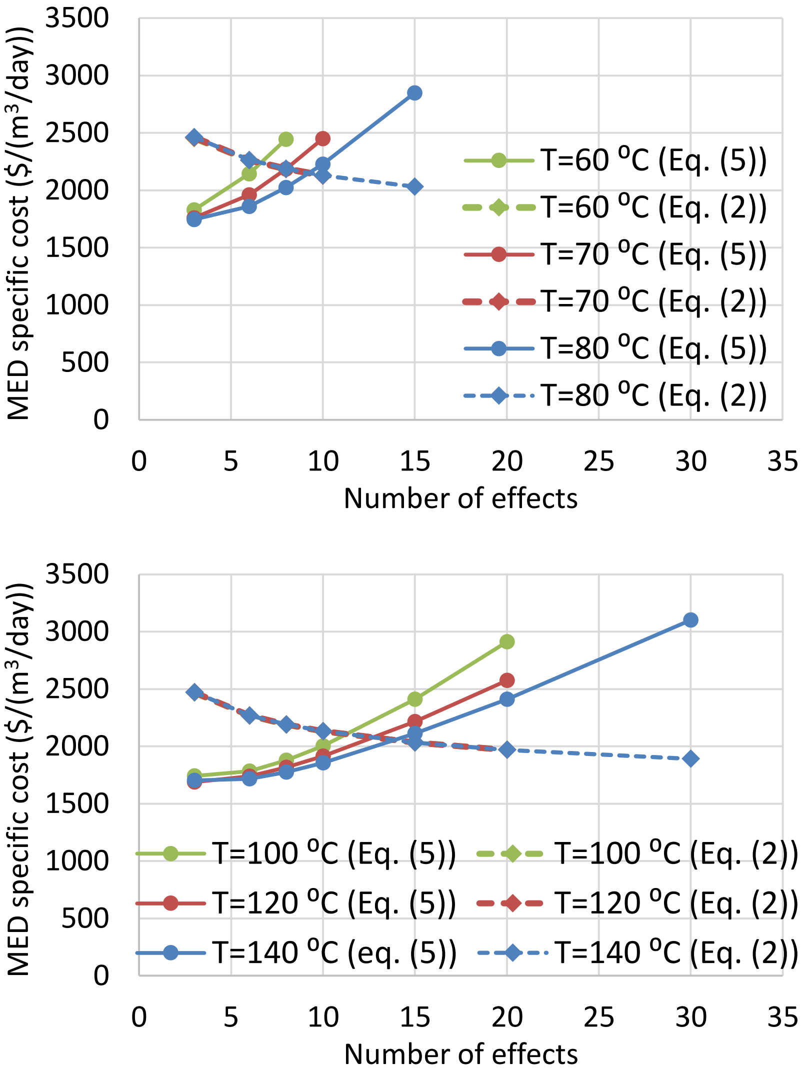

Fig. 6. MED specific cost for variable number of effects and heat source temperature (top: 60-80 °C, bottom: 100-140 °C)

For the same heat source temperature, a higher number of effects brings an increase to the specific cost, due to the increase of the required HEX area. The resulting effect is similar to the one presented in Ref. [8]. The standard correlation always predicts lower specific cost for increasing number of effects, due to the increase of the distillate flow rate, which is not a reliable outcome due to the higher HEX area for more MED effects, while the proposed correlation effectively overcomes this limitation.

6. Sensitivity analysis

The previous analysis and presentation of results has been conducted with constant coefficients of Eq. (5): the HEX cost fraction of 40% and the exponent of 0.8. The effect of these two coefficients on the specific cost is presented in this section with a sensitivity analysis.

The HEX cost fraction can decrease in case the heat source temperature increases and an additional pre-treatment is required, in order to avoid scaling. Moreover, the MED plant capacity could have some role on this fraction, which is not clear and no relevant data can be found in the literature. Having the above in mind, a sensitivity analysis is presented here, in order to identify the effect of the HEX cost fraction on the specific capital cost. This fraction ranges from 20 up to 60% (±50% variation of the reference value of 40%) and a typical case with 6 effects and heat source temperature of 70 °C is considered with the results shown in Fig. 7 (the specific cost of the reference case with 8 effects gives exactly the same results). In the same figure is also shown the effect of the exponent value, ranging from 0.4 up to 1.0 (from -50% up to +25% variation compared to the value of 0.8 used) on the MED specific cost.

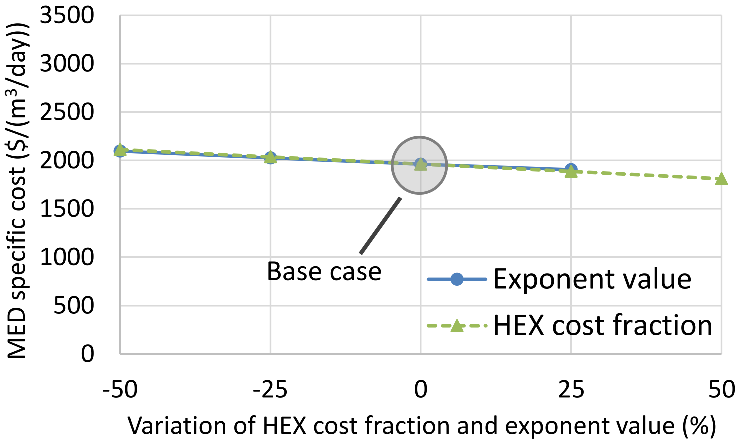

Fig. 7. Sensitivity analysis of the HEX cost fraction and the exponent value on the MED specific cost

The variation of the specific cost is less than 7.7% and well within the uncertainty of Eq. (2). Similar variation range is also calculated for the other cases examined. In any case, if the HEX cost fraction can be estimated with higher accuracy and even expressed as a function of MED design parameters, it can be easily integrated in the proposed cost correlation.

7. Conclusions

A new correlation of the MED specific cost as a function of the plant capacity has been developed, considering actual plants for municipal water supply. The large deviation of the real costs from the fitted expression, even with a factor of 2 for moderate plant sizes, motivated the authors to further examine the reasons behind this discrepancy. This analysis concluded that the plant design specifications have a major role on this. Therefore, the methodology for deriving to an improved correlation of the MED specific cost has been developed and presented in this work.

This methodology required the use of a MED model, whose results are then fitted to polynomial correlations between the plant capacity and HEX area. This procedure has been implemented for a large range of design conditions for the heat source temperature and the number of effects. These correlations are then used in the proposed cost correlation, in order to estimate the MED plant specific cost, when the main design parameters are varied. This improved correlation separates the HEX cost fraction, making it possible to better capture the cost trend for various configurations, including any feed configuration (forward or parallel feed).

The calculations of the improved correlation have been compared with the actual cost data of existing MED plants for validation purposes. This sample was limited, due to the difficulty of obtaining the number of effects for various plants. However, this comparison showed that the improved correlation provides more accurate results in most of the cases, and in general reduces the deviation between calculated and actual MED specific cost.

Then, cost calculations have been implemented for variable heat source temperature and number of effects. This analysis revealed the weaknesses of the standard correlations for MED costs, with its formulation ensuring that it provides at least quantitatively more correct results. Moreover, the use of a reference case minimizes the significance of any simulation error that could exist, due to some design uncertainties of the MED model. The intention of the authors was not to invest on the design results of MED configurations, but to suggest a new methodology to conduct quick and reliable comparisons of the MED specific cost, providing the trend and being quantitatively correct. The validation process of this correlation is on-going, by expanding the sample and by examining other possible parameters that could have a significant role in the specific cost.

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Appendix

The numerical results of the forward-feed MED numerical model are presented and briefly discussed. The effect of the main design parameters is investigated, in order to extract correlations of plant capacity and HEX area as a function of the heat source temperature and number of effects. For all cases a constant heat input of 10 MW (corresponding to the reference MED plant) and feed water salinity of 40,000 ppm is considered (average salinity between Mediterranean and Arabian Gulf values). Calculations have been also conducted with different salinities (32,000 and 36,000 ppm) and the results show that the effect of this salinity variation is negligible, and are thus not shown. Other parameters and input are defined in the MED model description.

FF-MED: Variable number of effects

The effect of the number of effects and heat source temperature on total distillate mass flow rate and top brine temperature is depicted in Fig. A1.

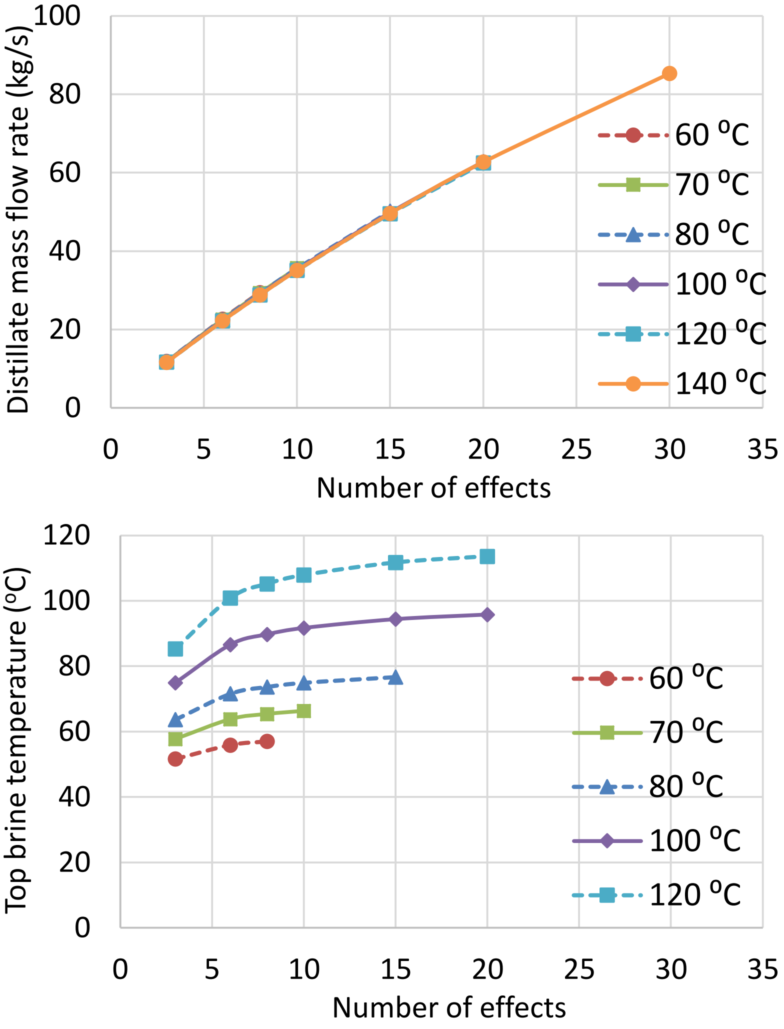

Fig. A1. Distillate mass flow rate and top brine temperature as a function of the number of effects for various heat source temperatures

The distillate mass flow rate is almost linearly correlated to the total number of effects. Moreover, the heat source temperature has a small effect on the mass flow rate for the same number of effects, since temperature has a weak effect on the latent heat of steam. Moreover, the TBT approaches the heat source temperature in case of a high number of effects (difference of about 3-4 K), while the TBT is 10-20 K lower for few effects.

In order to keep an almost constant plant capacity, when varying the heat source temperature, as shown in Fig. A1, the total HEX area is greatly increased for low temperatures for a fixed number of effects, as is clearly shown in Fig. A2, since the temperature difference between effects decreases.

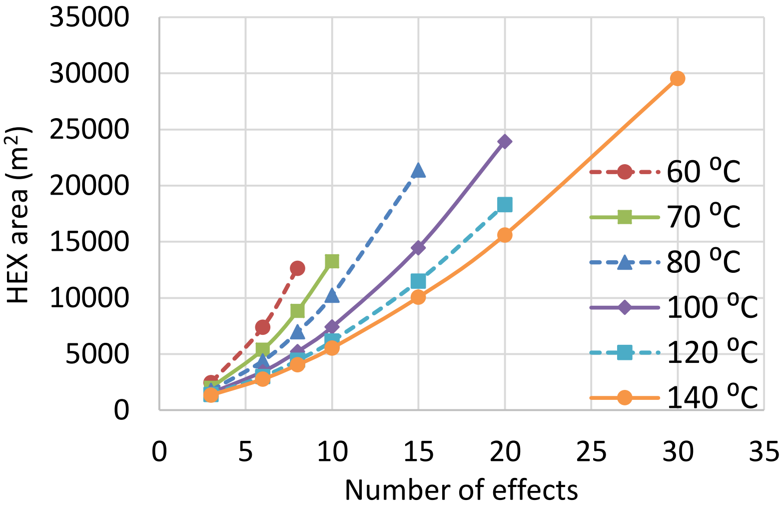

Fig. A2. Total HEX area as a function of the number of effects for various heat source temperatures

For higher temperature, the HEX area is much lower for the same number of effects. This shows that the MED cost can be greatly decreased in case the heat source temperature increases, which is not reflected in the available MED specific cost correlations (Eqs. (1) and (2)). The combined effect of distillate mass flow rate and HEX area is expressed as specific HEX area, in $m^2/(kg/s)$, shown in Fig. A3.

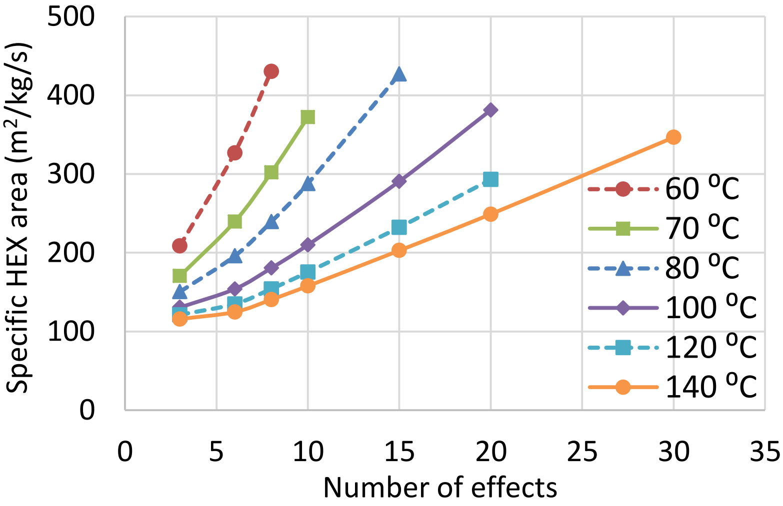

Fig. A3. Specific HEX area as a function of the number of effects for various heat source temperatures

The specific HEX area increase is smoother than the HEX area. It increases for high number of effects and especially for low heat source temperatures. This parameter is actually the inverse of the HEX effectiveness, which is low at the first MED effects (high temperature and high effectiveness), and then is increased (reducing effectiveness).

FF-MED: Variable heat source temperature

The effect of heat source temperature on the HEX area and specific HEX area is presented in Fig. A4 and on the distillate mass flow rate in Fig. A5 for the temperature range of 60-140 °C and for the case of 8 effects.

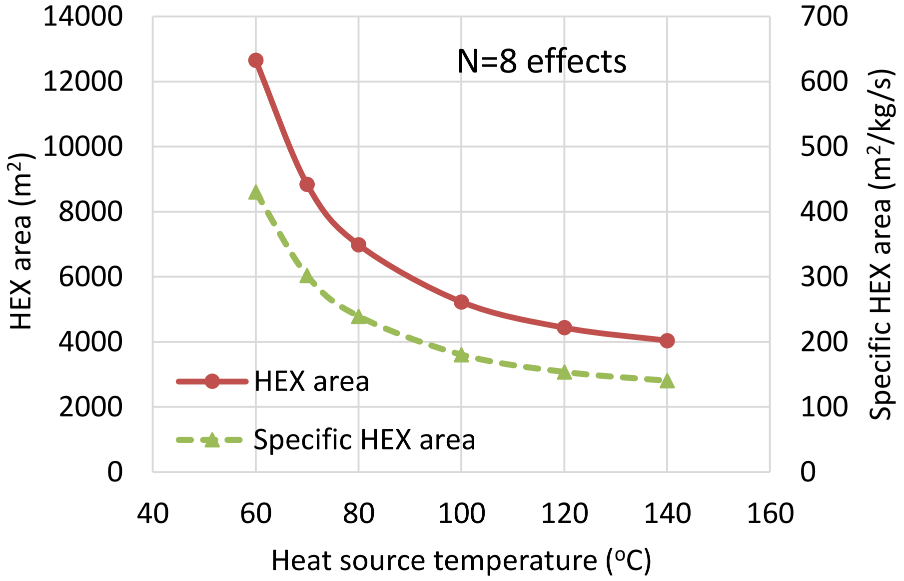

Fig. A4. Effect of heat source temperature on HEX area and specific HEX area for the case of 8 effects

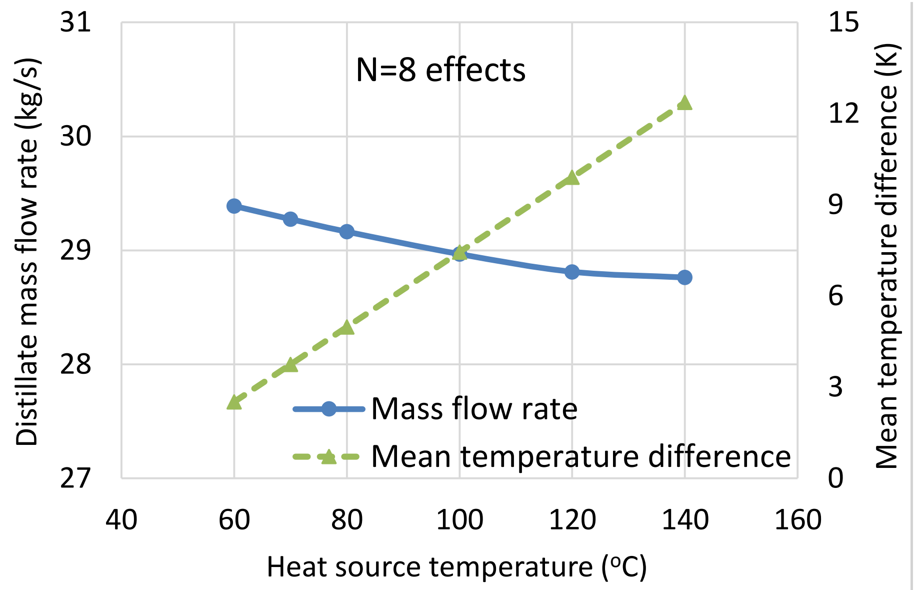

Fig. A5. Effect of heat source temperature on distillate mass flow rate and mean temperature difference of each effect for the case of 8 effects

Both HEX area and specific HEX area follow exactly the same trend, rapidly decreasing for higher heat source temperature. On the other hand, the distillate mass flow rate shows a small decrease with temperature for the range considered here, since the enthalpy of condensation of the heating steam slightly decreases for higher temperature. Finally, the mean temperature difference of each effect shown in Fig. A5 is linearly correlated to the heat source temperature, since it is a function of the number of effects (8 effects considered here), top temperature and condenser temperature (the latter is kept constant and equal to 35 °C).

MED-TVC numerical results

Simulations have been conducted for the case of parallel feed MED-TVC configurations for a similar range of heat source temperatures and number of effects. The results of the heat exchangers area and distillate mass flow rate for this configuration are compared to the previous FF-MED results. This comparison is shown in Fig. A6 for heat input temperature in the range of 60-100 °C as a function of the number of effects.

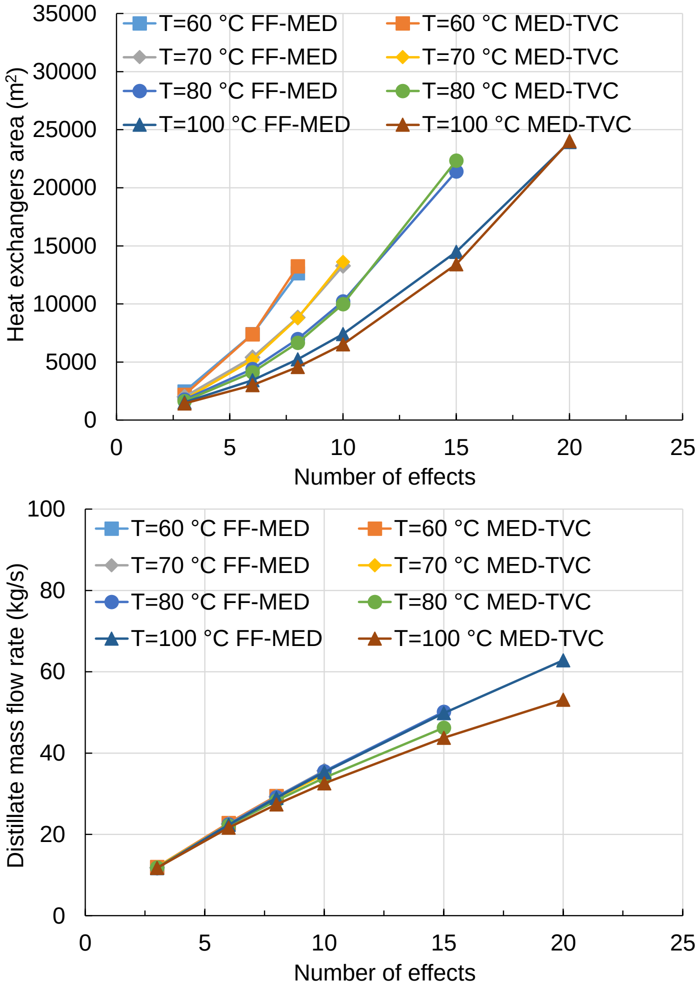

Fig. A6. Comparison of HEX area and distillate mass flow rate for FF-MED and MED-TVC configurations for various heat source temperatures as a function of MED effects

It becomes clear that the numerical results between these two MED plant configurations are very similar, and thus the correlations included in this study can be used for either plant type.