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Investigation of thermo-hydraulic design aspects in optimization of MED plants

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ABSTRACT

The purpose of this article is to investigate the thermo-hydraulic design aspects in optimization of heat exchangers that are called "effects" in multiple-effect distillation plants. Desalination costs have been continuously declining over the years because of advances in system designs and operating experiences, and the associated reductions in specific unit sizes and power consumptions. In this article, it is shown that the concurrent investigation of process design and mechanical design significantly influences the cost of raw materials, as the heat exchanger size and energy savings usually have a paradox with each other. The cost of shell material and tubes inside the effects are the most effective factors in the costs of desalination plant construction. A software for the process design analysis of MED-TVC (multi-effect desalination with thermal vapor compression) plants is developed in order to calculate the costs of the required tubes and the shell of the system. This software can provide an effective tool for the process simulation and economical evaluation of fixed capital cost, including those of shell and required tubes. The influence of all effective parameters in this evaluation is predicted in this software under design and operating conditions.

Keywords: MED-TVC; Economical evaluation; Process design; Thermo-hydraulic design

1. Introduction

The need for high-quality water and utilizing of desalination systems have significantly increased during the last decade. The lack of fresh water resources is the main reason of using desalination technologies to provide plants with industrial water. Desalination systems are the main sources of potable and industrial water for several countries. Development and improvement in desalination industry is associated with the reduction in energy consumption and cost. The costs of membrane-based desalination technologies have been reduced in comparison with current thermal desalination technologies. Therefore, the investigation of thermal desalination processes in terms of energy consumption and cost is necessary. Many researches, up to now, have been done to compare different routes of desalination; as for example, multi-effect desalination and reverse osmosis [1–3]. Reverse osmosis shows significant advantages in some aspects to multi-effect desalination; however, there are immense source of interest to use multi-effect desalination in the countries near Persian Gulf, where the resources of thermal energy is abundant [4].

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Uche et al. [5], Kafi et al. [6], Ettouney et al. [7], Jernqvist et al. [8], and Darwish et al. [9] attempted to develop simulation packages for thermal and membrane desalination processes in order to investigate energy consumption and cost. Ettouney developed a process-based computer package for evaluating thermal and membrane desalination technologies in 2004 [10]. Kouhikamali et. al. have carried out several works in order to investigate the performance of MED-TVC (Multi-Effect Desalination with Thermal Vapor Compression) systems from the point of view of energy consumption [11–13]. In the previous work done by the current author, multi-effect desalination unit was analyzed by the simulation code and then, the code was validated by experimental data [11,13]. Despite having noteworthy results, previous works did not consider economical aspects of MED construction.

Therefore, in this work, the simulation code is improved by attaching a new code, investigating economic aspects of a MED unit in order to obtain better knowledge of all parameters affecting the design of MED unit. This article focuses on the process design procedure of MED package in an economic point of view. The Investigation of process design and thermo-hydraulic design both together significantly affect optimizing the cost of the system; because, usually, the heat exchangers' size and energy reduction are in a paradox with each other. The costs of shell material and tubes inside the effects are the most important factors determining the construction cost of the plant. So, the main objective of this work is to evaluate and optimize the cost of tubes and the shell of a MED plant which is the major portion of overall cost.

2. Process simulation and thermo-hydraulic design aspects

Fig. 1 shows a schematic design of a MED-TVC system. The system consists of a number of evaporators that are called "effects," a condenser, and a thermo-compressor. In each effect, a part of seawater which is sprayed over the tubes evaporates and distills in the next effect. In the mathematical modeling, mass and energy balance equations have been developed for the system, and then, based on the results of mass and energy balance, the heat exchangers, thermo-compressor, and ejectors are designed.

Fig. 2 demonstrates the process design algorithm for shell and tube heat exchangers in terms of the effects of multiple effect desalination packages. Condenser is usually the shell and the tube type in MED systems which have the same design algorithm as the shell and tube evaporators in general, but the influence of noncondensable gasses on heat transfer coefficient should be considered as a resistance in the design algorithm. Many of researchers have investigated effect of noncondensable gasses on heat transfer coefficient [14].In addition, the allowable pressure drop for seawater as a single-phase liquid inside the tubes has been considered into account, according to the maximum allowable velocity inside the tubes that is mentioned in Tubular Exchanger Manufacturers Association (TEMA) standard. As it is shown in Fig. 2, in order to calculate the number of tubes inside the effects, the tubes' thickness, the diameter, and the length should be defined. These parameters affect the heat transfer coefficient, the required heat transfer surface area, and the number of tubes.

In industrial heat exchangers, increasing the heat transfer coefficient is necessary to decrease the required heat transfer surface area and the heat exchanger cost. However, it is clear that the total cost of a heat exchanger depends on the shell shape and its mechanical design parameters. Therefore, sheets' thickness and the number of sheets used during the construction of the shell are determining parameters which influence the total cost of a heat exchanger. So, in order to optimize a heat exchanger, the reduction of the required heat transfer surface area and influence of design parameters such as the number of required sheets in the construction of heat exchanger and sheets' thickness should be considered at the same time. The purpose of this paper is the concurrent investigation of thermo-hydraulic design and process design aspects to reduce the cost of thermal desalination.

3. Cost estimation of raw materials needed for construction of a MED

3.1. Mechanical design of multi-effect desalination by the computer package

Fig. 3 shows an image of the developed software to evaluate MED-TVC packages. The program is modular in structure and includes a number of modules for evaporators, condensers, thermo-compressors, steam jet ejectors, etc.

Each module has its own mathematical model. The program also includes a comprehensive database for the physical properties of seawater. There is also a library containing correlations for heat transfer coefficient of different heat transfer surfaces and flow regimes [15,16].

In order to investigate the process design from an economic point of view, first of all, the price of different sizes of tubes per meter and sheet price per ton of

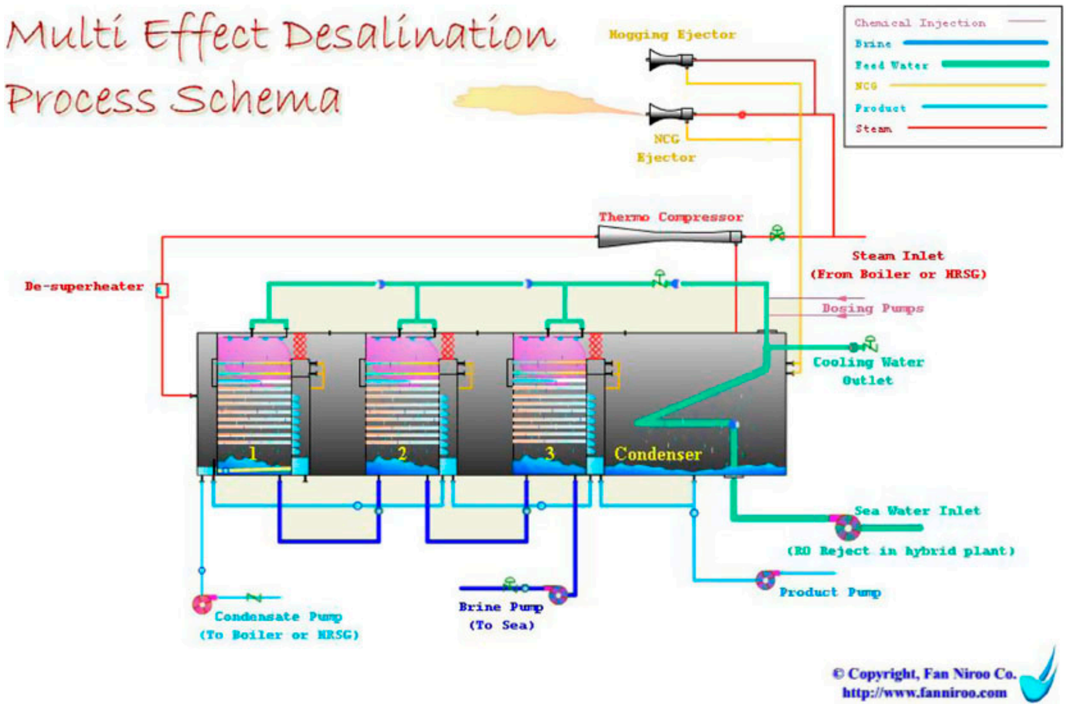


Fig. 1. Schema of a MED-TVC system [17]

weight should be defined in the simulation code. Then, by defining the width and length of standard sheets, the width and the length of tube sheets for triangular arrangement of tubes can be calculated as follows:

$$W = nS_n + 2d_G \tag{1}$$

$$H = \frac{N_t}{n} \times \frac{\sqrt{3}}{2} S_n + 2d_G \tag{2}$$

in order to calculate the shell diameter for horizontal demisters; the width of demisters beside the tube sheets is calculated according to Eqs. (3)–(5). Moreover, the distance between the top and the bottom of the tube sheets and shell should be calculated according to the process limitations of the system. To avoid the erosion problem, spray nozzles should be located at least 10–15 cm above the top row of the tubes. The distance between bottom of the tube sheets and shell should be calculated according to the required volume for brine water in the shell. Fig. 4 and Fig. 5 illustrate the position of the tube sheet and horizontal demisters in the shell.

$$A_D = \frac{M_v}{\rho_v V P_p} \tag{3}$$

$$W_D = \frac{A_D}{2L} \quad \text{The case when the number of demisters is 2} \tag{4}$$

$$W_D = \frac{A_D}{4L} \quad \text{The case when the number of demisters is 4} \tag{5}$$

The procedure for determining the pressure vessel's thickness is mentioned in American society of mechanical engineers (ASME) standard. According to this standard, the shell thickness strongly depends on the shell diameter. Based on Figs. 4 and 5, the shell diameter can be calculated from Eqs. (6) and (7) for the shell with two demisters besides tube bundles (one in the left and one in the right) and from Eqs. (7) and (8), when we use four demisters (double deck demisters) in the shell. Since demisters take up space, they make the shell diameter larger. Double-deck demister consists of four demisters instead of two in which a quarter of the vapor producing in the effect passes each one. The use of double-deck demister makes the shell smaller. Use of this type of demisters decreases the shell diameter effectively. Because of this, we use this type of demisters in all of units we design.

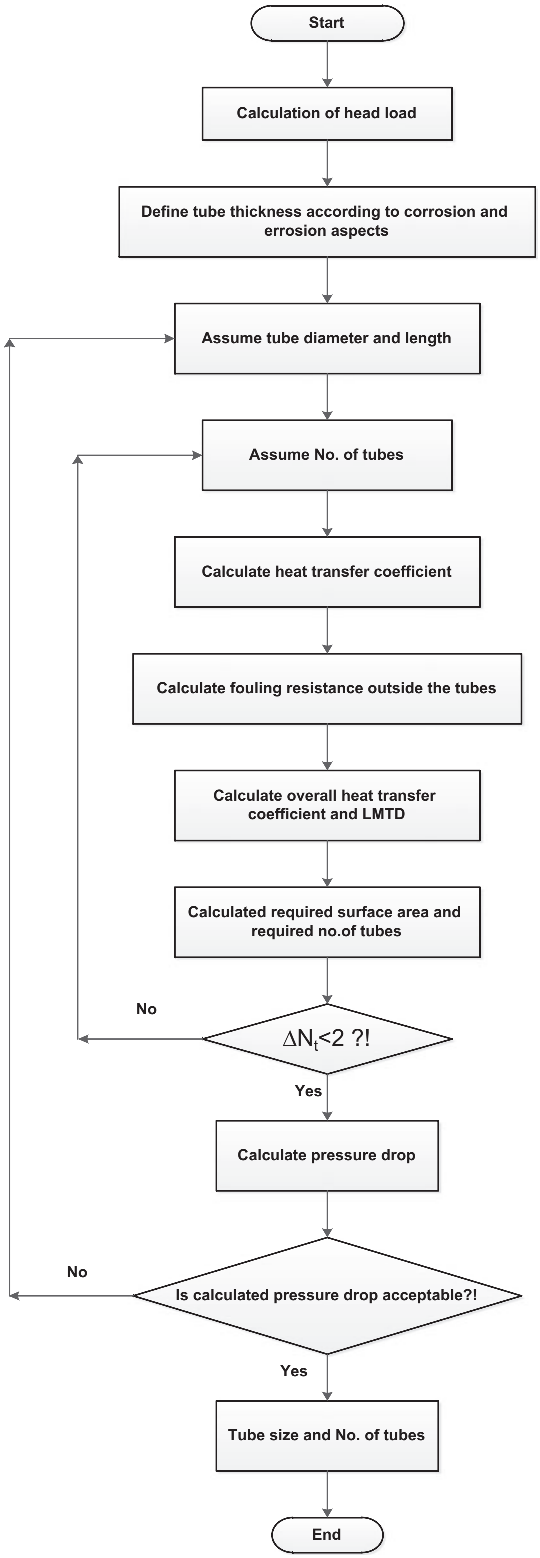


Fig. 2. Shell and tube evaporators' design algorithm.

$$D_{shell} = W + 2W_D \tag{6}$$

$$D_{shell} = H + h + h_{prim} \tag{7}$$

$$D^2_{shell} = (W + 2W_D)^2 + (H_D)^2 \tag{8}$$

Finally, the desirable shell diameter is the greatest D_{shell} that is calculated from Eqs. (6) and (7) for the shell with two demisters. When we use double-deck demisters in the shell, the desirable D_{shell} is the greatest value between Eqs. (7) and (8). Shell thickness can be determined from ASME standard and the total weight of shell can be calculated from Eq. (9).

$$W_{shell} = \rho_{sh}\pi D_{shell} t L_t \tag{9}$$

It should be noted that the sheets that are used in the construction of the shell have a standard width and length. In order to avoid wasting the plates, shell diameter should be calculated obedient to the ratio of equivalent length for D_{shell} and length of the standard sheet. Equations (10) and (11) illustrate the relations that are used for calculating the shell diameter if we desire no waste in plates during the manufacturing.

$$\pi D_{shell} = L_e \tag{10}$$

$$\frac{L_e}{L_s} = m \qquad m = 1, 1\frac{1}{4}, 1\frac{1}{2}, 2, 2\frac{1}{4}, 2\frac{1}{2} \tag{11}$$

3.2. The method of obtaining construction cost of a MED by mechanical design parameters

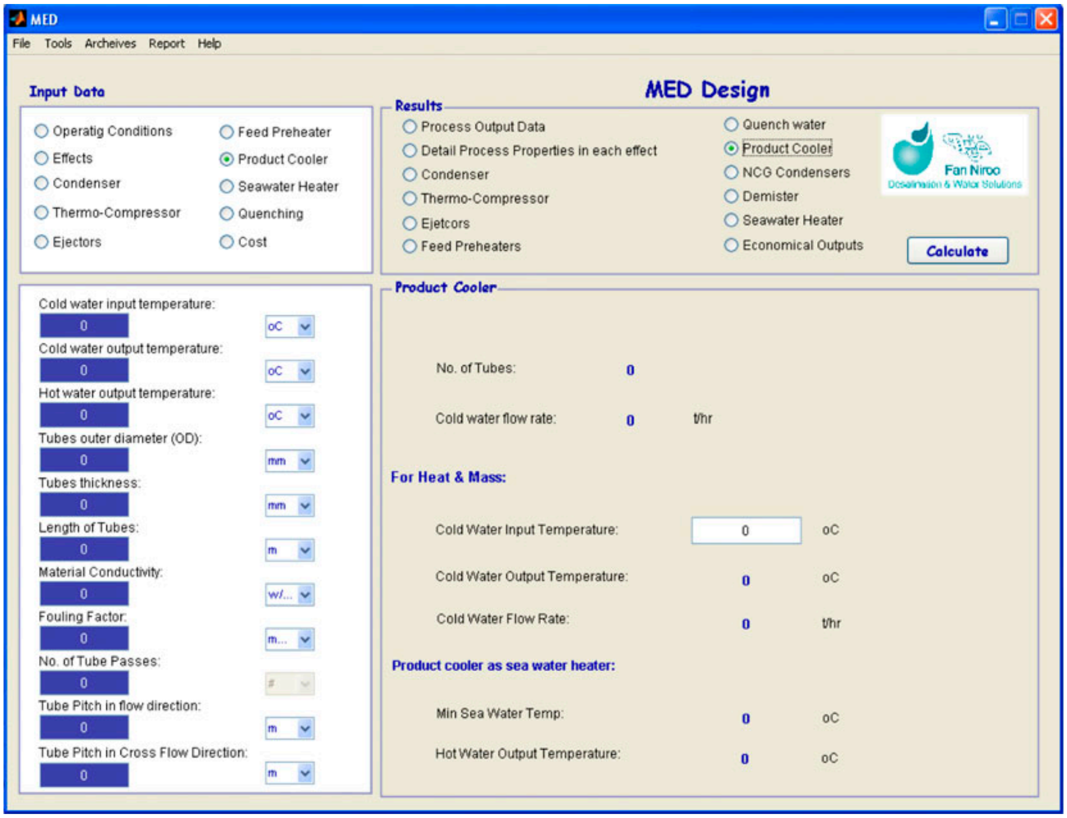
Now that all mechanical parameters were obtained by the method described in the last section, the cost of raw materials needed for construction of a MED, which consists of tubes and shell price, can be easily obtained as below:

Price of raw material = weight of raw material × Price per weight

So, for each case, at first, the process parameters of a MED are obtained by the simulation code. Then, mechanical parameters can be obtained as described. Finally, the cost of raw materials will be readily obtained by above equations.

4. A case study for optimization of a MED

The most important factors that affect the size of the shell diameter and length are the tube lengths and diameter. Moreover, these parameters affect the thermal performance, as well. As it was mentioned before, the investigation of the reciprocal effect of thermody-



MED Design

Input Data

○ Operatig Conditions
○ Effects
○ Condenser
○ Thermo-Compressor
○ Ejectors
○ Feed Preheater
● Product Cooler
○ Seawater Heater
○ Quenching
○ Cost

Results

○ Process Output Data
○ Detail Process Properties in each effect
○ Condenser
○ Thermo-Compressor
○ Ejetcors
○ Feed Preheaters
○ Quench water
● Product Cooler
○ NCG Condensers
○ Demister
○ Seawater Heater
○ Economical Outputs

Cold water input temperature: 0 oC
Cold water output temperature: 0 oC
Hot water output temperature: 0 oC
Tubes outer diameter (OD): 0 mm
Tubes thickness: 0 mm
Length of Tubes: 0 m
Material Conductivity: 0 w/...
Fouling Factor: 0 m...
No. of Tube Passes: 0 #
Tube Pitch in flow direction: 0 m
Tube Pitch in Cross Flow Direction: 0 m

Product Cooler

No. of Tubes: 0
Cold water flow rate: 0 t/hr

For Heat & Mass:

Cold Water Input Temperature: 0 oC
Cold Water Output Temperature: 0 oC
Cold Water Flow Rate: 0 t/hr

Product cooler as sea water heater:

Min Sea Water Temp: 0 oC
Hot Water Output Temperature: 0 oC

Fig. 3. A photo of developed simulation software.

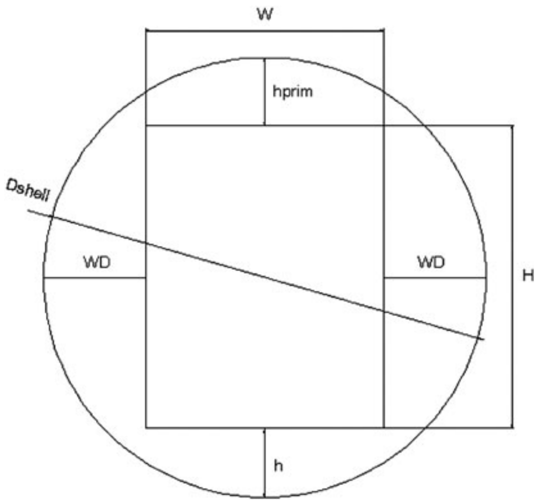


Fig. 4. A schema of a shell with two horizontal symmetric demisters.

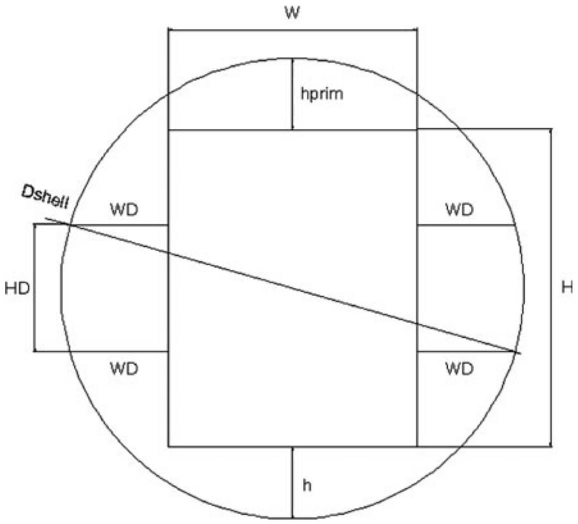


Fig. 5. A schema of a shell with four horizontal symmetric demisters.

namic design and thermo-hydraulic design on each other helps us to achieve an optimized system.

In order to verify the results of this model, a parametric study has been done, in which it investigates the design parameters for a system with 1,718 cubic meter per day capacity installed in Assaluyeh city near the Persian Gulf in Iran [17]. Fig. 6 shows a photograph of this plant and Table 1 shows some specifications of this unit. The specifications of this package are regarded as basic data in this article.

Figs. 7 and 8 show the variation of tube costs and shell cost in comparison with the basic model of the system as a function of tube lengths. It should be noted that in spite of various capabilities for tube lengths selection, some process aspect limitations, such as wetting rate and pressure drop in the tubes, restrict us to select suitable length for the tubes inside the package.

Fig. 7 shows that as the tube lengths increase, so does the tubecosts. Nevertheless, as it is shown in Fig. 8, the basic model has the minimum shell cost among the others. By increasing the tube length, the length of the shell will also increase, while the diameter of the shell will decrease. But, increasing the length of the shell in comparison with decreasing the diameter of the shell with a constant shell thickness leads to an increase in the required material for construction. Therefore, increasing the tube length according to Fig. 8 leads to a sharp increase in tube cost. On the other hand, in this case study, decreasing the tube length below 4 m, increases both the shell diameter and the thickness. Therefore, as is shown in Fig. 8, again, an increment in cost can be seen in tube lengths lower than 4 m due to the change in the required shell thickness.

It can be seen from Figs. 7 and 8 that the summation of tube costs and shell cost is minimum in those cases in which the tube length is around 4 m. This is the reason that the manufacturer of this package uses 4.1 meters for tube lengths.

Table 1
Mechanical data of MED-TVC package in Assaluyeh manufactured by Fanniroo Co. [17]

Net capacity (m^3/day)	1,718
Number of effects	4
Number of Tubes in each effect	2,736
Tube diameters (mm)	28.57
Tube lengths (m)	4.1
Shell Diameter (m)	3.2

Fig. 6. A photograph of installed plant with 1,718 m^3/day capacity, Assaluyeh, Iran [17].

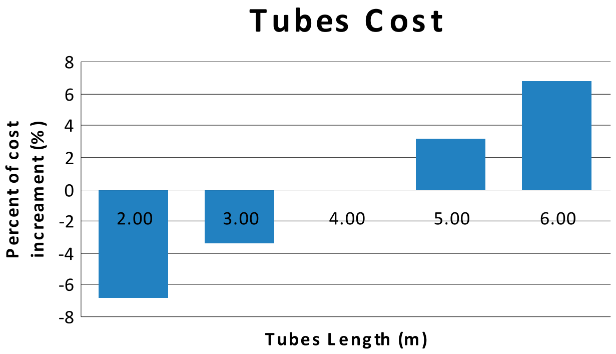


Fig 7. Variation in tube costs in comparison with the basic model as a function of tube length.

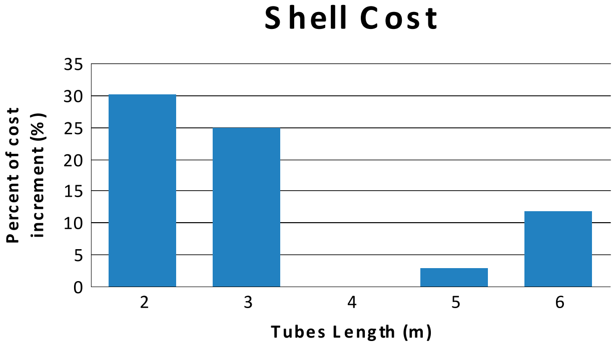


Fig. 8. Variation in shell cost in comparison with the basic model as a function of tube lengths.

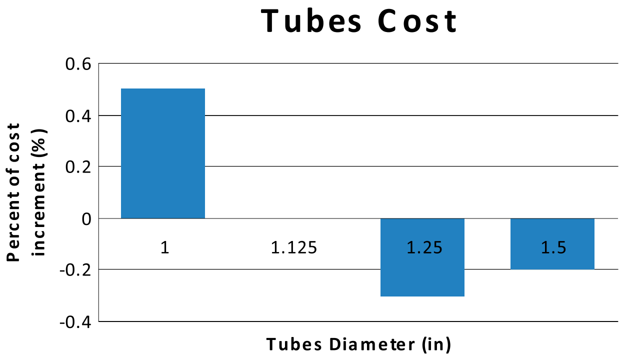


Fig. 9. Variation in tube costs in comparison with basic model as a function of tube diameters.

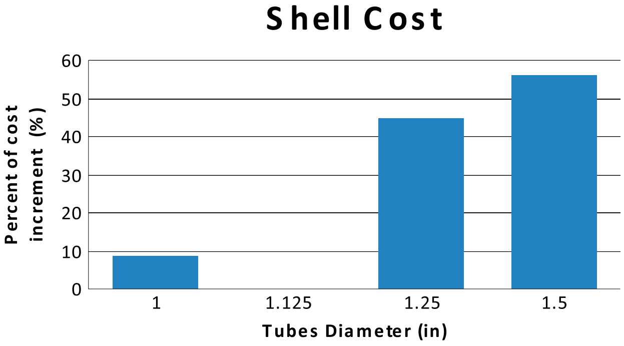


Fig. 10. Variation in shell cost in comparison with basic model as a function of tube diameters.

Tube diameters in the effects define the heat transfer coefficients of the steam condensation inside the tubes and seawater evaporation around the tubes. Therefore, the tube diameter is highly effective in determining the number of required tubes for the process. In the case of low heat transfer coefficient, the required number of tubes or the heat transfer surface area will increase. On the other hand, tube pitch is related to the tube diameters. Therefore, if we have the same heat transfer surface area with two different tube diameters, the tube pitch should be different [18]. In addition, the tube diameters define the dimension of the tube sheets and the shell diameter. Therefore, shell cost and tube costs will change by altering the tube sizes. Figs. 9 and 10 show the variation of tube costs and shell cost of the package with variation in tube diameters.

Fig. 9 shows that by augmenting the tube size, the tube costs decreases. The reason is related to the relationship between heat transfer coefficient, pressure drop, and tube diameters, but as it was mentioned before and can be seen in Fig. 10, basic model has the minimum shell cost among the others. Increasing the tube diameters results in increase in the required tube pitch and the shell cost. On the other hand, as the tube diameters decrease, the pressure drop and temperature difference between the effects increase and this leads to the increase of the required heat transfer surface area. Therefore, according to Fig. 10, the basic model has the minimum shell cost among the others.

5. Conclusion

It can be concluded from this article that, to have an optimum system, the process design and thermo-hydraulic design aspects should be considered together. Considering the thermodynamic design aspect is not individually a proper method to reduce the cost of MED plants, because optimum design point in terms of process design and cost evaluation may differ with each other. Among the different parameters, the length and diameter of tubes are the most important factors that can affect the price of the system; since, they can affect pressure drops and heat transfer coefficient of heat exchangers and thereby can dramatically change the heat transfer area of desalination unit.

Acknowledgment

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Symbols

A_D — total area of demisters in each effect (m^2)
D_{shell} — shell diameter (m)
d_G — tube outside diameter (m)
h — distance between bottom of the tube sheet and shell (m)
h_{prim} — distance between top of the tube sheet and shell (m)
H_D — vertical distance between demisters (m)
H — length of the tube sheet (m)
L — length of tubes (m)
L_t — total length of the shell (m)
L_e — equivalent length for shell diameter (m)
L_s — length of the standard sheet (m)
M_v — vapor mass flux (kg/s)
m — specific and constant coefficient
n — minimum number of tubes at the first row in each effect
N_t — total number of tubes in each effect
P_p — packing porosity
S_n — tube pitch (m)
t — shell thickness (m)
V — vapor velocity at demister surface (m/s)
W — width of the tube sheet (m)
W_{shell} — total weight of shell (kg)
W_D — width of each demister (m)

Greek symbols

ρ_v — vapor density (kg/m^3)
ρ_{sh} — standard sheet density (kg/m^3)

References

[1] J. Ralf Olwig, Tobias Hirsch, Christian Sattler, Heike Glade, Louisa Schmeken, Stefan Will, Andrea Ghermandi, Rami Messalem, Techno-economic analysis of combined concentratingsolar power and desalination plant configurations in Israel and Jordan, Desalin. Water Treat. 41 (2012) 9–25.

[2] E. Tzen, M. Papapetrou, Promotion of renewable energy sources for water production through desalination, Desalin. Water Treat. 39 (2012) 302–307.

[3] W. Meindertsma, W.G.J.H.M. van Sark, C. Lipchin, Renewable energy fueled desalination in Israel, Desalin. Water Treat. 13 (2010) 450–463.

[4] R. Kouhikamali, A. SamamiKojidi, M. Asgari, F. Alamolhoda, The effect of condensation and evaporation pressuredrop on specific heat transfer surface area and energyconsumption in MED–TVC plants, Desalin. Water Treat. 46 (2012) 68–74.

[5] J. Uche, L. Serra, Comparison of heat transfer coefficient correlations for thermal desalination units, Desalination 152 (2002) 195–200.

[6] F. Kafi, V. Renaudin, D. Alonso, J.M. Hornut, New MED plate desalination process: Thermal performances, Desalination 166 (2004) 53–62.

[7] Hisham M. Ettouney, Hisham El-Dessouky, A simulator for thermal desalination process, Desalination 125 (1999) 277–291.

[8] M. Jernqvist, G. Jernqvist, Simulation of thermal desalination process, Desalination 134 (2001) 187–193.

[9] M.A. Darwish, A.A. EL-Hadik, "The Multi-Effect Boiling Desalting System and its comparison with the Multi-Stage flash system", Desalination 115 (1997) 223–238.

[10] H. Ettouney, Visual basic computer package for thermal and membrane desalination processes, Desalination 165 (2004) 393–408.

[11] R. Kouhikamali, A. Abbassi, S.A. Sadough, M. SaffarAvval, Thermodynamic Design and Parametric Study of MED-TVC, Desalination 222 (2008) 596–604.

[12] R. Kouhikamali, Numerical simulation and parametric study of forced convective condensation in vertical channels in multiple effect desalination system, Desalination 254 (2010) 49–57.

[13] R. Kouhikamali, A. Abbassi, S.A. Sadough, A simulation model and parametric study of MED-TVC process, Desalination 235 (2009) 340–351.

[14] Hisham El-Dessouky, Imad Alatiqi, S. Bingulac, Hisham Ettouney, Steady-state analysis of the multiple effect evaporation desalination process, Chem. Eng. Technol. 21 (1998) 5.

[15] Luo-peng Yang, Sheng-qiang Shen, Huawei Hu, Xue Chen, Thermal analysis of the internal condensation process in a horizontal tube of falling film evaporation, Desalin. water treat. 24 (2010) 101–108.

[16] P. Gao, L. Zhang, H. Zhang, Study on heat transfer of falling film evaporation characteristics on heat pipes in negative pressure, Desalin. water treat. 10 (2009) 311–316.

[17] www.fanniroo.com, webssite of Fanniroo incorporation, projects' documents section, phase project "9&10project".

[18] D.Q. Kern, Process Heat Transfer, McGraw-Hill, New York, NY, 1950.