CHEMICAL ENGINEERING TRANSACTIONS

VOL. 76, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976109

Impact of Cumulative Fouling Characteristics on Full-cycle Operation Optimisation of Multi-effect Distillation Desalination System

Chun-bo Chen, Lin Sun, De-jun Liu, Xiong-Lin Luo*

Department of Automation, China University of Petroleum Beijing, 102249, China
luoxl@cup.edu.cn

Cumulative fouling characteristics are often overlooked by researchers when optimising the operation of multi-effect distillation seawater desalination system. In order to analyse the influence of fouling cumulation on the optimisation operation, an eight-effect dynamic model for multi-effect distillation with thermal vapour compression (MED-TVC) seawater desalination system has been established and the cumulation of fouling has been considered in this model. Operation parameters of the eight-effect MED-TVC desalination system have been optimised repeatedly at different times (namely at different levels of fouling cumulation) throughout the full-cycle. Results indicate that the cumulation of fouling will gradually let the system deviate from the optimal operation condition, resulting in decrease in fresh water production, and operation re-optimisation at different times gets different results, which can efficiently reduce the influence of fouling and obtain better operational benefits. This work concludes that fouling cumulation has a big impact on operation optimisation of MED-TVC systems, and it is necessary to timely re-optimise operation parameters.

1. Introduction

Water shortage has become one of the most serious problems facing humanity in the 21st century, which is not only a problem limited to arid zones (Chee et al., 2014). As an effective way to cope with fresh water crisis, seawater desalination technology is being applied more and more widely in the Middle East and coastal cities around the world. Multi-effect distillation seawater desalination technology is one of the most promising seawater desalination methods. It connects multiple evaporators in series and utilizes the secondary steam generated in one evaporator to provide the evaporation energy required for the next evaporator, thus getting a great advantage on energy saving. A thermal vapour compression is usually used in the MED system to entrain steam from the last effect and mix with motive steam as heating steam of first effect, and significantly reduces motive steam assumption. A MED system with TVC has the ability of utilizing low-grade energy, e.g. solar energy, geothermal energy and waste heat (Liu, 2014), which makes it easy to combine with power plants and other plants.

Since seawater fouling cumulation is easy to happen during evaporation, evaporator fouling has always been a major challenge for MED systems, although this issue has been alleviated by lowering the evaporation temperature below 70 degrees Celsius (Gustavo et al., 1996), which is called low temperature multi-effect distillation (LT-MED) desalination technology. Fouling cumulation gradually reduces heat transfer efficiency of evaporators, hence deteriorates the performance of MED system (Gogenko et al., 2007), leading to the system's periodically shutting down for fouling removal. Operation optimisation of MED system has been carried out by many researchers to get higher operation efficiency. Paula et al. (2013) built a mathematical model that included different alternative flow-patterns for seawater and steam, and simultaneously optimised the model to determine the best stream flow-patterns, the size of each evaporation effect and the operating conditions. Iman et al. (2012) investigated input variables, such as temperature difference, motive steam mass flow rate and preheated feed water temperature, using response surface methodology (RSM) and Partial Least Squares (PLS) technique, then minimize total annual cost (TAC) and Gain Output Ratio (GOR) by making use of genetic algorithm-based multi-objective optimisation. Somayyeh et al. (2017) used multi objective optimisation to get the best trade-off

Paper Received: 11/03/2019; Revised: 12/04/2019; Accepted: 25/04/2019
Please cite this article as: Chen C.-B., Sun L., Liu D.-J., Luo X.-L., 2019, Impact of Cumulative Fouling Characteristics on Full-cycle Operation Optimisation of Multi-effect Distillation Desalination System, Chemical Engineering Transactions, 76, 649-654 DOI:10.3303/CET1976109

between GOR and heat transfer area with the help of exergetic and heat transfer analysis. But the critical fouling problem has not been considered in their operation optimisation. Consequently, status change of MED system during the full-cycle has been ignored. That results in bad performance of the optimisation results throughout the full-cycle operation.
Aiming at this problem, this paper has compared the relationship between fouling cumulation and optimal operating condition in the full-cycle of MED seawater desalination system and has illustrated the impact of fouling cumulation on operation optimisation.

2. Modelling and verification

In order to verify the influence of fouling cumulation on the full-cycle operation optimisation of seawater desalination system, this paper established an eight-effect MED-TVC dynamic model using gPROMS software. The model consists of eight evaporators, eight preheaters and eight flash tanks after each effect as well as a steam jet ejector which works with 0.5 MPa motive steam. Referring to the system construction in Anwar et al. (2009), the feed seawater is preheated by each effect preheater in series, and then flows into each effect in a parallel-cross-feed mode, then seawater absorbs heat from the heated steam in tubes and evaporates to generate new steam, which is called secondary steam. The remaining concentrated brine flows from the bottom of the evaporator into the next evaporator to flash and produce a small amount of steam. A small part of the secondary steam produced by evaporation of seawater is used for preheating feed seawater of each effect, and the rest of the steam flows into the tubes of next evaporator and condenses after heating seawater that flows outside the tubes. The condensed steam flows into flash tanks for flashing operation, and a small amount of steam generated by flashing also flows as heating steam to the next effect. The steam jet ejector entrains a part of the secondary steam from the last effect, and mixes the motive steam outside the system to increase its temperature and pressure, then provides heating steam to the first effect. The stream flow pattern is shown in Figure 1.

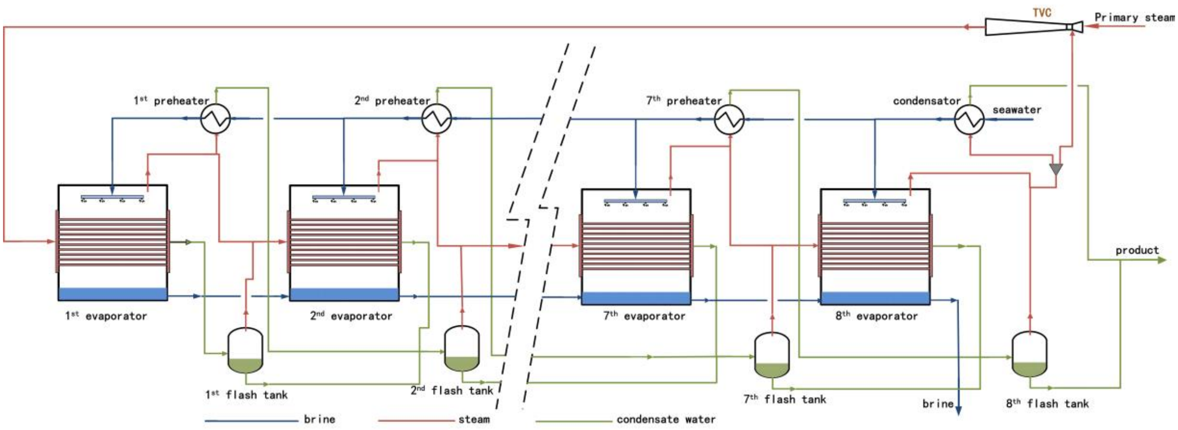

Figure 1: The construction of the eight-effect MED-TVC dynamic model

During the evaporation process, seawater tends to crystallization due to the increase in brine salinity, resulting in fouling cumulation outside heat exchanger tubes. In order to simulate the change of fouling thermal resistance in the evaporator, this paper refers to Taborek's crystallization fouling model (Yang et al., 1995) to simulate the scaling process on the outer wall of the evaporator heat exchange tubes. Mathematical equation is shown below.

$$R_f = \frac{k_1}{k_2} \frac{C_b^n \exp\left(-E/RT_s\right)}{V^{2+\gamma-\alpha}} \left[1-\exp\left(-k_2 V^{2-\alpha} t\right)\right] \qquad (1)$$

Where C_b is the average concentration of the fouling substance, kg/m^3; V is the fluid flow rate, m/s; T_s is the temperature of the fluid deposition layer, K; E is the reaction activation energy, kJ/(kg·mol); and R is the ideal gas constant, kJ/(kmol·K). Equation parameters α, ϒ, k_1, k_2 are determined by industrial data. Eq(1) considers that the fouling resistance is only related to the current system state and operating time, making it unsuitable for dynamic processes. Eq(2) is obtained by taking the derivative of Eq(1), which shows that the rate of increase in fouling thermal resistance is related to seawater salinity, the flow rate of feed seawater, and fouling temperature. Eq(2) let the current fouling resistance connected with previous operation conditions.

$$\frac{\partial R_f}{\partial t} = k_1 C_b^n \frac{\exp(-E/RT_s)}{V^{\gamma}} \exp\left(-k_2 V^{2-\alpha} t\right) \tag{2}$$

In order to verify the validity of this newly established model, a desalination system with the same construction was constructed using Aspen Plus software which is commonly used in the chemical industry. Aspen Plus is a large-scale general-purpose process simulation system for production unit design, steady-state simulation and optimisation. The world's major chemical, petrochemical, refining and other process industry manufacturing companies and well-known engineering companies are Aspen Plus users. Due to the lack of evaporator modules in Aspen, it is replaced with two heaters, a pressure reducing valve and a flash tank, with reference to the Aspen modelling method proposed by Hao et al. (2011). The steam heater transfers heat to the seawater heater to superheat the seawater, and the seawater is decompressed by a pressure reducing valve to perform vapour-liquid separation in the flash tank. Splitters are used to separate feed seawater and secondary steam, and the mixture of secondary steam from evaporators and flash steam from flash tanks is achieved by mixers. The specific construction of the eight-effect MED-TVC Aspen model is shown in Figure 2, in which the blue lines represent seawater flow, the red lines represent vapour steam and the green lines represent condensate water, same as Figure 1.

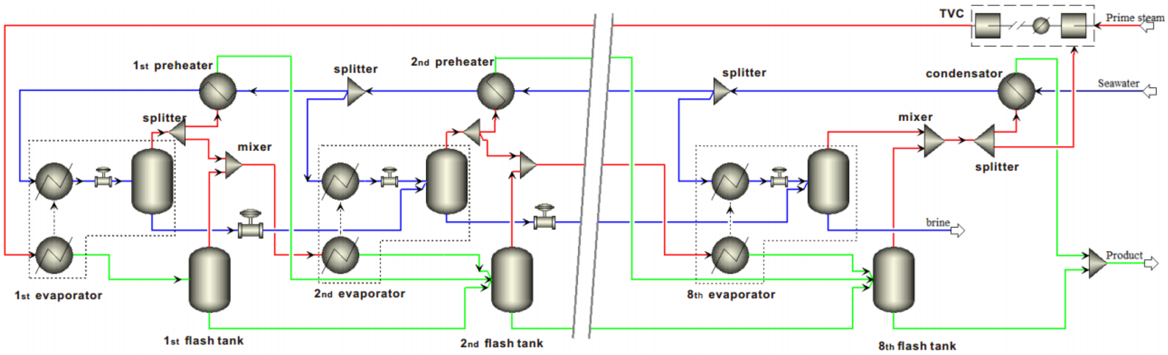

Figure 2: Aspen model of the eight-effect MED-TVC system

Steady-state simulations in gPROMS and Aspen were executed separately given the same operation conditions, including feed flow rate, evaporator pressure and seawater preheating temperature in each effect, as well as the flow rate of entrained steam. Simulation results are shown in Table 1.
It can be seen from the comparison of the results that the two models differ only 0.75 % in fresh water production and Performance Ratio (PR), which is defined as the ratio of generated fresh water flow rate to motive steam flow rate. And other indexes such as top brine temperature (TBT) and outlet concentrated seawater salinity are very close, indicating the validity of the model built in this work.

Table 1: Comparison of simulation results between gPROMS model and ASPEN model

Parameters	Motive steam	fresh water	PR	TBT	Brine salinity
gPROMS model	0.5 MPa, 6.337 kg/s	61.789 kg/s	9.7506	67.327 °C	38.469 g/kg
ASPEN model	0.5 MPa, 6.337 kg/s	62.253 kg/s	9.8237	67.300 °C	38.558 g/kg

3. Simulation

gPROMS software has easy-to-call optimisation tools, including Outer Approximation (OA) algorithm, Sequential Quadratic Programming (SQP) method and Control Vector Parameterization (CVP) method, etc. In this paper, CVP method is used to optimise the system’s operational parameters. Because of the long time lag of the eight-effect MED-TVD dynamic model, dynamic optimisation cannot achieve the desired optimisation effect, therefore steady-state optimisation strategy is chosen for operation optimisation of the MED-TVC system. Considering the impact of variables on the system and the operability of parameters, this work chooses pressure and feed flow rate of each effect, as well as flow rate of entrained steam from the last effect as optimisation variables. The system should be operated with TBT not exceeding 70 degrees Celsius, and in order to maintain sufficient heat transfer temperature difference in evaporators and preheaters, variables constraints are imposed on the evaporator pressure and the temperature change of each preheater. The evaporation temperature and temperature of the feed seawater in each effect are constrained within a reasonable range.

This work uses the simulation results in Section 2 as the system's pre-optimisation running results, and uses the CVP method to optimise the operational parameters of the system. Results before and after optimisation are shown in Table 2. The fouling resistance of the system during this optimisation is set to 0, and the optimisation results are executed in the whole cycle as the conventional single optimisation results. Referring to the pickling cycle of the desalination plant in Huanghua Power Plant (Zhang et al., (2013)), the operating cycle of the eight-effect MED-TVC system in the simulation is set to two years.
In order to analyse the impact of fouling cumulation on operation optimisation, a comparative simulation is executed in this work. Unlike the single optimisation simulation, the comparative simulation uniformly chooses five optimisation points in the whole operation cycle, including the beginning and the end of the operation cycle, resulting in an interval of half a year between each optimisation point. The simulation process is as follows: Firstly the five optimisation points divide the whole cycle into four segments, then the single optimisation result in Table 2 is used as the optimisation result at the first optimisation point, subsequently operation conditions is changed accordingly and the optimisation result is executed for a quarter cycle, which is half a year, and the second optimisation point is reached. Afterwards, the system is reoptimised according to its new operating status and the new optimisation result is carried out for another half a year. Repeat the above process until the entire operation cycle is finished. It should be noted that the fifth optimisation result is not implemented, which is used only for comparative analysis of optimisation results. As operation optimisation is carried out repeatedly, this optimisation method is called multiple optimisation in this work.

Table 2: Single operation optimisation results of eight-effect MED-TVC system

Decision variables	Evaporator pressure (Pa)							
	1st effect	2nd effect	3rd effect	4th effect	5th effect	6th effect	7th effect	8th effect
Initial value	27186.7	23757.7	20713.8	17981.2	15596.2	13469.5	11593.9	9947.4
Optimal value	27680.5	24105.9	20865.4	17912.8	15522.5	13235.1	11295.8	9600
Decision variables	Feed seawater flow (kg/s)							
	1st effect	2nd effect	3rd effect	4th effect	5th effect	6th effect	7th effect	8th effect
Initial value	33.1	35.9	34.2	32.6	31.1	29.6	28.3	27.1
Optimal value	20.1	20.5	20.2	19.9	48.0	55.2	40.5	39.2
Decision variables	Entrained steam flow (kg/s)							
Initial value	1.132							
Optimal value	4.0							

4. Results and discussion

In the previous section, full-cycle dynamic simulations are performed on single optimisation strategy and multiple optimisation strategy respectively. This section analyses the previous results of the two simulations.
Figure 3 shows the execution result of single optimisation in the full-cycle. Taking the first effect as an example, Figure 3a illustrates the fouling resistance change, Figure 3b shows the change of heat transfer coefficient, Figure 3c represents the feed seawater temperature change trend, and the total fresh water production change curve is provided in Figure 3d. It can be seen from Figure 3 that with the operation of the system, the fouling thermal resistance of the first effect evaporator is gradually increased, resulting in a decrease in the heat transfer coefficient of the evaporator, and the total fresh water production of the system is also gradually reduced. The change in total fresh water production reflects a reduction in the amount of secondary steam produced by each effect of seawater evaporation, and the amount of heating steam used for preheating feed seawater is also reduced, resulting in a decrease in the temperature of the first effect feed seawater. Figure 3 reveals the system's operating status change with the cumulation of fouling, which indicates the influence of fouling cumulation on the MED-TVC system.
The first effect evaporator is still taken as an example to analyse the relationship between fouling cumulation and system optimisation results. Figure 4 shows the variation curve of fouling thermal resistance in the first effect and the optimal fresh water production after operation optimisations at the five optimisation points. There is a change in the increasing rate of the fouling thermal resistance in the figure, which is caused by the change of operation conditions which is caused by the five optimisations, including the feed seawater flow rate in each effect, the temperature of seawater outside heat exchange tubes, and the salinity of brine, etc. Comparing the trends of the two curves, it can be clearly seen that the optimal fresh water production decreases with the increase of the fouling thermal resistance, reflecting the great influence of the cumulative fouling on the operation optimisation of MED-TVC system.

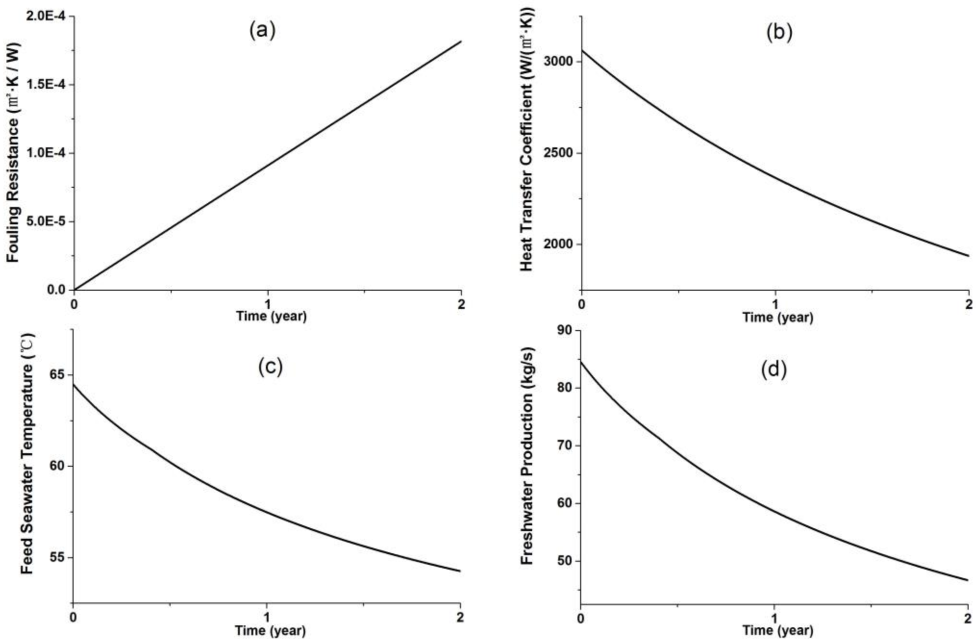

Figure 3: Variables change throughout the full-cycle in single optimisation

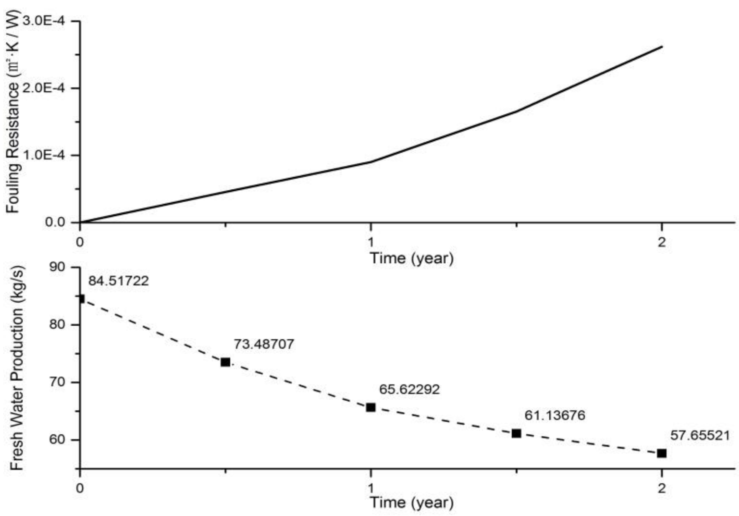

Figure 4: Variation curves of the first-effect evaporator fouling thermal resistance and optimal fresh water production

Furthermore, Figure 5 shows the full cycle fresh water production comparison curve between single optimisation strategy and multiple optimisation strategy. As a reference, the fresh water production variation curve in the absence of optimisation is also displayed.

It can be seen from Figure 5 that the fresh water production remains unchanged first and then gradually reduced in the entire cycle when there is no operation optimisation. This is due to the fact that production fluctuations are taken into account in the modelling, so each evaporator has 20 % heat exchange area margin, thus fouling cumulation has little influence on the system at the beginning. But with the increase of fouling thermal resistance, evaporator area margin is exhausted, leading to fresh water production decrease. Single optimisation has a higher fresh water production than that without optimisation at the beginning of the full-cycle, that's because operation optimisation makes area margin fully utilized. However, when the fouling thermal resistance is too high and becomes a key factor limiting the yield of fresh water, the operational benefits of single optimisation and the case without optimisation are close. In contrast, multiple optimisation takes fouling thermal resistance into account and increases fresh water production at each optimisation point, therefore achieves better economic benefits than the other two strategies over the full cycle, which can be seen clearly from Figure 5.

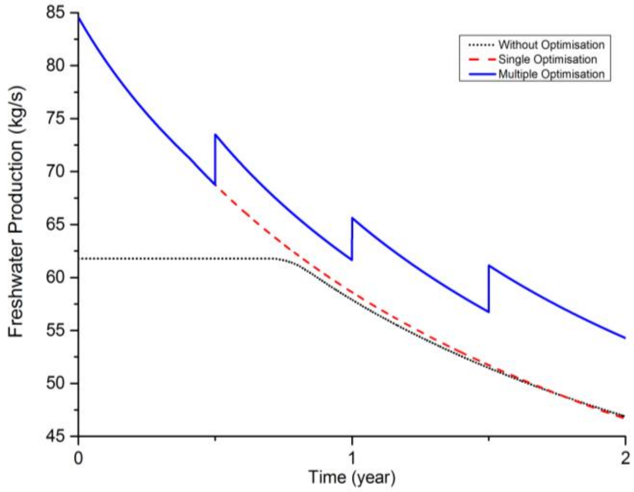

Figure 5: Fresh water production with single optimisation, multiple optimisation and without optimisation

5. Conclusions

In this work, an eight-effect MED-TVC dynamic model is established and verified. Then the system runs in full-cycle using single optimisation strategy and multiple optimisation strategy respectively to study the impact of cumulative fouling on operation optimisation of the desalination system. The main conclusions from the simulations are summarized as below:

(1) Fouling cumulation has a large negative impact on the full-cycle operation of MED-TVC desalination system, leading to the system's fresh water production decrease and the change of operation status.

(2) When fouling cumulation is considered during operation optimisation, optimisation results vary with fouling thermal resistance, and the higher fouling thermal resistance corresponds to the worse optimisation results.

(3) Multiple optimisation can significantly improve the operating efficiency of the MED-TVC system throughout the cycle, and gets better earnings than single optimisation strategy over the full-cycle. It can be inferred that, when fouling cumulation is taken into account, the more times of operation optimisation, the higher the operating benefits of the system in the whole cycle.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (21676295).

References

Anwar B, 2009, Development and Optimisation of ME-TVC Desalination System, Desalination, 249, 1315-1331.

Chee Y.T., Ta Y.W., 2014, the Potential Use of Natural Coagulants and Flocculants in the Treatment of Urban Waters, Chemical Engineering Transactions, 39, 1603-1608.

Gogenko A.L., Anipko O.B., Arsenyeva O.P., Kapustenko P.O., 2007, Accounting for Fouling in Plate Heat Exchanger Design, Chemical Engineering Transactions, 12, 207-212.

Gustavo K, 1996, Cogeneration with the LT-MED Desalination Process, Desalination, 108, 287-294.

Hao D.Q., Sha Z.L., Wang Y.F., Shu C, 2011, Aspen Plus Simulation of a Low Temperature Multi-Effect Desalination System, Journal of Tianjin University of Science & Technology, 26(1), 47-50.

Iman J.E., Abtin A, Vidya S.K., Taesuk O, 2012, Modeling and Genetic Algorithm-Based Multi-Objective Optimisation of the MED-TVC Desalination System, Desalination, 292, 87-104.

Liu F, 2014, Review on Ejector Efciencies in Various Ejector Systems, 15th International Refrigeration and Air Conditioning Conference at Purdue, Paper 1533.

Paula D, Pio A, Sergio M, 2013, Optimisation of Multi-Effect Evaporation Desalination Plants, Desalination, 311, 1-15.

Somayyeh S, Ramin H.K., Mohammad A, 2017, Multi Objective Optimisation of the MED-TVC System with Exergetic and Heat Transfer Analysis, Energy Equipment and Systems, 5(4), 419-430.

Yang S.R., Xu Z.M., 1995, Fouling and countermeasures of heat exchange equipment, Science Press, Beijing, China.