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# DOE Method for Optimizing Desalination Systems

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## 1. Introduction

Fresh water production is one of the main concerns in the new century. Population grows fast and potable water resources are decreased. In the other hand energy crises would also be another issue that must be well addressed by the politicians and also scientists. Developing desalination plant with using renewable energy (particularly solar energy) is one of the important options to overcome these concerns. Thus many researchers have been working on different desalination plants to find the best conditions and to realize the most efficient performances for different cycles. Different approaches have been used to achieve the most efficient conditions or to find the optimum operation and design conditions. Some of the researchers used parametric study approach while many other adopted different conventional optimization algorithms for these tasks. The algorithms such as gradient based algorithm, genetic algorithm, search and pattern algorithm and neural network method have been used in the field of desalination. For instance; Ophir and Lokiec (2005) described the design principles of a MED plant and various energy considerations that result in an economical MED process and plant. Kamali and Mohebbinia (2007) showed that parametric study as one of the optimization methods on thermo-hydraulic data strongly helps to increase GOR value inside MED-TVC systems. Shamel and Chung (2006) used parametric study to find the optimum condition of a Reverse Osmosis (RO) system for sea water desalination. Metaiche et al (2008) developed optimization software, Desaltop, for RO system for water desalination. They used genetic algorithm to find suitable operating parameters and also to find appropriate type of membrane. Al-Shayji (1998) used neural network method for optimization of large-scale commercial desalination plants. Djebedjian et al. (2008) used genetic algorithm for optimization of a reverse osmosis desalination system. Mussati et al. (2003) used an evolutionary algorithm for the optimization of Multi Stage Flash (MSF) system. Finding the optimum conditions is a major challenge on the desalination plant studies. The plant performance depends on several different variables and constraints that need exhausting efforts to find the optimum conditions.

This chapter introduces Design of Experiment (DOE) method as a statistical tool for optimization of desalination systems. Thus two different desalination plants; Multi-Effect Desalination (MED) system and solar desalination using humidification–dehumidification cycle (SDHD) have been considered to show the ability of DOE method for optimizing such systems. These both desalination plants could use the low graded heating energy sources

such as solar energy. Thus it is very important to know the best thermodynamic conditions (variables) for which the desired objectives (objective functions) could be attained based on the technological and economical constraints. General perspective of effects of these thermodynamic conditions at different points of the plant on the rate of fresh water production and also the quantity and quality of heating energy sources would be very important and very useful for a plant designer. DOE method could show the optimal thermodynamic conditions of these systems.

Thus, first DOE method is briefly presented and then this method is adopted to investigate the MED plant and a solar desalination using humidification-dehumidification system.

## 2. Principles of Design of Experiments

Design of Experiment (DOE) is a statistical approach that could clearly show how much several parameters of a system as well as their interactions are important on the plant output and how these parameters could affect the objective function. DOE Method is capable to investigate simultaneously the effects of multiple parameters on an output variable (response). To illustrate statistically reasonable conclusions from the experiment, it is necessary to integrate an efficient statistical method into the methodology of experimental design. In the context of DOE in designing, one may encounter two types of plant variables or factors: qualitative and quantitative factors. For quantitative factors, the range of settings must be decided by designer. For instance, pressure, temperature or heat transfer surface are examples of quantitative factors. Qualitative factors are discrete in nature. For example, types of materials, nature of heating source, and types of equipments are examples of qualitative factors. A factor may take different levels, depending on the character of the factor- quantitative or qualitative. In general, compared to a quantitative factor, more levels are required by a qualitative factor. "Level" in this chapter refers to a specified value or setting of the factor that would be examined in the plant experiment. For instance, if the experiment is to be performed at three different pressures or using three different types of preheaters, then it could be said pressure or preheater has three levels. Three fundamental approaches on experimental design are replication, blocking, and randomization. The first two help to increase precision in the experiment; the last one is used to reduce bias. These three principles of experimental design can be used by industrial designer to improve the efficiency and performance of a product (see Behzadmehr et al. 2006a, 2006b). In addition these principles of experimental design are applied to decrease or even remove experimental bias. It should be mentioned that the large experimental bias could result in wrong optimal conditions or sometimes it could mask the effect of the really significant factors. This could cost lost of a primary factor for plant improvement.

Details and mathematical concepts of DOE are out of this chapter objective. The interested reader would find complete description of this method in the relevant text books such as Antony (2003) or book by Montgomery (2001).

## 3. Case I) Thermodynamic optimization of MED plant using DOE method

The multi-effect desalination (MED) plant is one of the most efficient thermal desalination processes currently in use. Development of MED in the last few years has brought this process to the point of competing economically and technically with the multi-stage flashing (MSF) process. MED process is based on the pressure reduction of water in each effect.

Many researchers have studied this process. Among them Sharmmiri and Safar (1999) discussed the general aspects of some commercial MED plants and also some of their specifications such as type of plant configuration, gain output ratio, number of effects, operating temperature and the construction material for the evaporator, condenser and preheaters. Ophir and Lokiec (2005) described the design principles of a MED plant and various energy considerations that result an economical MED process and plant. They also provided an overview of various cases of waste heat utilization, and cogeneration MED plants operating. Aybar (2004) considered a multi effect desalination system using waste heat of a power plant as energy source. A simple thermodynamic analysis of the system was performed with using energy and mass balance equations. Khademi et al. (2009) focused on the development of a steady-state model for the multi-effect evaporator desalination system. Hatzikioseyan et al. (2003) reviewed and developed a simulation program based on design parameters of the plant. They used mass and energy balance through each effect of the MED unit to predict the performance of the unit in terms of energy requirements. Kamali and Mohebbinia (2007) showed that parametric study as one of the optimization methods on thermo-hydraulic data strongly helps to increase GOR value inside MED-TVC systems. El-Nashar (2000) simulated part-load performance of small vertically stacked MED plants of the HTTF type using hot water as source of energy. Their model was validated with the experimental data obtained from an existing plant in operation. Narmine and El-Fiqi (2003) described a steady state mathematical model to analyze both multi-stage and multi-effect desalination systems. Relationships among the parameters which controlling the cost of fresh water production to the other operating and design parameters were presented. Parameters include plant performance ratio (PR), specific flow rate of brine, top brine temperature, and specific heat transfer area.

Here as an example the sensitivity of some important parameters on the minimum and maximum distilled water production is analyzed. Therefore the effects of feed water flow rate and its temperature, the number of effects, preheater temperature difference (performance of each preheater), and minimum pressure (at the end stage) are studied. Thus the mass, energy and salinity balance equations are solved for each effect to calculate temperature, pressure salinity of brine, enthalpies of outlet at each effect and mass flow rate of distilled water. For thermodynamic analysis and plant optimization, design of experiment method (DOE) is used to find the effective parameters on the minimum and maximum fresh water production.

### 3.1 Plant description

The multi effect desalination is an important process that has been used for desalination particularly in large scale plants. This method reduces considerably the production cost (Ophir and Lokiec 2005). The main parts of MED plant are: 1-Condenser, 2-Evaporator, 3-Collector (thermal source) and 4-Preheaters (heat exchanger). Each effect except the last one includes a preheater and an evaporator. The hot water circulates between the top effect evaporator and solar collector to supply thermal energy to the evaporator in the form of hot water flowing through the tube bundle of the first effect. The preheated sea water is sprayed on the tube bundle of first evaporator and vapour is generated. In the other effects, vapour is generated by both boiling and flashing processes. Pressure reduces on each effect to produce more vapours. Figure 1 shows a vertical configuration of MED plant.

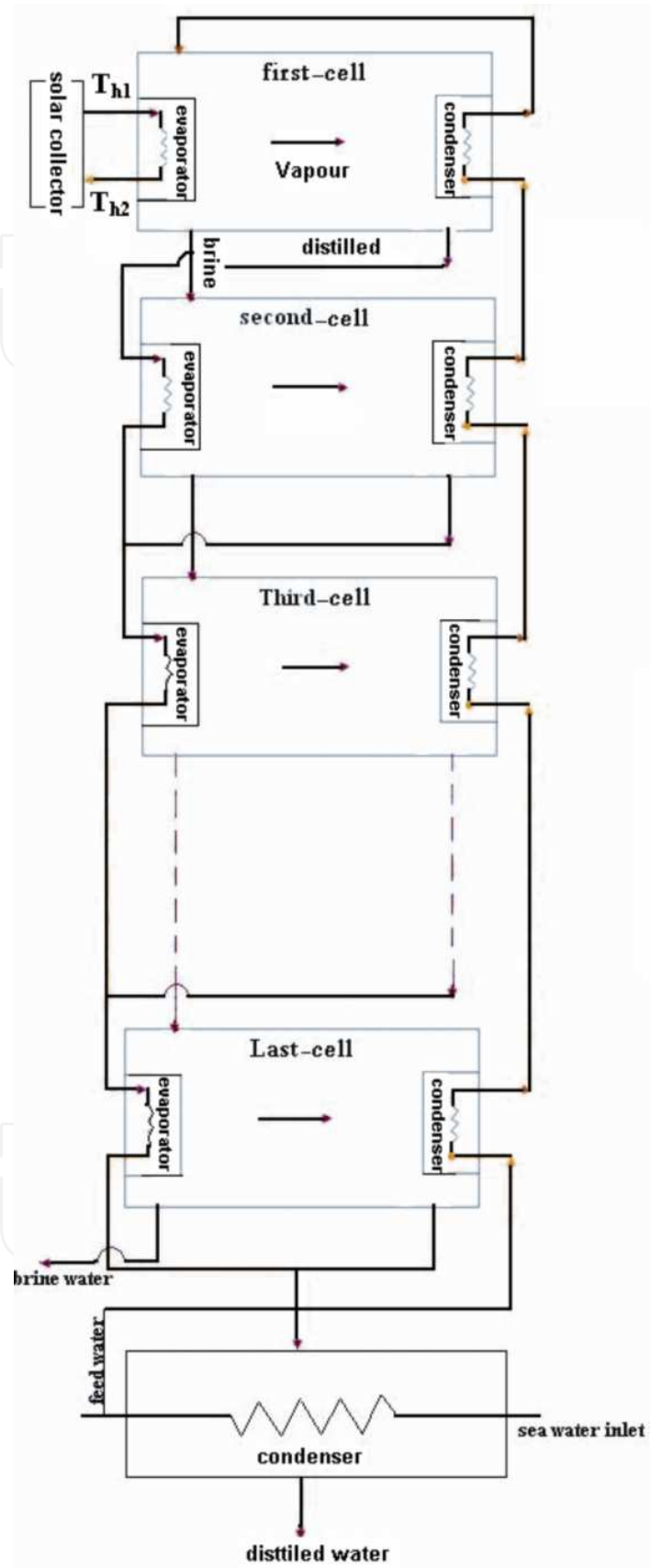


Fig. 1. Schematic diagram of MED plant

### 3.2 Mathematical modeling

A schematic of main multi effect desalination plant's parts is shown in Fig. 2. As seen in Fig. 2a the mass, energy and salinity balance equations for evaporator at the first effect (top effect) are as follow:

Mass balance equation:

$$\dot{m}_f = \dot{m}_b(1) + \dot{m}_v(1) \quad (1)$$

Balance of salinity:

$$\dot{m}_f X_{sw} = \dot{m}_b(1) X_b(1) \quad (2)$$

Balance of energy:

$$\dot{Q} + \dot{m}_f h_{fo}(1) = \dot{m}_b(1) h_b(1) + \dot{m}_v(1) h_v(1) \quad (3)$$

It is well known that the enthalpy of brine in each effect could be considered a function of salinity and temperature while the enthalpy of saturated vapour is only a function of temperature. Thus these equations are used to find temperature and salinity relationship. As shown schematically in Fig. 2b, preheaters consider being shell and tube heat exchanger. The mass and energy balance for all preheaters are as follow:

Mass balance equation

$$\dot{m}_d(i) = \dot{m}_v(i) \quad (4)$$

Energy balance equation:

$$\dot{m}_d(i) h_d(i) + \dot{m}_f h_{fo}(i) = \dot{m}_f h_{fi}(i) + \dot{m}_v(i) h_v(i) \quad (5)$$

Figure 2c shows the evaporator of the second effect. The mass, energy and salinity balance equations for this part are:

Mass balance equation:

$$\dot{m}_b(1) = \dot{m}_b(2) + \dot{m}_v(2), \quad \dot{m}_{oe}(1) = \dot{m}_d(1) \quad (6)$$

Salinity balance equation:

$$\dot{m}_b(1) X_b(1) = \dot{m}_b(2) X_b(2) \quad (7)$$

Energy balance equation:

$$\dot{m}_b(1) h_b(1) + \dot{m}_d(1) h_d(1) = \dot{m}_b(2) h_b(2) + \dot{m}_v(2) h_v(2) + \dot{m}_{oe}(2) h_{oe}(2) \quad (8)$$

Energy balance equation:

$$\dot{m}_b(1) h_b(1) + \dot{m}_d(1) h_d(1) = \dot{m}_b(2) h_b(2) + \dot{m}_v(2) h_v(2) + \dot{m}_{oe}(2) h_{oe}(2) \quad (8)$$

Other evaporators are fed from both outlet of the previous evaporator and from the exit of distilled water side (mixture of vapour and condensed water) of the previous preheater. This is shown in Fig. 2d. The balance equations can be written as follows:

Mass balance equation:

$$\dot{m}_b(i-1) = \dot{m}_b(i) + \dot{m}_v(i) \text{ , } \dot{m}_{oe}(i) = \dot{m}_{ie}(i) \tag{9}$$

Balance of salinity:

$$\dot{m}_b(i-1)X_b(i-1) = \dot{m}_b(i)X_b(i) \tag{10}$$

Balance of energy equation:

$$\dot{m}_b(i-1)h_b(i-1) + \dot{m}_{ie}(i)h_{ie}(i) = \dot{m}_b(i)h_b(i) + \dot{m}_v(i)h_v(i) + \dot{m}_{oe}(i)h_{oe}(i) \tag{11}$$

Where:

$$\dot{m}_{ie}(i) = \dot{m}_{oe}(i-1) + \dot{m}_d(i-1) \text{ , } i = 3,4,\dots,n \tag{12}$$

$$h_{ie}(i) = \frac{\dot{m}_{oe}(i-1)h_{oe}(i-1) + \dot{m}_d(i-1)h_d(i-1)}{\dot{m}_{oe}(i-1) + \dot{m}_d(i-1)} \text{ , } i = 3,4,\dots,n \tag{13}$$

The last effect of MED plant just includes a condenser (see Fig. 2e).

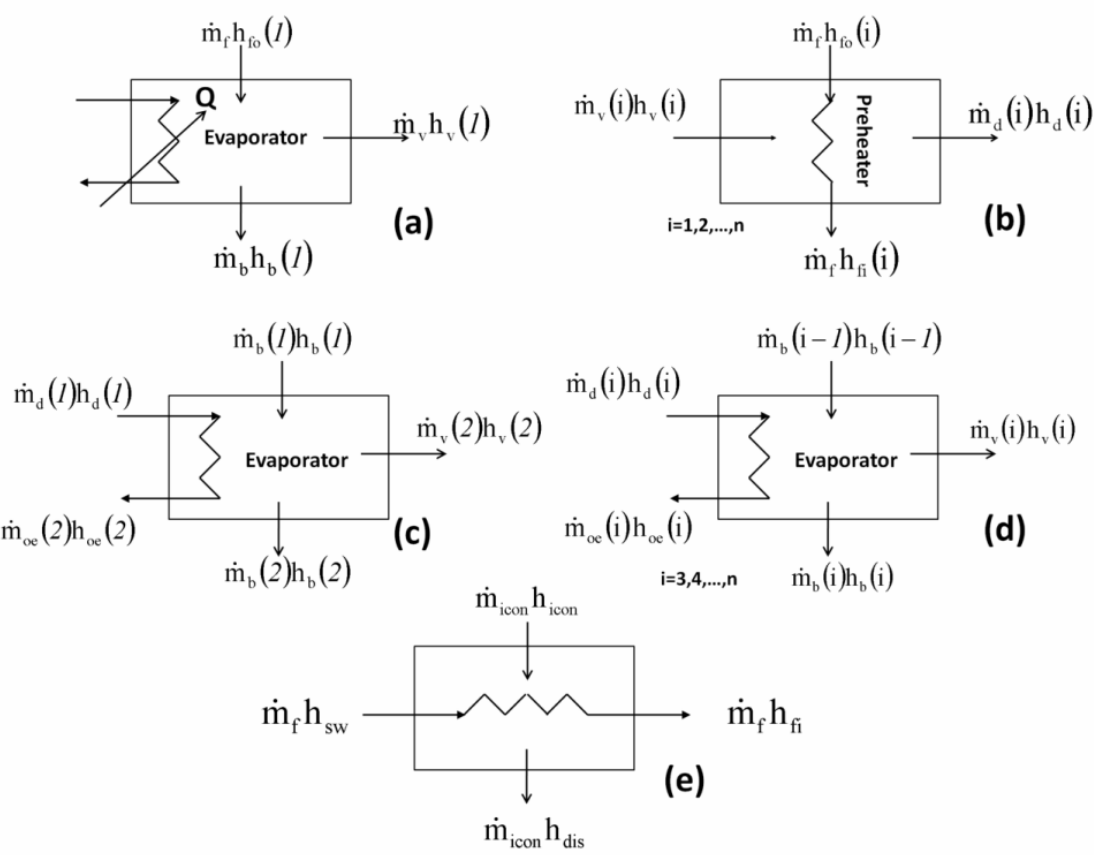


Fig. 2. Control volume of MED parts

The mass and energy balance in this stage are:

Mass balance equation:



$$\dot{m}_{icon} = \dot{m}_{dis} \tag{14}$$

Energy balance equation:

$$\dot{m}_{icon} h_{icon} + \dot{m}_{sw} h_{sw} = \dot{m}_f h_{fi}(n) + \dot{m}_{dis} h_{dis} \tag{15}$$

Where:

$$\dot{m}_{icon} = \dot{m}_{oe}(n) + \dot{m}_d(n) \tag{16}$$

$$h_{icon} = \frac{\dot{m}_{oe}(n)h_{oe}(n) + \dot{m}_d(n)h_d(n)}{\dot{m}_{oe}(n) + \dot{m}_d(n)} \tag{17}$$

The equations (1)-(17) are simultaneously solved to predict the thermodynamic properties of water and steam (temperature, pressure, enthalpy and salinity) at each part. The thermodynamic properties of distilled water, water vapour and brine are calculated for known parameters and  $P_{out}$  in the simulation code. Since these parameters have been specified in the simulation code, the input heating energy ( $\dot{Q}$ ) must be limited to a particular range based on these parameters in order to achieve the balanced thermodynamic conditions at all parts of MED plant. Therefore for given input parameters minimum and maximum values for the heating energy is calculated for which equations (1)-(17) would be thermodynamically balanced with real physical conditions. More details of numerical procedure and validation could be found in the work by Kazemian et al. (2010).

3.3 Results and discussions

The effects of different parameters such as feed water flow rate, temperature of feed water, number of effects, temperature difference of preheaters and output pressure on the rate of fresh water production have been studied. Therefore to be more efficient the test conditions are design based on the method of design of experiment (DOE). DOE is performed on k parameters at two or more than two levels to understand their direct effects and also their interactions on the desired responses (Montgomery 2001). First a  $2^k$  factorial design is chosen to construct the tests table. Five parameters are selected to study their effects on the minimum and maximum distilled water. These parameters are: feed water flow rate (A), temperature of feed water (B), number of effects (C), temperature difference of preheater (D) and output pressure (E).

Factors	Parameters	Level 1	Level 2	Level 3
A	Feed water ( kg / s )	30	60	90
B	Temperature of seawater (°C)	25	30	32.5
C	Number of effects	12	15	18
D	Temperature difference of each pre-heater (°C)	1	3	5
E	Out-put pressure (MPa)	0.003	.004	0.005

Table 1. Parameters and their three levels value for  $3^k$  factorial model of minimum distillate



Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	2076.82	20	103.841	846.4712	< 0.0001	Significant
A- $m_f$	597.2135	1	597.2135	4868.251	< 0.0001	Significant
B- $T_{sw}$	3.868855	1	3.868855	31.5374	0.0002	Significant
C-n	549.1412	1	549.1412	4476.385	< 0.0001	Significant
D- $\Delta T_{pr}$	539.6624	1	539.6624	4399.118	< 0.0001	Significant
E- $P_{out}$	42.44459	1	42.44459	345.9918	< 0.0001	Significant
AB	0.617234	1	0.617234	5.031455	0.0464	Significant
AC	87.78436	1	87.78436	715.5839	< 0.0001	Significant
AD	86.38329	1	86.38329	704.1629	< 0.0001	Significant
AE	6.796065	1	6.796065	55.39888	< 0.0001	Significant
BC	1.162114	1	1.162114	9.473101	0.0105	Significant
BD	0.561878	1	0.561878	4.580208	0.0556	Non significant
BE	4.281921	1	4.281921	34.90455	0.0001	Significant
CD	126.191	1	126.191	1028.66	< 0.0001	Significant
CE	5.539345	1	5.539345	45.15458	< 0.0001	Significant
DE	1.563831	1	1.563831	12.74774	0.0044	Significant
ABE	0.684065	1	0.684065	5.576231	0.0377	Significant
ACD	20.19142	1	20.19142	164.5926	< 0.0001	Significant
ACE	0.884603	1	0.884603	7.210942	0.0212	Significant
BCD	0.431494	1	0.431494	3.517369	0.0875	Non significant
BDE	1.416334	1	1.416334	11.5454	0.0060	Significant

Table 2. analysis variance of  $3^k$  factorial model for minimum distillate

A  $2^k$  factorial with two levels for the minimum distilled water has been performed to see if there are any non significant parameters. It should be mentioned that the signification of the parameters are quantified by the p-value, a p-value less than 0.05 indicates significance (Montgomery 2001) and are specified as significant parameter. The results show that the effects of these parameters on the minimum distilled water are significant (see Fig. 3).

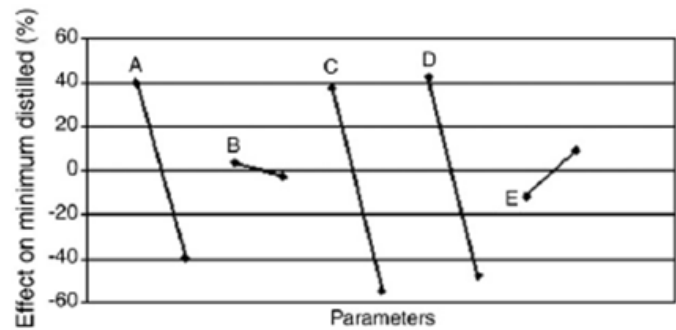


Fig. 3. Response of first DOE for minimum distilled water

Thus in order to have more accuracy a new DOE with three levels is performed to study the effects of these parameters on the minimum distilled water a  $3^k$  factorial test table is designed which is shown in table 1.

Therefore 243 ( $3^5$ ) tests have been executed to find the response of the objective function (minimum distilled water) on the variations of these parameters. Analysis variance of the  $3^k$  factorial tests is shown in table 2. Then a regression has been performed on the results of factorial to show and also to predict the effects of these parameters on the minimum water distilled. Equation (19) is the regression function estimated from DOE analysis of minimum amount of distilled water.

$$\begin{aligned} \sqrt{(\dot{m}_d)_{\min}} = & -11.01593 - 0.023307 m_f + 0.35466 T_{sw} + 0.014194 n + 2.64044 \Delta T_{pr} \\ & + 3042.42454 P_{out} + 1.73109 \times 10^{-3} m_f \times T_{sw} - 1.177766 \times 10^{-3} m_f \times n \\ & + 1.39631 \times 10^{-4} m_f \times \Delta T_{pr} + 6.08346 m_f \times P_{out} + 3.14011 \times 10^{-3} T_{sw} \times n \\ & - 0.090929 T_{sw} \times \Delta T_{pr} - 95.27274 T_{sw} \times P_{out} + 0.049661 n \times \Delta T_{pr} - 26.34805 n \times P_{out} \\ & - 749.91251 \Delta T_{pr} \times P_{out} + 1.71863 \times 10^{-5} m_f \times T_{sw} \times n - 1.19483 \times 10^{-4} m_f \times T_{sw} \times \Delta T_{pr} \\ & - 0.34827 m_f \times T_{sw} \times P_{out} + 5.14699 \times 10^{-4} m_f \times n \times \Delta T_{pr} + 0.28864 m_f \times \Delta T_{pr} \times P_{out} \\ & + 0.19816 m_f \times n \times P_{out} - 9.56007 \times 10^{-4} T_{sw} \times n \times \Delta T_{pr} + 0.18593 T_{sw} \times n \times P_{out} \\ & + 24.71972 T_{sw} \times \Delta T_{pr} \times P_{out} + 1.57852 n \times \Delta T_{pr} \times P_{out} \end{aligned} \tag{19}$$

For given values of the parameters the prediction contours of minimum water distilled can be plotted by this equation. In order to see the precision of the predicted results by these contours, comparisons are done with the results obtained directly from the simulation code. As seen in table 3, within the range of performed tests, these results are very close while out of the range of executed tests the concordance between the results is acceptable (6.59%).

	Prediction	Actual	Error%
In the range	8.958	8.896	0.69
Out of the range	34.398	36.8249	6.59

Table 3. Predicted error for the minimum distilled water

The same approach is also adopted for the maximum distilled water. The results of  $2^k$  factorial tests for the maximum amount of distilled water shows that the effect of parameter B ( $T_{sw}$ ) on the maximum amount of distilled water is negligible (see in Fig. 4). Thus another tests routine with factorial is performed. The parameters and their levels (three for each) are shown in table 4. The tests table for analysis of variance of maximum amount of distilled water consists of 81 tests ( $3^4$ ) which is presented in table 5.

Factors	Parameters	Level 1	Level 2	Level 3
A	Feed water (kg/s)	30	50	70
B	Number of effects	12	15	18
C	Temperature difference of each pre-heater (°C)	2	3	4
D	Output pressure (MPa)	0.003	.0045	0.006

Table 4. Parameters and their three levels value for  $3^k$  factorial model of maximum distillate

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	4974.632	11	452.2393	3444.212	< 0.0001	significant
A-mf	2447.064	1	2447.064	18636.61	< 0.0001	Significant
B-n	661.6533	1	661.6533	5039.089	< 0.0001	Significant
C-deltpr	1583.357	1	1583.357	12058.69	< 0.0001	Significant
D-Pout	0.278922	1	0.278922	2.124243	0.1495	Non- significant
AB	70.48853	1	70.48853	536.834	< 0.0001	Significant
AC	168.8939	1	168.8939	1286.28	< 0.0001	Significant
AD	0.03011	1	0.03011	0.229317	0.6335	Non- significant
BC	29.61552	1	29.61552	225.549	< 0.0001	Significant
CD	9.119239	1	9.119239	69.45126	< 0.0001	Significant
ABC	3.161682	1	3.161682	24.07907	< 0.0001	Significant
ACD	0.970699	1	0.970699	7.392755	0.0083	Significant

Table 5. analysis variance of 3<sup>k</sup> factorial model for maximum distilled water

The estimated function resulted from DOE analysis for maximum distilled water is as follow:

$$\begin{aligned}(\dot{m}_d)_{\max} = & -9.98114 \times 10^{-3} + 0.02892 m_f + 1.11264 \times 10^{-3} n + 3.24331 \times 10^{-4} \Delta T_{pr} \\ & - 0.7575 P_{out} + 5.17374 \times 10^{-3} m_f \times n - 0.012606 m_f \times \Delta T_{pr} \\ & - 21.07516 m_f \times P_{out} - 1.28832 \times 10^{-4} T_{sw} \times n + 0.34856 \Delta T_{pr} \times P_{out} \\ & + 6.04926 \times 10^{-3} m_f \times n \times \Delta T_{pr} + 6.70371 m_f \times \Delta T_{pr} \times P_{out}\end{aligned}\tag{20}$$

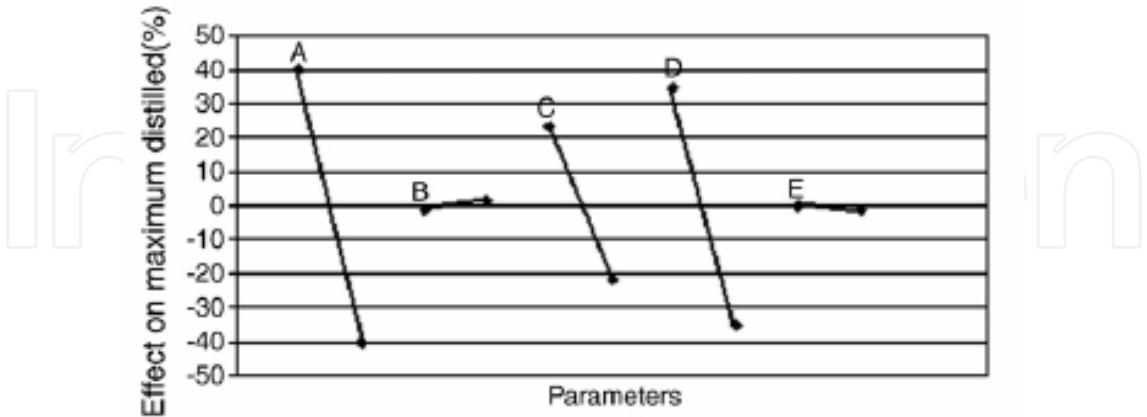


Fig. 4. Response of first DOE for maximum distilled water

To show the precision of this equation comparisons are done with the direct results of the simulation code. As seen in table 6 within the range of performed tests, the results are very close while at the out of range the concordance between the results is acceptable (4.33%).

Error%	actual	Prediction	
1.27	13.5522	13.724	In the range
4.33	44.9896	43.0413	Out of the range

Table 6. Predicted error for maximum distilled water

Thus at this step the contours for prediction of minimum and maximum distilled water could be presented and discussed.

As mentioned the regression functions are obtained by using the responses of the parameters on the objective function. These functions are composed of the effective parameters and their interactions. The contours of responses on each parameter could be plotted using these equations. These contours are an excellent tools to show the effect of each parameter rather than calculating by the simulation code.

Several contours are shown in Figs 5-10 (these results were presented by Kazemian et al. 2010). It is shown that the amount of feed water mass flow rate has a significant effect on increasing the amount of minimum distilled water. As seen in Fig. 5, for a given feed water mass flow rate, increasing the temperature of the inlet feed water slightly augments the amount of minimum distilled water.

There are two parallel phenomena to increase the amount of minimum distilled water by increasing the numbers of effects (see Fig. 6). The top brine temperature is increased by increasing the effects, so the salt concentration in the first effect is increased and more vapours is produced. On the other hand, the pressure and temperature differences of effects are decreased by increasing the effects. Therefore the salt concentration differences at each effect would be decreased and the amount of distilled water would be increased. The influence of increasing temperature difference of preheaters on the minimum distilled water production is fairly the same as the one that was seen by increasing the numbers of effects (Fig. 7).

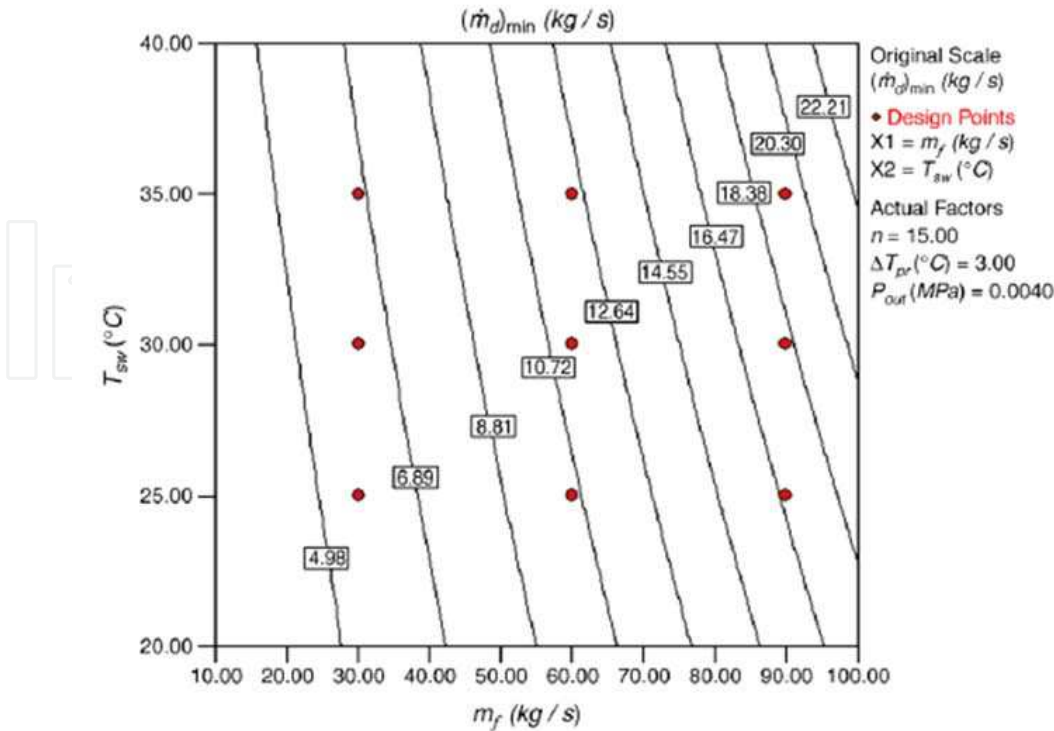


Fig. 5. Contour of minimum distilled water for N=15,  $\Delta T_{pr}$ =3°C,  $P_{out}$ =0.004MPa

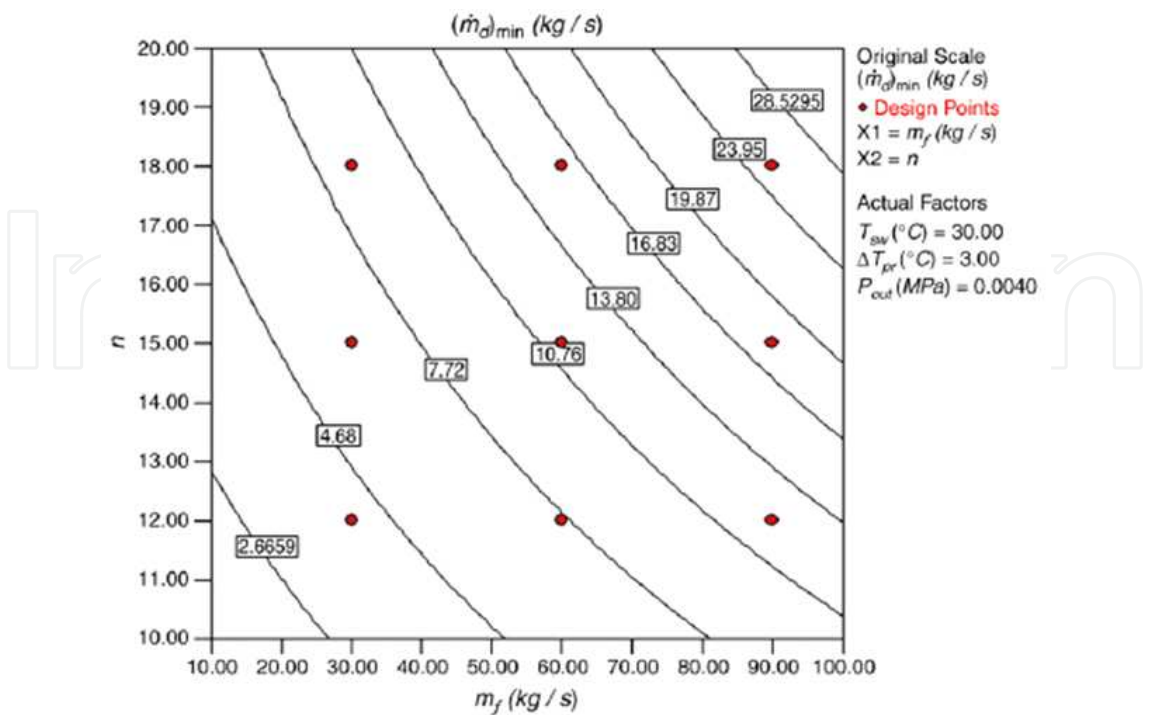


Fig. 6. Contour of minimum distilled water for  $T_{sw}=30^\circ\text{C}$ ,  $\Delta T_{pr}=3^\circ\text{C}$ ,  $P_{out}=0.004\text{MPa}$

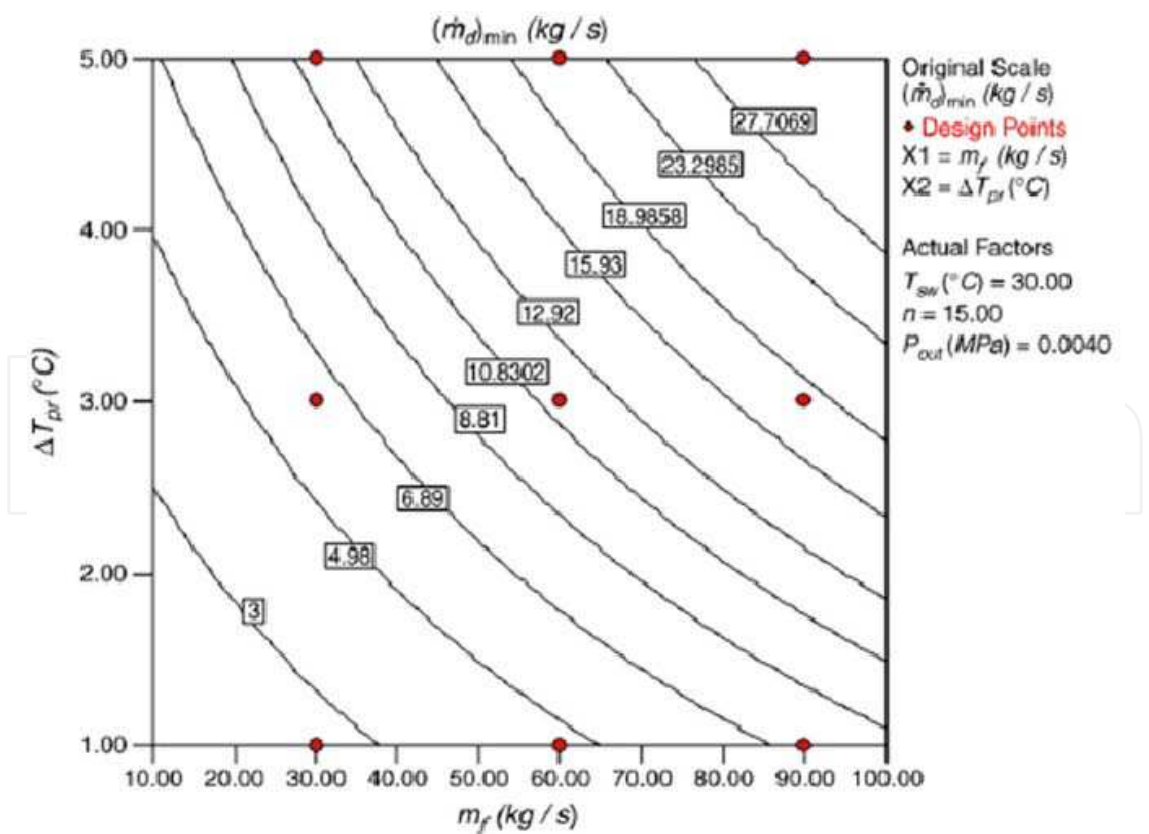


Fig. 7. Contour of minimum distilled water for  $N=15$ ,  $T_{sw}=30^\circ\text{C}$ ,  $P_{out}=0.004\text{MPa}$

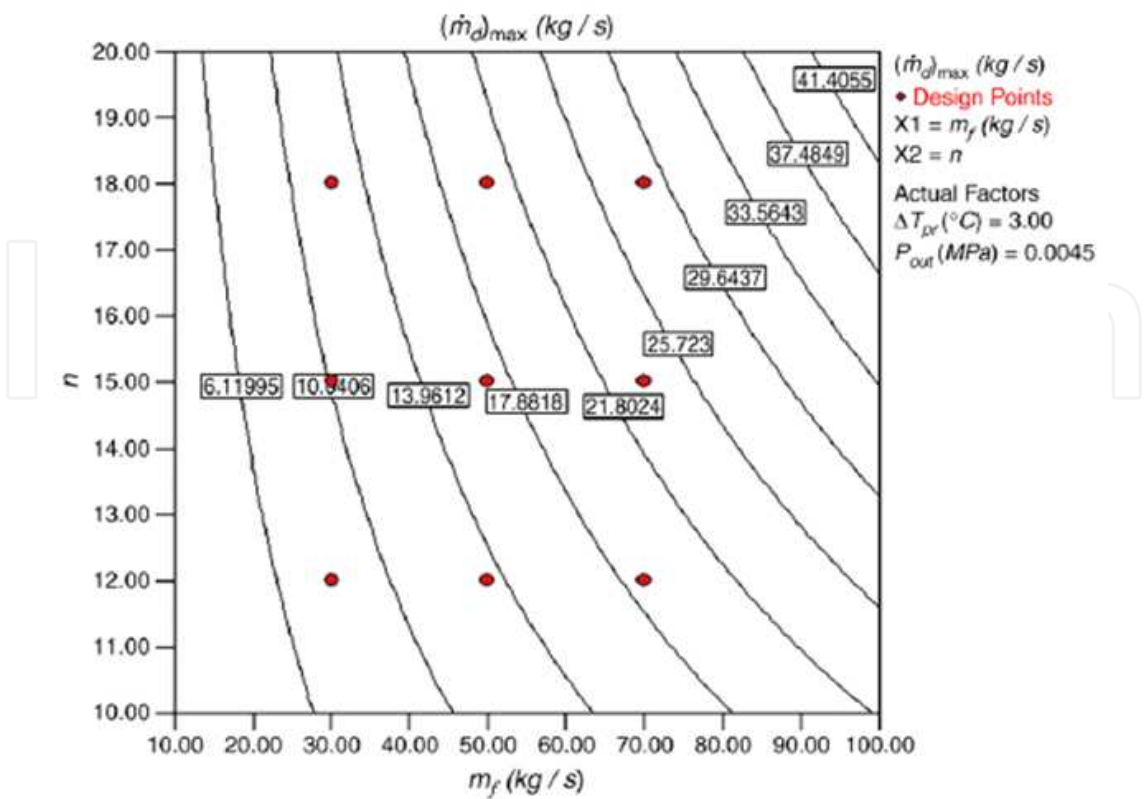


Fig. 8. Contour of maximum distilled water for  $T_{sw}=30^{\circ}C$ ,  $\Delta T_{pr}=3^{\circ}C$ ,  $P_{out}=0.004MPa$

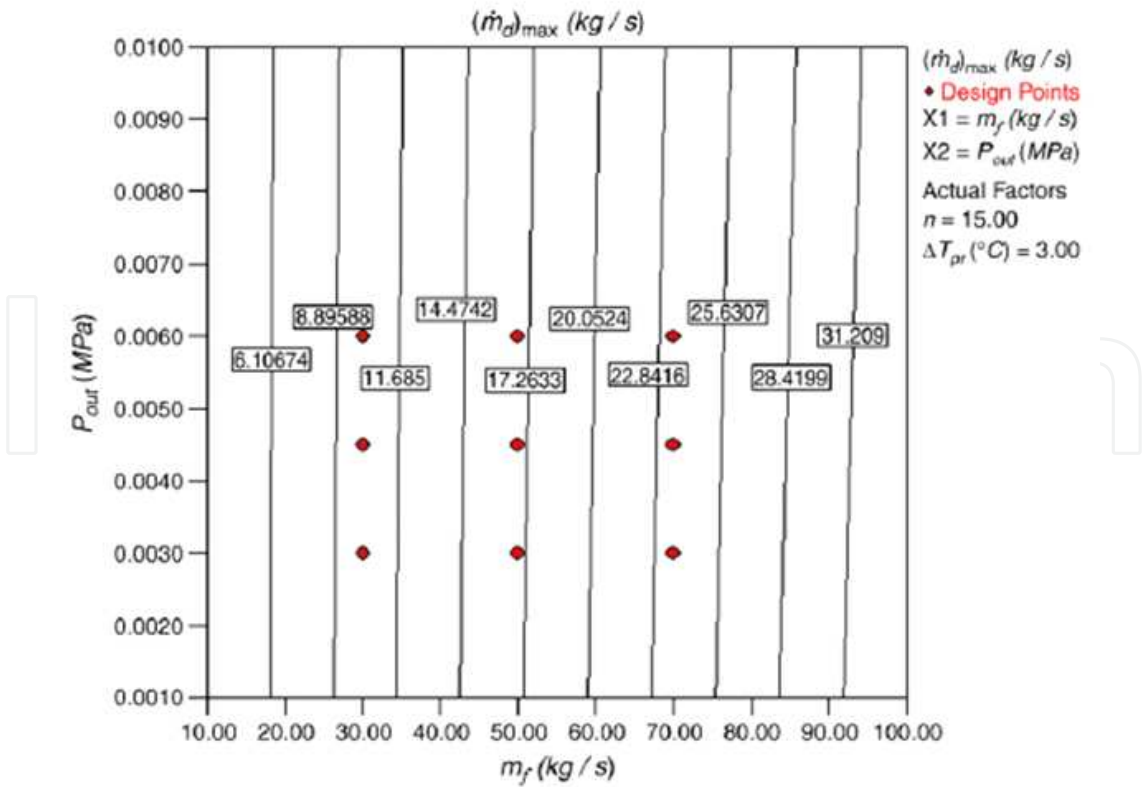


Fig. 9. Contour of maximum distilled water for  $N=15$ ,  $\Delta T_{pr}=3^{\circ}C$



In the case of maximum distilled water, the top brine temperature and also salt concentration of the first effect are increased by the numbers of effects. Consequently the amount of vapour on the first effect is augmented. Therefore it causes to enhance the amount of maximum distilled water which can be seen in Fig. 8. The temperature difference of condenser is reduced by augmenting pressure output, thus the top brine temperature is decreased and the heating energy is increased. On the other hand increasing of heating energy is restricted with the maximum distilled water. So as seen in Fig. 9 the sensitivity of pressure output on the maximum distilled water is negligible. The influence of increasing temperature difference of preheaters on the maximum distilled water is fairly similar to the one that was seen in the minimum distilled water approach (see Fig. 10).

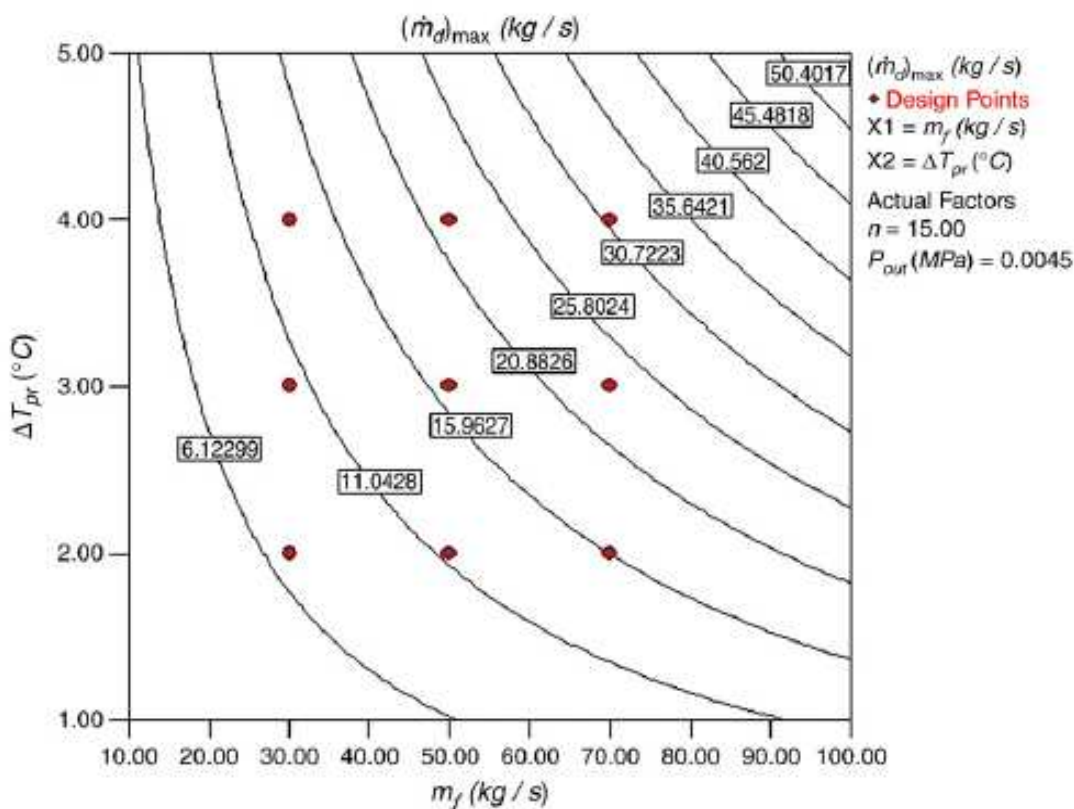


Fig. 10. Contour of maximum distilled water for  $N=15$ ,  $P_{out}=0.0045$ MPa

#### 4. Case II) Optimization of a SDHD plant using DOE method

One of the plants that potentially could supply fresh water at the humid regions (such as the Persian Gulf region) is solar desalination with using humidification-dehumidification (SDHD) process. Because of importance of this system, it is chosen to investigate using DOE method as the second case study. This process is, mainly, based on the ability of air to be saturated with water. Thus it would be very efficient at the regions for which the relative humidity of air is significant.

Many studies have been carried out on the various types of humidification-dehumidification (HD) cycle desalinations. These studies investigated different methods of increasing the production of desalinated water and on augmenting performance of the



plants. Goosen, et al. (2000) with the aid of HD process, examined some economic and thermodynamic aspects of solar desalination. Their report was based on this fact that commercial production of solar desalination is economically and efficiently advantageous. Parekh et al. (2004) carried out a comprehensive study on the background of solar desalination using humidification-dehumidification (SDHD) systems. They studied development of solar stills historically, and concluded that frequent use of the latent heat of condensation is the major factor of the development of these systems. They concluded that most of the researchers have indicated the effect of inlet air flow rate in the cycle is insignificant. However, the effect of feed water flow rate on the efficiency of a SDHD unit has been described as significant. Al Hallaj et al. (1998) undertook an experimental study on a SDHD unit. In their unit the air circulates by natural or forced convection and is humidified by the constant water obtained either from a collector (indoor type) or from an electrical heater (outdoor type). Their results in indoor and outdoor conditions showed factors of performance and daily production of desalinated water. In outdoor conditions, the results showed higher production of desalinated water compared to that of solar stills, whereas the effect of air velocity was formerly regarded only in lower performance temperatures. Nafey, et al. (2004) carried out an experimental work on SDHD process. Their plant consists of humidification and dehumidification towers, which are located next to flat-plate solar collectors (for air heating) and water concentrator (for heating water). They found that the effect of air velocity is insignificant, while great influence of inlet water and air temperatures on the production of desalinated water is observed. They predicted the fresh water production numerically. Their experimental and theoretical findings are in good agreement (Nafey, et al 2004). Multi-effect humidification-dehumidification (MEHD) is another interesting plant that was studied by Chafik. (2002), Ben Amara et al. (2004). This technique includes humidification and air heating in several stages which leads to an increase in the moisture density in air flow. Hou, et al. (2005) mentioned that in most of the previous studies concerning SDHD technology, obtaining optimal conditions of design, has been a difficult and complicated procedure. Using Pinch method, they proposed a design for optimizing the performance of SDHD process. Results show that as the temperatures of the sprayed (humidifier tower) and cooling water (in condenser) are known, there is an optimal rate of flow for the ratio of water to dry air. Recently, Farsad et al (2010) numerically investigated SDHD process. They showed that based on the conditions and desired fresh water production, condenser characteristic and humidifier characteristic has an optimum configuration (performance-economy).

This section intends to investigate the optimum condition of several parameters on the fresh water production of SDHD plant using DOE method.

#### 4.1 Plant description

The analyzed system consists of main sections including air and water solar collectors, condenser and humidifier tower. Figure 11 illustrates a schema of this system. Feed water (brackish water, turbid water, flowing water with high heaviness and seawater) flows into the condenser through point number one. Normally, the model of condenser for air-water flows is a type of extended surface heat exchanger. In this system, extended surface heat exchanger is used because heat transfer coefficient at the air side is far smaller than that of liquid side, and more heat transfer surface is needed at the air side.

Therefore, the humid air starts flowing at the air side of the vanes which are fixed on the tubes. Feed water runs through the tubes and is preheated by the recovery of condensation latent heat. Then it is heated in the solar collector and after that flows into the humidifying

tower. Humidifying tower consists of packing. Packing material is selected from wooden chips which are laid on each other separately by some distribution porous plates. Hot water stream flows into the humidifier through the top and is sprayed on the packing. Thus, the contact level of air and water is increased and heat and mass transfer between the two streams augments. Humid air at the exit of humidifier then passes through the condenser to be cold and fresh water to be distilled.

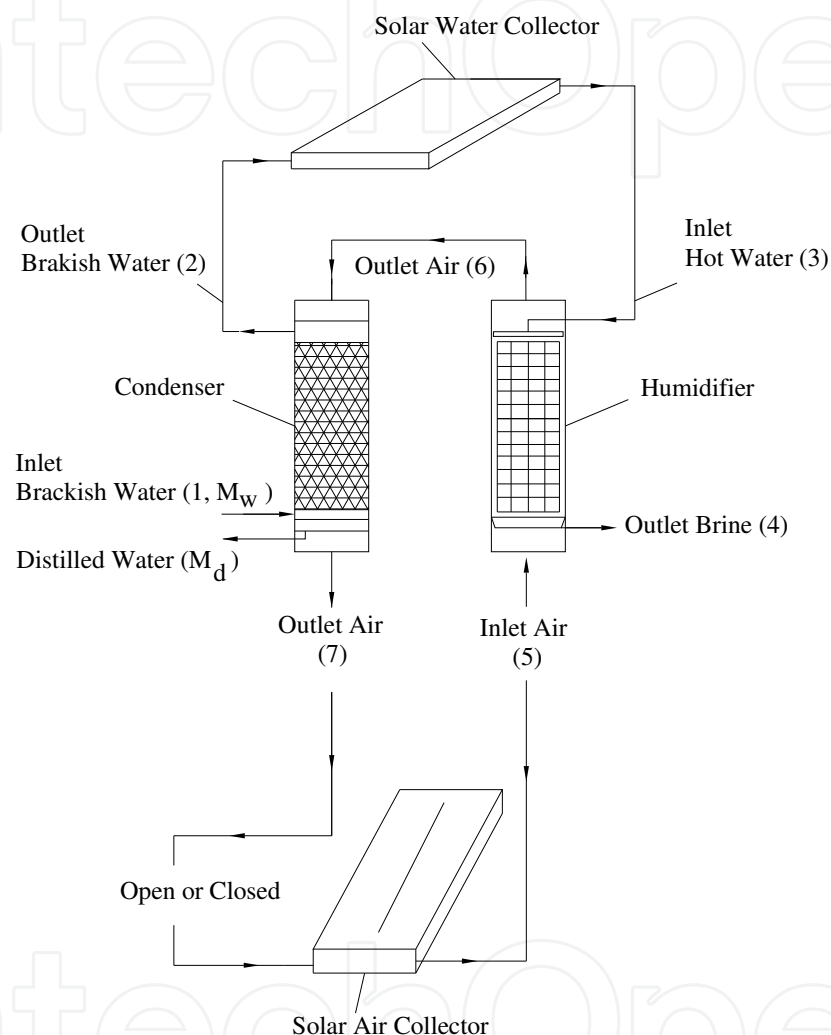


Fig. 11. Schematic of SDHD plant

#### 4.2 Mathematical formulation

(Energy and mass balance equations have been considered for all parts of the cycle. Few assumptions that believed do not have significant effect on the analysis, is considered for simplicity of calculation. These are as follows:

1. The process is assumed to be in steady state condition.
2. Heat loss is neglected.
3. Since the operating pressure is close to the atmospheric pressure air and water vapor are assumed behave as ideal gas.
4. Saturated air at the exit of humidifier and also at the exit of condenser.
5. Kinetic and potential energy changes are neglected.

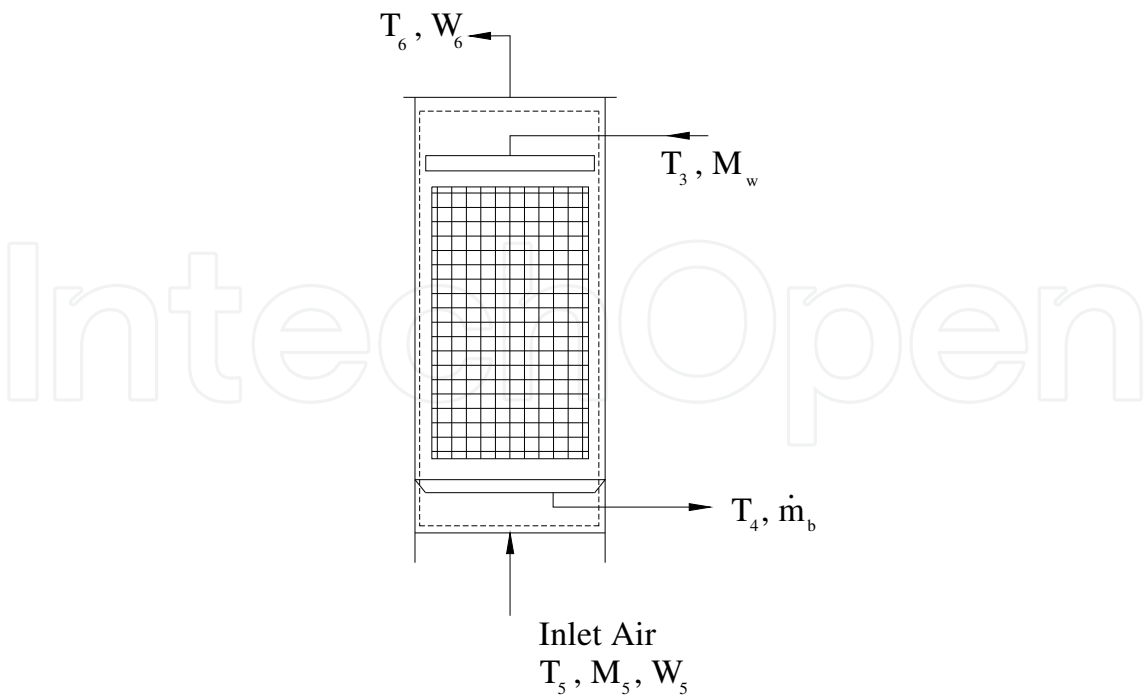


Fig. 12. Humidifier

Accordingly, mass and energy balance equations in the humidifier (Fig.12) are defined as:

$$\dot{m}_a h_{a5} + \dot{m}_{v5} h_{v5} + \dot{m}_{w3} h_{f3} = \dot{m}_a h_{a6} + \dot{m}_{v6} h_{v6} + \dot{m}_{b4} h_{f4} \tag{21}$$

$$\dot{m}_{v6} + \dot{m}_{b4} = \dot{m}_{v5} + \dot{m}_{w3} \tag{22}$$

$$M_5(h_6 - h_5) = Ka V \left[ \frac{(h_3 - h_6) - (h_4 - h_5)}{\ln \frac{h_3 - h_6}{h_4 - h_5}} \right] \tag{23}$$

In the above equation KaV, the humidifier characteristic, could be determined by the following imperial equation (Nafey et al. 2004):

$$\frac{KaV}{M_w} = 0.07 + A.N \left( \frac{M_w}{M_5} \right)^{-n} \tag{24}$$

where A and n are constant value for a kind of packing material (see Table 7). Humidity ratio is characterized as a function of atmospheric pressure, steam partial pressure and dry bulb temperature.

$$w_n = \frac{m_{vn}}{m_a} = 0.622 \frac{P_{vn}}{P - P_{vn}} \tag{25}$$

Relative humidity is also defined as follow:

$$\Phi_n = \frac{P_{vn}}{P_{gn}} \tag{26}$$

n	A	Type of Packing
0.62	0.060	A
0.62	0.070	B
0.60	0.092	C
0.58	0.119	D
0.46	0.110	E
0.51	0.100	F
0.57	0.104	G
0.47	0.127	H
0.57	0.135	I

Table 7. Constant value of n and A used in Eq.24 (Frass 1989)

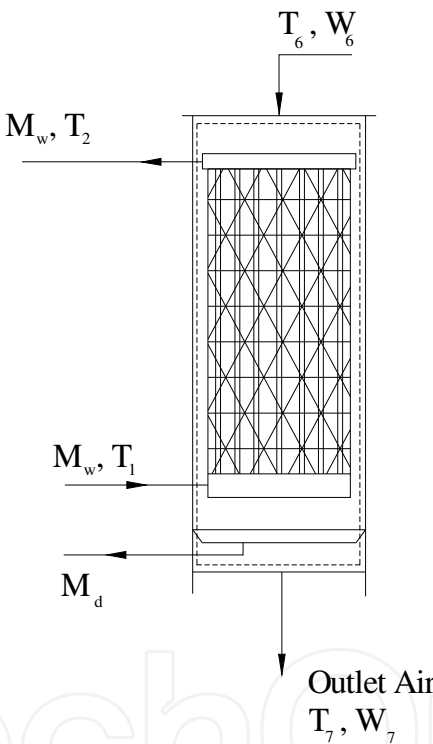


Fig. 13. Condenser (dehumidifier)

The energy and mass balance equations for the condenser which is shown in Fig. 13 are defined as:

$$\dot{m}_a h_{a6} + \dot{m}_{v6} h_{v6} + \dot{m}_{w1} h_{f1} = \dot{m}_a h_{a7} + \dot{m}_{v7} h_{v7} + \dot{m}_d h_{f7} + \dot{m}_{w2} h_{f2} \tag{27}$$

$$\dot{m}_d = \dot{m}_{v6} - \dot{m}_{v5} \quad \& \quad \dot{m}_{w1} = \dot{m}_{w2} = \dot{m}_{w3} = M_w \tag{28}$$

$$Q_c = M_w C_{pw} (T_2 - T_1) = U_{cond} A_{cond} LMTD \tag{29}$$

LMTD is condenser’s logarithmic average temperature difference which is described by:

$$LMTD = \frac{(T_6 - T_2) - (T_7 - T_1)}{\ln \frac{(T_6 - T_2)}{(T_7 - T_1)}}$$

(30)

Enthalpy and humidity ratio for saturation can be obtained from the following relationship.

$$h = 0.00585 T^3 - 0.497 T^2 + 19.87 T - 207.61$$

(31)

$$W = 2.19 T^3 (10^{-6}) - 1.85 T^2 (10^{-4}) + 7.06 T (10^{-3}) - 0.077$$

(32)

Heating input energy at the flat-plat solar collector is calculated by:

$$Q_u = F_R A_c [I \tau \alpha - U_L (T_i - T_a)]$$

(33)

These equations have been solved simultaneously to find the plant performance. Details of numerical procedure and validation could be found in the work by Farsad et al. (2010).

5. Results and discussions

The adopted mathematical formulation and numerical procedure could determine the thermodynamic properties of air and water streams throughout the cycle and fresh water production for inlet air and water conditions. Therefore air and water flow rates, temperature and, inlet relative humidity and input heating energy (solar collectors) are considered as variable to see their effects on the fresh water production. Design of experiment (DOE) is performed on k parameters at two or more than two levels to understand their direct effects and also their interactions on the desired responses. Therefore, at first a 2<sup>k</sup> factorial approach with two levels is chosen to see if there are any non significant parameters on the fresh water production. Therefore 64 (2<sup>6</sup>) tests have been executed to find the response of objective function (fresh water) on the variations of these parameters. Providing the P-value model shows that all the parameters are effective in water production and are evaluated as significant in the table. Therefore, to have more accuracy a new DOE with three levels (capturing nonlinear effects) is performed to study the effects of these parameters on the distilled water production. Therefore the parameters are written in three levels (see table 8) and 3<sup>k</sup> factorial model is designed for the tests. Thus 729 (3<sup>6</sup>) tests have been performed to see the effects of these parameters on the fresh water productions. The results from the Analysis of Variance using backward elimination regression method are displayed in table 9. Then a regression has been performed on the

Factors	Parameters	Level 1	Level 2	Level 3
A	Inlet Water Temperature (°C)	15	20	25
B	Inlet Air Temperature (°C)	5	20	35
C	Input Heat Flux (kW)	50	75	100
D	Acond Ucond (kW/°C)	8	13	18
E	Mass Flow Rate Of Water (kg/s)	0.4	0.9	1.4
F	Mass Flow Rate Of Air (kg/s)	0.4	0.8	1.2

Table 8. Parameters and their three levels value for 3<sup>k</sup> factorial model of fresh water production.

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	324.6028	27	12.02233	210.7277	0.0001	significant
A-T <sub>1</sub>	13.83002	1	13.83002	242.4131	0.0001	significant
B-T <sub>5</sub>	19.65184	1	19.65184	344.4581	0.0001	significant
C-Q	75.669	1	75.669	1326.329	0.0001	significant
D-A <sub>cond</sub> U <sub>cond</sub>	16.12721	1	16.12721	282.6782	0.0001	significant
E-M <sub>w</sub>	15.04927	1	15.04927	263.7842	0.0001	significant
F-M <sub>5</sub>	30.03497	1	30.03497	526.454	0.0001	significant
AB	0.911795	1	0.911795	15.98197	0.0004	significant
AC	2.526584	1	2.526584	44.28605	0.0001	significant
AD	0.343341	1	0.343341	6.018092	0.0206	significant
AE	1.104146	1	1.104146	19.35351	0.0001	significant
AF	5.187897	1	5.187897	90.93363	0.0001	significant
BC	0.953295	1	0.953295	16.70938	0.0003	significant
BF	11.33596	1	11.33596	198.697	0.0001	significant
CD	2.717269	1	2.717269	47.62838	0.0001	significant
CE	19.13845	1	19.13845	335.4595	0.0001	significant
DE	12.8603	1	12.8603	225.4157	0.0001	significant
EF	26.65787	1	26.65787	467.26	0.0001	significant

Table 9. Analysis of variance of 3<sup>k</sup> factorial model for fresh water production results of factorial to show and also to predict the effects of these parameters on the fresh water production. Equation (34) is the regression function estimated from DOE analysis of 3<sup>k</sup> factorial model to predict distilled water (M<sub>d</sub>).

$$\begin{aligned} \ln(M_d) = & 4.04483 - 0.098587(T_1) - (7.19727 \times 10^{-3})(T_5) + 0.019074(Q) \\ & + 0.043618(A_{cond}U_{cond}) + 1.14683(M_w) - 0.80018(M_5) + (1.11087 \times 10^{-3})(T_1 \times T_5) \\ & + (9.40156 \times 10^{-4})(T_1 \times Q) + 0.031299(T_1 \times M_w) - 0.083390(T_1 \times M_5) \\ & - (2.97633 \times 10^{-4})(T_5 \times Q) - (4.84324 \times 10^{-3})(T_5 \times M_w) + 0.031011(T_5 \times M_5) \\ & + (8.14539 \times 10^{-3})(Q \times M_w) + (6.66603 \times 10^{-3})(Q \times M_5) \\ & + 0.045739(A_{cond}U_{cond} \times M_w) + 1.70131(M_w \times M_5) - (1.79173 \times 10^{-4})Q^2 \\ & - (2.09743 \times 10^{-3})(A_{cond}U_{cond})^2 - 2.06950(M_w)^2 - 0.68742(M_5)^2 \end{aligned} \tag{34}$$

For given values of the parameters the prediction contours of water production can be plotted by using this equation. In order to see the precision of the predicted results by these contours, comparisons have been done with the results obtained directly from the simulation code. As seen in table 10, within the range of performed tests, these results are

very close while out of the range of executed tests the concordance between the results is acceptable (8.78%).

	Response	Prediction	Actual	Error %
Within the range	$M_d(\text{kg/s})$	98.9881	101.9117	2.87
Out of the range	$M_d(\text{kg/s})$	91.9274	100.77	8.78

Table 10. Error of predicted fresh water production by the regression equation.

As mentioned the regression functions are obtained by using the responses of the parameters on the objective function (fresh water production). These functions are composed of the effective parameters and their interactions. These contours are an excellent tool to show the effect of each parameter simultaneously rather than calculating one by one by the simulation code.

To show this ability, for instance, Figs. 14-17 present the effects of some of the parameters on the fresh water production. Fig. 14 presents the effect of inlet air and water temperature on the fresh water production for give conditions ( $Q, M_w, M_5, A_{\text{cond}}U_{\text{cond}}$ ). It shows that with decreasing the inlet water temperature and increasing the air inlet temperature distilled water production enhances. The effects of inlet water temperature and total heat flux on the fresh water production is shown in Fig.15. As shown decreasing the inlet water temperature reduces the necessary input energy. Interesting information is found in Fig.16; the effects of water inlet temperature and water mass flow rate on the distilled water production. As seen, for given conditions there are two different inlet water temperatures that could produce similar fresh water production (because of its different effects on the humidifier and

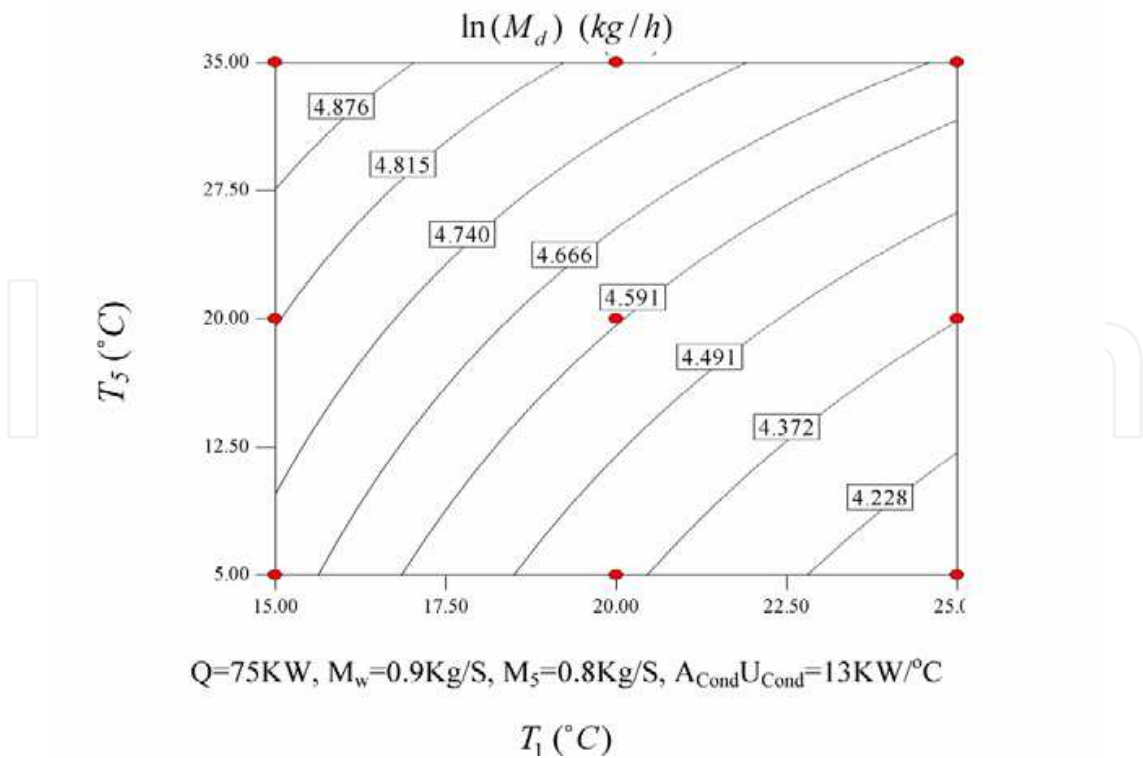


Fig. 14. Contour of variation of inlet air and water temperatures on the fresh water production.



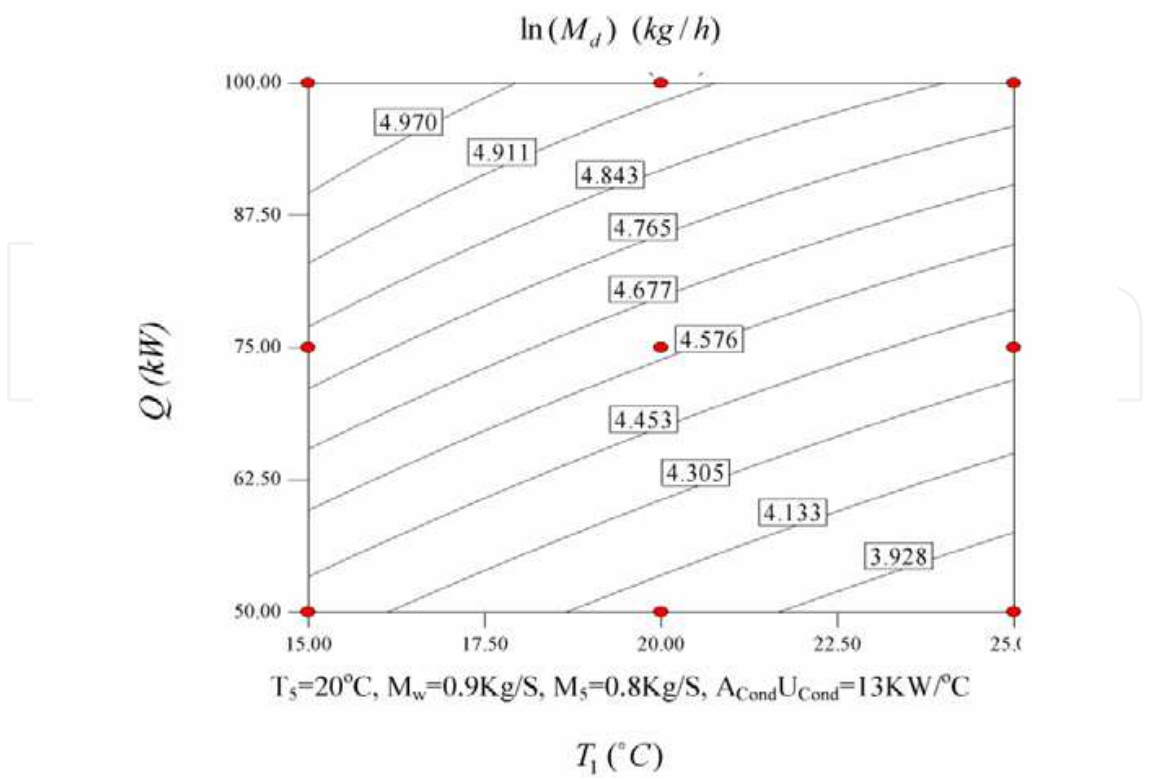


Fig. 15. Contour of feed water temperature and the given total heat flux of the cycle on the fresh water production.

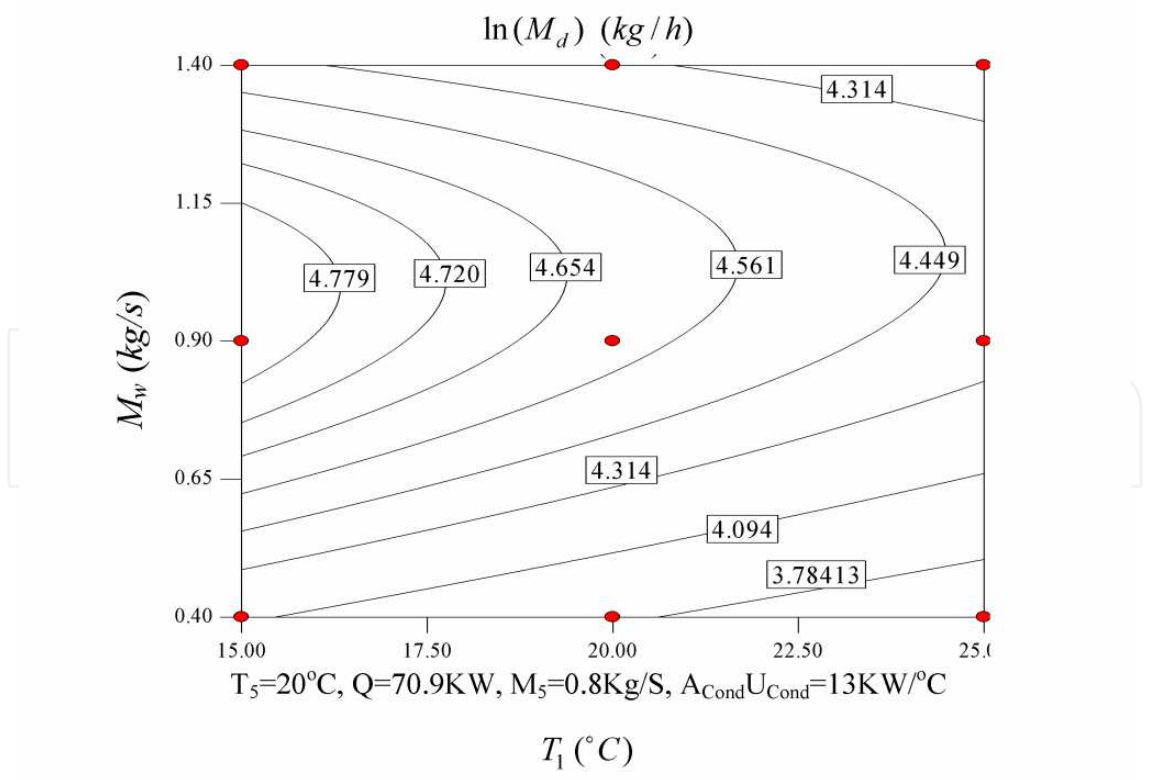


Fig. 16. Contour of the inlet water temperature and its mass flow rate on the fresh water production.

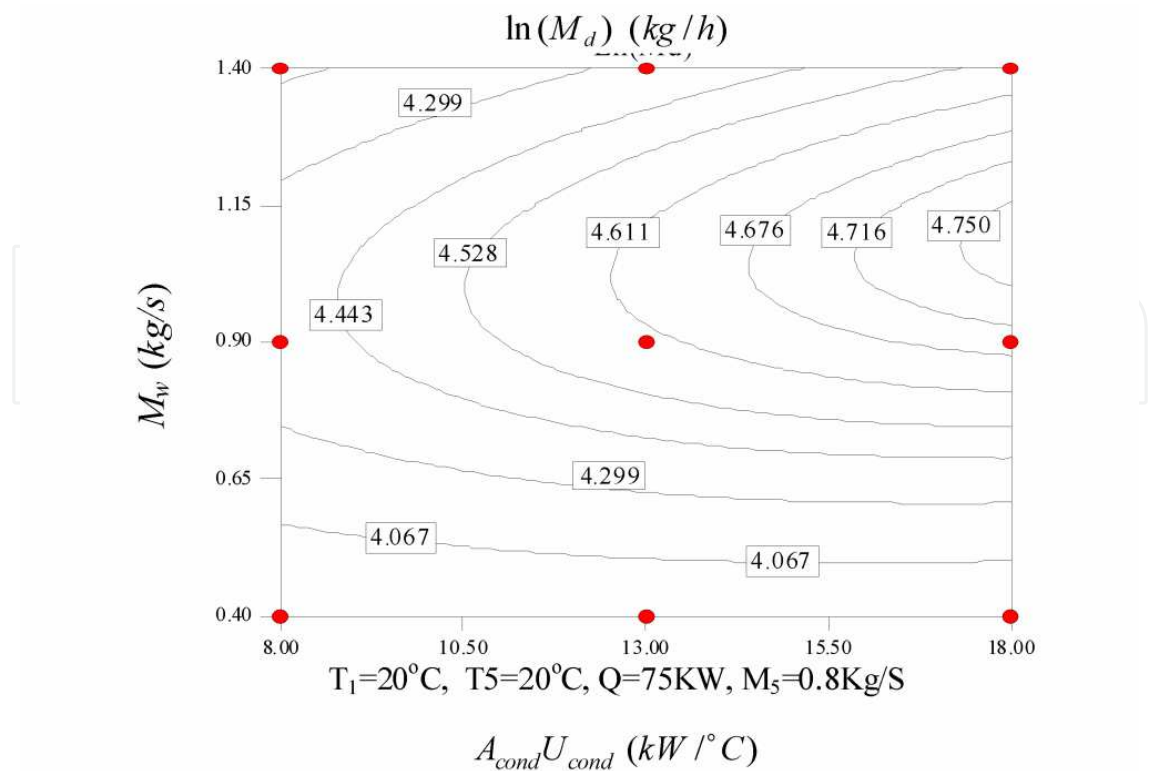


Fig. 17. Contour of condenser characteristic parameter and the feed water flow rate on the fresh water production.

condenser). Another contour that could show the effect of condenser’s design parameter on the fresh water production is presented in Fig.17. As shown there are different condenser characteristic that could produce particular distilled water.

6. Conclusion

This chapter introduces Design of Experiment (DOE) method as a statistical tool for optimization of desalination systems. Two different desalination plants; Multi-Effect Desalination system and solar desalination using humidification–dehumidification cycle have been numerically investigated to show the ability of DOE method for optimizing such systems. Thus several different contours that could help a designer to achieve the best thermodynamic conditions in these systems are presented and discussed. It is shown that DOE method is capable to well determine the optimum conditions for such systems.

Nomenclature:

$A_c$	Solar collector area	$n$	Number of effect	$b$	Brine
$A_{cond}$	Condenser heat transfer area	$P$	Pressure	$con$	Condenser
$a$	Area per volume of humidifier	$Q$	Input heating energy	$d,dis$	Distilled water
$C_p$	Specific heat	$T$	Temperature	$e$	evaporator
$F_R$	Solar collector heat	$U_1$	Overall loss coefficient	$f$	Feed water

	removal factor		of the collector		
h	Enthalpy	$U_{cond}$	Overall heat transfer coefficient of the condenser	O,out	Outlet
I	Solar irradiance	V	Volume of humidifier	pr	Preheater
K	Mass transfer coefficient	X	Salt concentration	sw	seawater
M	Mass flow rate	Subscript		v	vapor
$\dot{m}$	Mass flow rate	a	air	w	water

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## **Desalination, Trends and Technologies**

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The book comprises 14 chapters covering all the issues related to water desalination. These chapters emphasize the relationship between problems encountered with the use of feed water, the processes developed to address them, the operation of the required plants and solutions actually implemented. This compendium will assist designers, engineers and investigators to select the process and plant configuration that are most appropriate for the particular feed water to be used, for the geographic region considered, as well as for the characteristics required of the treated water produced. This survey offers a comprehensive, hierarchical and logical assessment of the entire desalination industry. It starts with the worldwide scarcity of water and energy, continues with the thermal - and membrane-based processes and, finally, presents the design and operation of large and small desalination plants. As such, it covers all the scientific, technological and economical aspects of this critical industry, not disregarding its environmental and social points of view. One of InTech's books has received widespread praise across a number of key publications. Desalination, Trends and Technologies (Ed. Schorr, M. 2011) has been reviewed in Corrosion Engineering, Science & Technology – the official magazine for the Institute of Materials, Minerals & Mining, and Taylor & Francis's Desalination Publications. Praised for its “multi-faceted content [which] contributes to enrich it,” and described as “an essential companion...[that] enables the reader to gain a deeper understanding of the desalination industry,” this book is testament to the quality improvements we have been striving towards over the last twelve months.

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