MULTI-STAGE FLASH SYSTEM PERFORMANCE WITH REFERENCE TO SOLAR ENERGY

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ABSTRACT

The performance of multi-stage flash, MSF, desalination system is studied during the design stage. Effects of number of stages, top brine temperature and feed-desalinated water ratio on MSF system operating limits, coefficient of performance and system size are investigated. In addition, the investigation is extended to study the effect of the variation of the operation conditions due to weather changing on the performance and production of an existing MSF system.

Keywords: MSF, Desalination, Performance, Solar energy

INTRODUCTION

The desalination process is the process of separating salt from water. There are two najor types: membrane processes (e.g. everse osmosis and electrodialysis) and hermal processes (e.g. multi-effect distillation, multi-stage flash, and nechanical vapour compression). Large scale desalination began with the development of multi-stage flash (MSF) desalination process in 1960's. The cost of production of distilled water depends on the ost of energy. Consequently, the limination of energy cost by using enewable energy source such as solar nergy can help in reducing the total roduction cost. In addition, with rogressive decrease in fossil fuel, and nproving emission standards, desalination sing clean energy sources seems very ttractive. Therefore, interest is growing in ne utilization of solar energy in desalination lants [1]. Solar distillation can be either irect type or indirect type. The direct type tilizes the green house effect. On the other and, the indirect solar distillation involves ne use of a solar energy collecting system to ollect thermal energy, a storage system, and a system to use this hot water to separate fresh water from the saline water. The heat collection system can be flat plate collectors, evacuated glass tube collectors as those used by El-Nashar [2,3], or line collectors as those used by Moustafa *et al.* [4].

The performance of a desalination system is affected by a number of factors including input sea water temperature, hot brine temperature, sea water flow rate, ambient air temperature, rate of removal of non-condensable gases, and pressure level in various stages. El-Nashar [5] showed that the specific heat consumption decreases as the saline water temperature increases, although the heat losses is increased due to the increase in the temperature difference with respect to the surroundings.

The current investigation aims at investigating different parameters affecting the design and the performance of MSF systems. Effects of operating condition changes due to weather changes on the performance and productivity of MSF systems are also investigated. This investigation is an introductory to a research program directed to develop a MSF

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system utilizing solar energy. Many mathematical models were developed for once through MSF systems. Investigations including Minnich *et al.* [6], El-Dessouky and Bingulac [7], Aly and Fathalah [8], Reddy *et al.* [9], and Scenna [10] investigated effects of different parameters on the performance of under design MSF systems. However, the design and operating limits of MSF systems, and the performance of operating systems are not widely investigated.

DESIGN STAGE ANALYSIS

MSF Mathematical Model

Consider a once through MSF system. The system consists of a recovery section of N stages, and a brine heater. The saline water feed rate F enters the system at a temperature T_f. The feed is heated to T_1 as it flows through the recovery stages. In these sections, the feed saline water is heated by the latent heat of the flashing vapour. The feed is heated in the brine heater to To; top brine temperature. This hot brine is fed to the flashing chambers in the recovery section where its pressure is decreased in steps. Vapour is generated due to consequent flashing processes. The released vapour heats the feed saline as it flows through the system and consequently the vapour is condensed. This condensate represents the fresh water product.

Consider the following assumptions to simplify the current problem: no heat losses to surroundings, no pressure losses due to demisters, water, vapour and brine properties are obtained by correlating the data of Beaton and Hewitt [11] for water, vapour and brine of 35 ppm concentration in the temperature range from 0 to 100°C, and the desalination production per stage is constant.

For stage number i shown in Figure 1, the temperature drops from T_{si-1} to T_{si} due to flashing process. The hot brine, which is flashed, enters this stage at the rate of $F-(i-1)*D_i$, where D_i is the amount of vapour generated per each stage. The condensate enters the condensate tray at a rate of $(i-1)*D_i$ and a temperature of T_{si-1} and leaves at a rate of $i*D_i$ and a temperature of T_{si}. The cold brine flows at a rate of F and is heated from T_{bi-1} to T_{bi} in the recovery heater. The flashing process can be considered as a constant enthalpy process. By applying the last assumption, the vapour temperature at every flashing stage can be estimated from the following equation:

$$T_{si} = [(F/D- i+ 1)C_{bsi-1}\, T_{si-1} - h_{gi})]/((F/D-i)\, C_{bsi}) \quad (1)$$

where C_b is the brine specific heat. Applying a heat balance on the stage no. i gives:

$$\begin{aligned} T_{bi} = [&F/D\, C_{bi+1}T_{bi+1} + (i-1)\, h_{fi-1} / N + \\ &(F/D-(i-1))\, C_{bsi-1}\, T_{si-1} / N - \\ &(i/N)\, h_{fi} -(F/D-i/N)\, C_{bsi}\, T_{si}]/(F/D\, C_{bi}) \quad (2) \end{aligned}$$

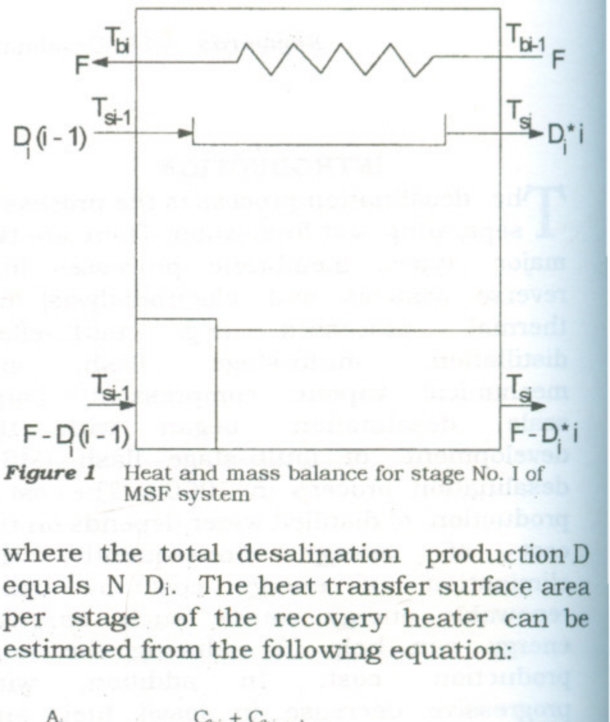

Figure 1 Heat and mass balance for stage No. I of MSF system

where the total desalination production D equals N D_i. The heat transfer surface area per stage of the recovery heater can be estimated from the following equation:

$$\frac{A_i}{DC_{ba} / U} = F / D \frac{C_{bi} + C_{bi+1}}{2C_{ba}} \ell n((T_{si}-T_{bi+1})/(T_{si}-T_{bi})) \quad (3)$$

where C_{ba} is brine average specific heat along the recovery heater, and U is overall heat transfer coefficient. The left-hand side of the above equation is called the specific heat transfer area per stage, A_i^*. The total specific heat transfer area A^* is the summation of A_i^*. The system coefficient of performance COP is the ratio between the heat energy recovered in the recovery heater sections and the heat added in the brine heater,

The above equations were solved simultaneously for different top brine temperatures in the range from 40 to 100 °C, and feed temperature of 20°C. First, the F/D ratio was kept fixed while effects of the stage number on the system performance were investigated under given top and feed brine temperatures. Then, the F/D ratio was increased in steps to investigate its effects on the system performance.

RESULTS AND DISCUSSIONS

Typical results for system COP and total specific heat transfer area are shown in Figures 2 and 3. Figure 2 shows system COP versus number of stages for various F/D ratios. These results indicate that, for a given F/D ratio, the effect of the number of stages is very weak on the COP. The system COP falls as the F/D ratio increases simply because of the waste of energy with the brine leaving the system.

Limits for the number of stages corresponding to each F/D ratio were observed; no solution was found beyond these limits. The reason is that the brine temperature can not go above the flashing vapour temperature in any stage of the recovery heater. As shown in Figure 2, the left ends of the curves represent the minimum number of stages required for a system working under certain conditions. The COP at these points represents the maximum expected COP corresponding to a system with a given number of stages. It was found that the left ends of the curves in the figure and for similar curves for different top brine temperatures fall on the single straight line shown in Figure 4. When these points were plotted as N versus F/D $(T_o - T_f)$ the single curve in Figure 5 was obtained. From this diagram, the minimum number of stages required for a MSF system to operate under given conditions can be determined. It was also found that for each top brine temperature, there is a minimum F/D ratio. The minimum F/D ratio versus top brine temperature was shown in Figure 6. For example, for Figure 2 at T_o = 100 °C no solution was found for F/D ratio less than 8.097. If this ratio goes below this value the brine temperature at the recovery heater outlet, T_1, will reach or go above the top brine temperature, T_o. Consequently, the COP will have too high value, infinity, or a negative value that is not true. The minimum number of stages obtained in the current investigation was compared to the analytical results of Darwish *et al.* [12] as shown in Figure 4. In their analysis, the properties of water and brine were assumed constant and the differences between brine and water properties are ignored. The figure shows that the current results are very close to Darwish's results.

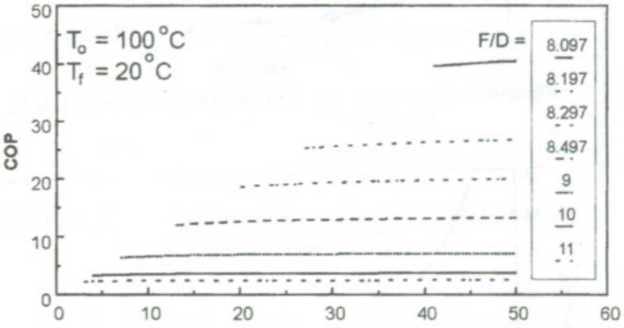

Figure 2 COP of MSF system

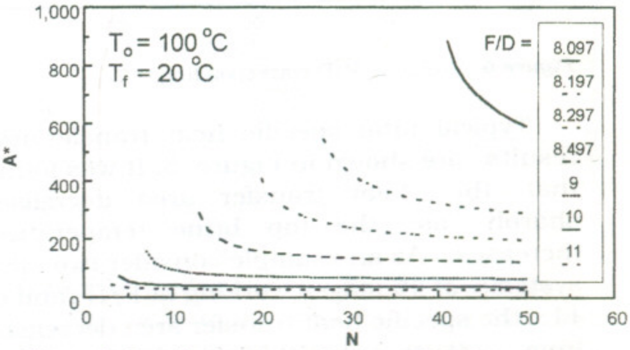

Figure 3 Specific heat transfer area of MSF systems

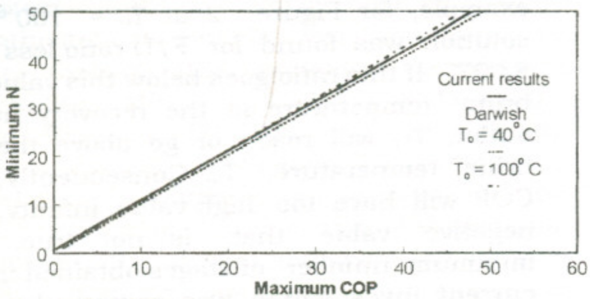

Figure 4 Minimum number of stage versus maximum COP at this number

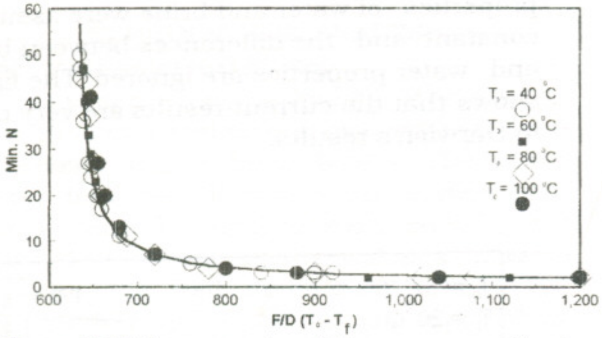

Figure 5 Minimum number of stages corresponding to F/D (T_o-T_f)

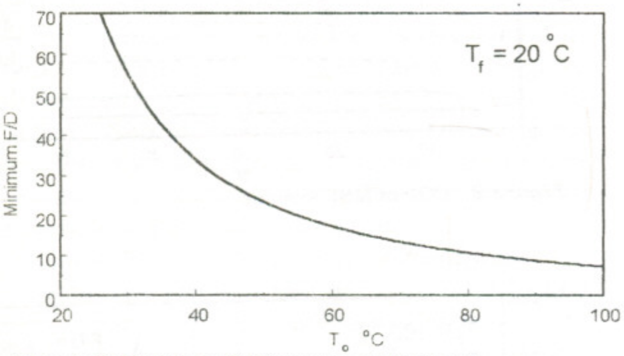

Figure 6 Minimum F/D corresponding to T_o

Typical total specific heat transfer area results are shown in Figure 3. It was found that the heat transfer area decreases sharply as the top brine temperature increases. As an example consider two MSF systems of 40 stages working at F/D ratio of 11, the specific heat transfer area decreases from 300 to about 30 as the top brine temperature increases from 80 into 100°C. However, the COP will fall from 20 to about 3 for the same conditions. Simply, it can be said that the fixed cost will fall 10 times while the running cost will increase 6.6 times. The effect of the number of stages on the specific heat transfer area is shown in Figure 3. The heat transfer area decreases as the number of stages increases. The rate of decrease starts steeply but flatten up as the number of stages increases. It is also clear that the effect of the number of stages is higher at low F/D ratios. As the number of stages increases the available latent heat per stage, from condensing flashing vapour, decreases. As a result, the brine outlet temperature of any recovery heater stage decreases slightly. Consequently, the logarithmic mean temperature difference in the heat transfer equation, Equation 3, increases. That decreases the heat transfer area. In another words, as the number of stages decreases, the brine temperature at the exit from any stage approaches the vapour temperature which leads to a decrease in the logarithmic mean temperature difference. Consequently, the heat transfer area increases. The decrease in F/D ratio leads also to the same scenario.

The choice of the appropriate design conditions, is not as simple as the above discussions indicate. Besides the above parametric study, an optimization for the total cost is required.

EFFECTS OF OPERATING CONDITIONS CHANGE

For a MSF system utilizing solar energy, the operating conditions may change according to weather change. Assume that an existing MSF system of N stages is designed to work under a specific F/D ratio, a feed water temperature T_f and a top brine temperature T_o to produce a certain desalinated water amount D. From the previous analysis, the system COP and specific heat transfer area can be determined. Now if one of the operating conditions is changed the system COP and desalination production will change. Generally, the previous analysis is still valid however for the system under study, the heat transfer area per stage and the stage number are known. The previous equations can be solved simultaneously by trial and error to obtain the system COP and desalination production D'.

Effect of reducing top brine temperature

Assume that the feed rate and feed brine temperature are maintained at the design conditions F and T_f while the top brine temperature T_o is reduced. Figures 7 and 8 show the effects of reducing the top brine temperature on the new water production D' and coefficient of performance of systems of 40 stages. The reduction in the desalination production equals (D - D')/D. As shown in the figures, the reduction in top brine temperature decreases the system production of desalinated water linearly. The system COP decreases slightly as the top brine temperature decreases.

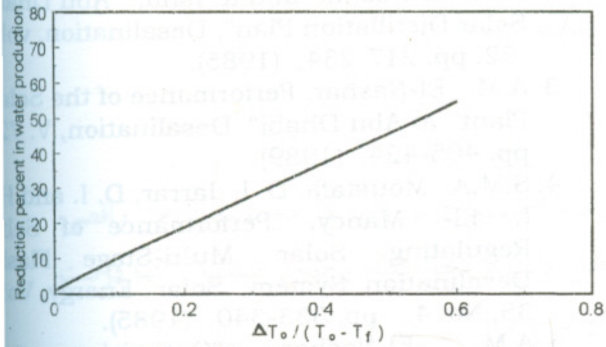

Figure 7 Effect of top brine temperature reduction on MSF system water production

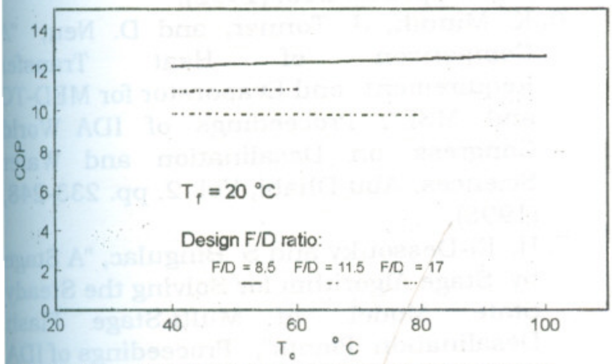

Figure 8 Effect o top brine temperature reduction on MSF system performance

Effect of Feed Temperature Change

The feed temperature is related to the ambient weather conditions. Assume the feed rate F' and top brine temperature T'_o are maintained at the design conditions F and To while the feed temperature T'_f is changed above and below the design condition, 20 °C in current cases. Figures 9 and 10 show the effects of varying the feed brine temperature on the water production and coefficient of performance of 40-stage systems. As shown in the figures, the reduction in the feed temperature increases the system production of desalinated water while increasing the feed temperature decreases the production. The decrease in the feed temperature increases the flashing in each stage. The system COP increases slightly as the feed temperature decreases.

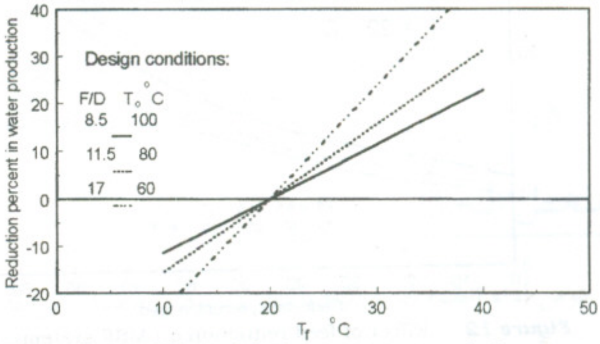

Figure 9 Effect of feed temperature variation on MSF system water production

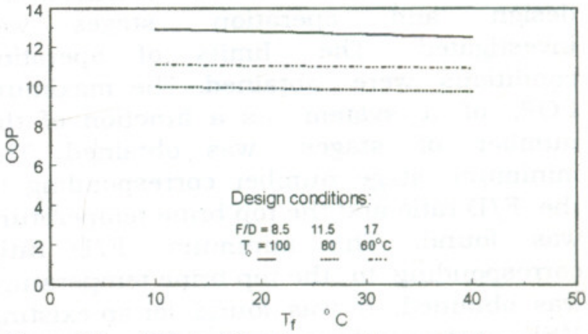

Figure 10 Effect of feed temperature variation on MSF system performance

Effect of Reducing the Feed Flow Rate

The effect of reducing feed flow rate while maintaining the top brine and feed temperature is investigated. As shown in Figures 11 and 12, the reduction in water production is proportional linearly to the reduction in feed flow rate, (F-F')/F. The system COP increases as the feed rate decreases. The reason is that the system heat transfer area is large enough to heat

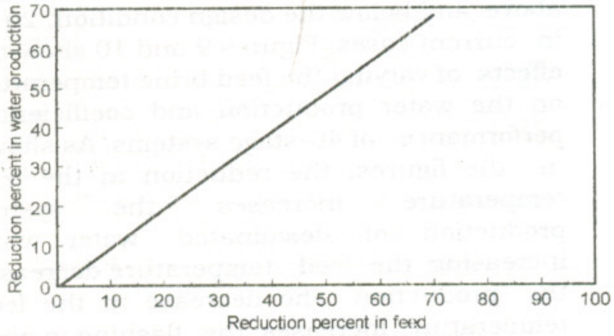

Figure 11 Effect of feed reduction on MSF system water production

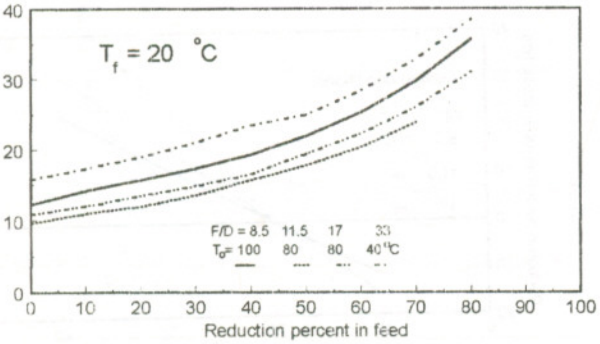

Figure 12 Effect of feed reduction on MSF system performance

CONCLUSIONS

The performance of MSF systems in the design and operation stages was investigated. The limits of operating conditions were obtained. The maximum COP, of a system as a function of the number of stages, was obtained. The minimum stage number corresponding to the F/D ratio and the top brine temperature was found. The minimum F/D ratio corresponding to the top brine temperature was obtained. It was found for an existing MSF system, the water production was reduced linearly as the top brine temperature decreases, feed temperature increases, or the feed rate decreases.

NOMENCLATURE

A_i	Surface area per stage, m²
A_i'	Specific heat transfer area, defined in Equation 3
A'	Total specific heat transfer area
C_b	Brine specific heat, J/kg K
COP	System coefficient of performance
D	Desalinated water production rate, kg/s
F	Saline water feed rate, kg/s
h_f	Saturated water enthalpy, J/kg
h_g	Saturated vapour enthalpy, J/kg
N	Number of stages
T_f	Temperature of feed saline water,°C
T_o	Top brine temperature, °C
T_s	Saturation temperature, °C
U	Overall heat transfer coefficient, W/m² K

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أداء أنظمة تحلية المياه بالبخر الوميضى متعددة المراحل مع مرجعية للطاقة الشمسية

عبيدة زيتون
قسم هندسة القوى الميكانيكية- جامعة الاسكندرية

ملخص البحث

درس أداء أنظمة تحلية المياه بالبخر الوميضى متعددة المراحل أثناء مرحلة التصميم. درس تأثير كل من عدد المراحل وأقصى درجة حرارة للمياه المالحة ونسبة مياه التغذية الى المياه المالحه على معامل الأداء وحجم النظام وحدود التشغيل. كما درست تأثير تغير ظروف التشغيل نتيجة لتغير أحوال الجو على أداء المنظومة وانتاج المياه.