# Optimal Operation of MSF Desalination Process to Meet the Daily Variable Demand of Freshwater Consumption with Changing Seawater Temperature

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**ABSTRACT**

This work investigates how to control and optimize the Multi Stage Flash ( MSF) process in order to maintain the variable freshwater consumption and varying intake seawater temperatures during a day with fixed top brine temperature. A storage tank is added to MSF plant to provide additional operating flexibility and to make sure that fresh water is available to clients at all times. A steady state process model for MSF operation coupled with a dynamic storage tank model has been developed within the gPROMS modeling program. MSF desalination performance is evaluated in terms of reducing total daily operating costs. Single and multiple intervals operating parameters strategies are used, yielding optimal seawater makeup and brine recycle policy . From the optimization results, the total daily operating cost using three time intervals is lower than that using two time intervals. Moreover, the effect on the marine environment will be more when MSF operates with two control intervals due to high discharge temperature.

**keywords:** MSF process , Variable freshwater demand, Optimization, Operating cost, Time intervals operating

## 1. Introduction

Freshwater shortage is not a temporary problem in one country, but a long-term and significant problem of human survival and community development in most countries [1,2]. About forty percent of the world's population suffers from a lack of drink water, and this trend is expected to increase in the future. Seawater desalination has become a major source of potable water for human survival and industry application in many countries. Among the various desalination processes, MSF is a thermal process and a major freshwater source worldwide [2].

Generally, selecting of the optimal design and operation of MSF units aims to reduce the cost of energy and operation such as electric power, steam and others. The past investigations studied the optimization of MSF process using gPROMS software technology, but their work has been limited to investigating the design and optimization of constant fresh water demand throughout the day [3,4]. However, in fact the demand for fresh water [5] as well as seawater temperature [6] varies throughout the day. Due to consistent design and operating conditions, freshwater production varies greatly with seawater temperature variation, resulting in more freshwater at night (lower seawater temperature) than noon (high temperature) [3].

Unfortunately, this is not true with demand, which is greater during the day (for example at noon) than at night [4]. These differences will affect the rate of freshwater production using MSF throughout the day. Recently, a number of authors including [1] have focused on the role of changing freshwater consumption with variability in seawater temperatures within a day and its impact on the total daily cost of desalination using only three time intervals control. This work investigates how to reduce the total daily cost of MSF desalination required while optimizing the operating parameter using single and multiple time intervals strategies. In order to avoid any shortage of fresh water, an intermediate storage tank (Figure 1) is added between the plant and the users. The gPROMS 2.3.4 model building software is used for model development and optimization.

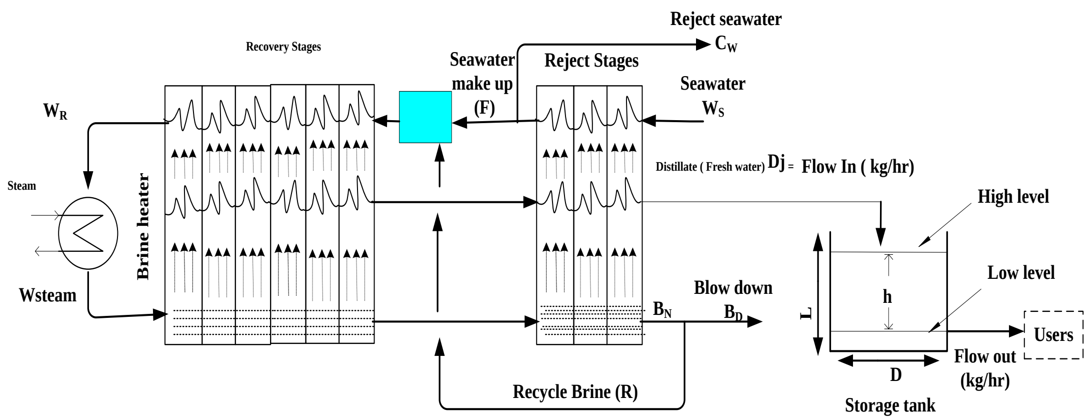


Figure 1 A typical MSF desalination process with storage tank [1]

## 2. Stage Model [4]

Mass Balance in the flash chamber: $B_{j-1} = B_j + D_j$; Stage salt balance: $X_{bj}\ B_j = X_{bj-1}\ B_{j-1}$

Mass balance for distillate tray: $\sum_{k=1}^{j} D_k = \sum_{k=1}^{j-1} D_k + D_j$;

Enthalpy balance : $\frac{B_J}{B_{J-1}} = \frac{(h_{Bj-1} - h_{vj})}{(h_{Bj} - h_{vj})}$

$h_{Vj} = f(T_{Vj}),\ h_{Bj} = f(T_{Bj}\ ,X_{Bj})$

Overall energy balance on stage : $M_R\ cp_j(T_{Fj} - T_{Fj+1}) =$

$\sum_{k=1}^{j-1} D_k\ cp_{Dj-1}\left(T_{Cj-1} - T^*\right) \sum_{k=1}^{j} D_k\ cp_{Dj}(T_{Cj} - T^*) + B_{j-1}\ cp_{Bj-1}\left(T_{Bj-1} - T^*\right)\ - B_j\ cp_{Bj}\left(T_{Bj} - T^*\right)$

Heat transfer equation : $M_R\ cp_j(T_{Fj} - T_{Fj+1}) = U_j\ A_J\ \ LMTD$ ; $LMTD = \frac{(T_{Fj} - T_{Fj+1})}{\ln[\ (T_{Cj} - T_{FJ+1})\ /\ (T_{CJ} - T_{Fj})]}$

$\boldsymbol{U_j} = f(\ M_R\ ,T_{Fj}, T_{Fj+1}, T_{Cj}, ID, OD, F_j)$; $cp_j = f\left(T_{FJ+1},\ T_{Fj},\ X_R\right),\quad CP_{Bj} = f\left(T_{Bj},\ X_{Bj}\right), CP_{Dj} = f\left(T_{Dj}\right)$

$T_{Bj} = T_{Cj} + TE_j + \Delta_j + \delta_j;\ \ T_{Vj} = T_{Cj} + \Delta_j;\ \ \Delta_j = f\left(T_{Dj}\right),\ TE_j = f\left(T_{Bj},\ X_{Bj}\right),\ \ \delta_j = f\left(T_{BJ},\ H_j,\ W_j\right)$

Brine heater model

$B_0 = W_R\ ,\ \ X_{B0} = X_R;\ B_0\ CP_{RH}\left(T_{B0} - T_{F1}\right) = W_{Steam}\ \lambda_s,\ \ \lambda_s = f(T_{Steam})$

Heat transfer equation: $W_R\left(T_{BO} - T_{F1}\right) = U_H\ A_H\ LMTD;$

$\boldsymbol{LMTD} = \frac{(T_{steam} - T_{F1})}{\ln[(T_{steam} - T_{F1})\ /\ (T_{steam} - T_{B0})]}$ ; $U_H = f(\ M_R\ , T_{Fj},\ T_{B0},\ T_{steam},\ ID,\ OD,\ \boldsymbol{f_{bh}})$;

Splitters Model

$B_D = \ \ B_{NS} - R \qquad ;\ C_W = W_S - F$

Makeup mixers model

$W_R = R + F$ ; $R\,X_{BNS} + F\,X_F = W_R\,X_{R,}$; $W_R\,h_m = R\,h_R + F\,h_F$; $h_M = f(T_{FM},\ X_R)$; $h_F = f(T_{FNR},\ X_F)$

**2.1 Estimation of Dynamic Seawater Temperature and Freshwater Consumption Profiles**

Figure 3 (a and b) show the variation of actual seawater temperature (C˚) and the trend of actual fresh water consumption '*F*low out' (liter/sec) with time (hr) during a day. The time duration for both figures were 24 hours. Using regression analyses, the following polynomials relationship are obtained the results of this computerized fitting ( Figure a and b). The following correlations were obtained with a correlation coefficient greater than 90% [1] .

$$T_{seawater} = -2\times10^{-16}\,t^6 + 6\times10^{-6}\,t^5 - 0.0003\,t^4 + 0.0032\,t^3 + 0.007\,t^2 - 0.1037\,t + 28.918 \qquad (A1)$$

$$Flow\ out = -0.00059\,t^5 + 0.0355t^4 - 0.757\,t^3 + 6.646\,t^2 - 17.56\,t + 40.88 \qquad (A2)$$

Equation (A1) intake seawater temperature profile and Equation (A2) freshwater consumption profile. In this work, midnight is the start time.

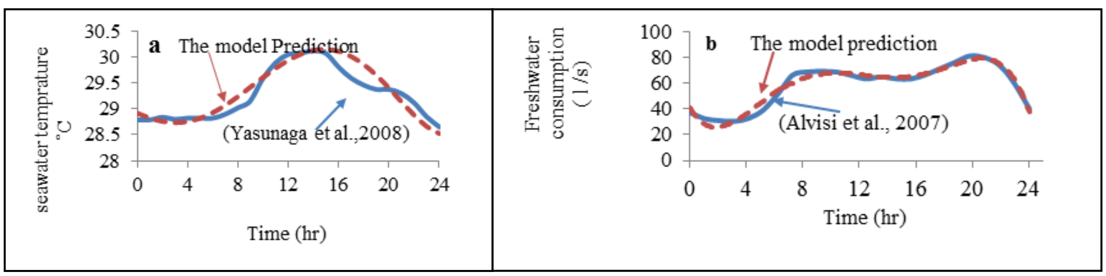


Figure 2 (a) Temperature of Seawater and (b) Fresh water demand/ consumption profiles[1]

In Figure 3, the storage tank operates without any level control, thus (h) exceeds $h_{max}$ limit or less than $h_{min}$ during MSF operation. At any time during the MSF operation, this violation of safe operation *V* can be defined As [1]:

$$V_1 = \begin{cases} (h(t) - h_{max})^2 & \text{if } h > h_{max} \\ 0 & \text{if } h < h_{max} \end{cases} \quad \text{And} \quad V_2 = \begin{cases} (h(t) - h_{min})^2 & \text{if } h < h_{min} \\ 0 & \text{if } h > h_{min} \end{cases}$$

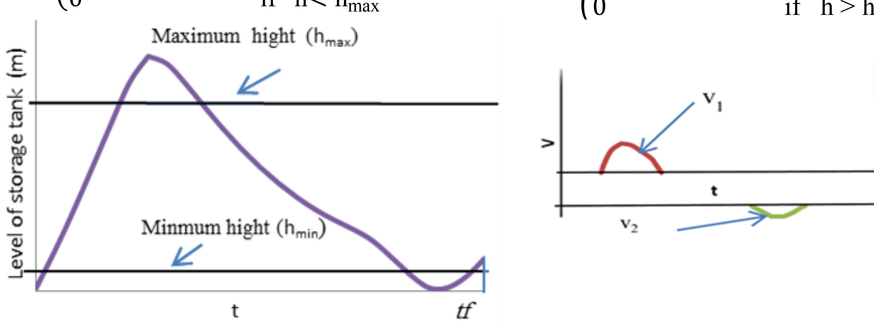


Figure 3 A typical storage tank level profiles

Figure 3 showed a typical plot of v1 and v2 versus time t in the total accumulated violation that can be written throughout the period

$V_T = \int_{t=0}^{tf} V(t)dt$ Therefore, $\begin{cases} \frac{dV_T}{dt} = v_1(t) = \left(h(t) - h_{max}\right)^2 & \text{(A3)} \\ \frac{dV_T}{dt} = v_2(t) = \left(h(t) - h_{min}\right)^2 & \text{(A4)} \end{cases}$

In this work, equations (A3) and (A4) are added to the model equations above. Also the following additional terminal constraint is added in each of the optimization formulation.

$$0 \leq V_T \text{ at } t_f \leq \varepsilon \quad \text{(A5)}$$

Where "ε" is a very small finite positive number specified. The above constraint will ensure that "h (t) will always be equal to or less than "$h_{max}$" and equal to or above "$h_{min}$". However, it should be noted that for the limits specified for the optimization variables (for example, seawater F for makeup and brine recycling rates R), the numerical value of the endpoint restrictions "Vt" at final time $t_f$ should be very small (close to zero) (in this work it was less than $10^{-6}$).

## 3. Case Study : Minimize the Total Daily Operating Cost within the Fixed Design

### 3.1 Case study

Here, one, two and three intervals are considered within 24 hours, makeup flow rate (F) and recycle flow rat (R) are optimized with intervals length while minimizing the total daily operating cost including steam, chemicals … etc. The geometry of storage tank with fixed roof is characterized with diameter (D=18m), and aspect ratio L/D = 0.55 [7]. The rejection section is consisted of 3 stages and the recovery section is 13 stages. For all cases, the flow rate of feed seawater is $1.13\times10^7$kg/h with salinity about 5.7wt% . Intake seawater temperature is calculated using equation (A1) and freshwater demand consumption is calculated using equation (A2). The end points constraint for the storage level ($0.5m \leq h \leq 9m$) is imposed to guarantee that the freshwater production and freshwater hold-up are at or between certain desired levels. The initial value of level of storage 'h' is 0.5 meter. In order to make sure that the storage tank level, 'h' does not go above $h_{max}$ and below $h_{min}$ at any time, a storage tank constraint on 'v' is imposed in the optimization problem. The all constant parameters and specifications which were used in this work were shown in Table1.

Table 1 Constant parameters and input data [4]

| | $A_j/A_H$ | $ID_j/ID_H$ | $OD_j/OD_H$ | $f_j/f_{bh}$ | $w_j/L_H$ | $H_j$ |
|---|---|---|---|---|---|---|
| Brine heater | 3530 | 0.022 | 0.0244 | $1.864\times10^{-4}$ | 12.2 | ----- |
| Recovery stage | 3995 | 0.022 | 0.0244 | $1.4\times10^{-4}$ | 12.2 | 0.457 |
| Rejection stage | 3530 | 0.0239 | 0.0254 | $.33\times10^{-5}$ | 10.7 | 0.457 |

### 3.2 Optimization Problem Formulation

MSF desalination process performance is evaluated in terms of reducing total daily operating costs

The optimization problem is described below.

Given: configurations of MSF unit, fixed specifications and design for all stage, storage tank size, intake seawater flowrate, freshwater demand and intake seawater temperature profiles

Determine: the optimum rates of seawater make-up (F) and recycled brine water (R)flow rats at different time intervals during a day

Minimize: the total daily operating cost (TOC).

Subject to: process constraints.

The optimization problem (OP) is mathematically described for any time period as follows:

$$\begin{aligned} &\text{Min} \quad TOC \\ &\text{OP} \quad R \text{ and } F \\ &\text{s.t.} \quad f(t, x^{\cdot}, x, u, v) = 0 \quad \text{(model equations)} \\ &\quad TBT = TBT^{*} \\ &\quad 0 \leq V_T \leq \varepsilon \\ &\quad (2\times10^6 \text{ kg/h})\ R_L \leq R \leq R_U\ (7.55\times10^6 \text{ kg/h}) \\ &\quad (2\times10^6 \text{ kg/h})\ F_L \leq F \leq F_U\ (7.55\times10^6 \text{ kg/h}) \end{aligned}$$

Where, "TBT *" is the highest constant brine water temperature (90 ° C). The subscribers (L) and (U) indicate the minimum and upper parameters. The typical equations presented in the previous section can be described form by $f(t, \dot{x}, x, u, v)$ where ("$\dot{x}$") represents all the state variables, non-linear sets of all algebraic and deferential variables, u is a control variable, such as recycling flow rate , seawater make up and composition, , etc., v is a set of fixed parameters

The total operating cost (TOC) consists of several components as described below. The MSF process model and dynamic tank model were presented above. This optimization problem reduces the total daily operating costs with changing seawater temperature, and freshwater demands during 24-hour. The optimal of R and F within 24-hour intervals are estimated in a single and multiple interval. The results obtained are then compared using signal and multiple intervals. The transient states which would occur in MSF operation due to change R , F and seawater temperature were ignored in this work. It is assumed that the length of these unsteady state cases is small.

The objective function is TOC (Total Daily Operating Cost) is defined as[8]:

TOC (Total daily Operating Cost) = [CC1 + CC2 + CC3 + CC4 + CC5] / 320

CC1 (Steam cost) = $8000 \times W_{steam} \times [(T_{steam} - 40) / 85] \times (0.00415)$

CC2 (Chemical cost)= $8000 \times [D_j / 1000] \times 0.025$

CC3 (Power cost) = 8000 × [$D_j$ / 1000] ×0.109
CC4 (Maintenance and spares cost) = 8000 ×[$D_j$ / 1000] ×0.082
CC5 ( Labor cost)= 8000 ×[$D_j$ / 1000] × 0.1

## 4. Results and Discussions

Case study provided by Russo et al. (1996) [9] (which relied on industrial data) was used here to validate the model. The specifications and constant parameters used by [9] and this work were shown in table 1. Both models calculate the temperature profiles, salinity and the flow rate of freshwater for each stages, Comparing the results in Figure 5 showed that there is a good agreement between them.

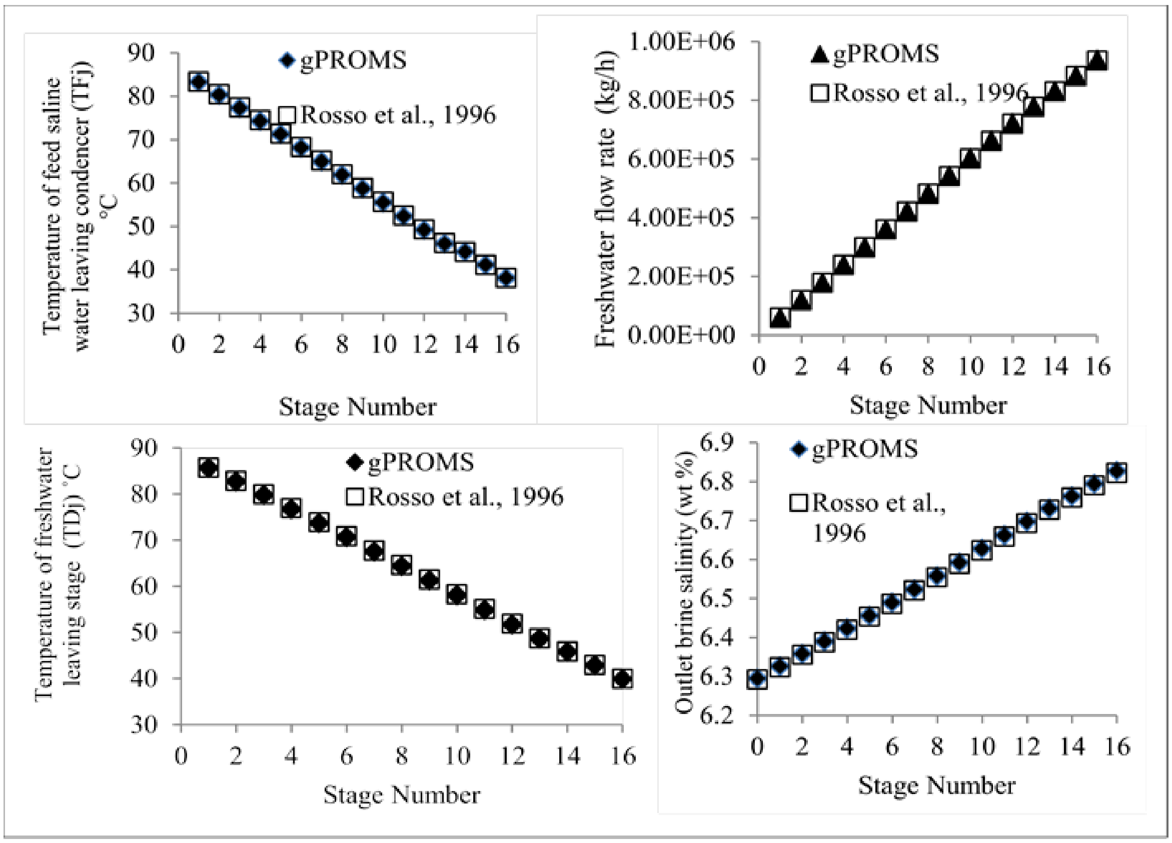


Figure 5 Compare the results of gPROMS and Rosso et al.,1996

The results showed that MSF process, operated with a single time interval for R, and F were insufficient to produce varying freshwater demand with changing intake seawater temperature during a day. Interval strategies (two and three) have been found to produce variable demand for freshwater with a changing intake temperature of seawater. Figure 6 showed the optimal makeup flow rate (F) and recycling flow rate (R) within one day. The results indicated that MSF desalination process should be operated at a higher flow rate of F and R using two time intervals.

Figure 7 presented steam consumption and temperature profiles for two and three time intervals control. It can be seen from the results that the rate of steam consumption and steam temperature using two time intervals were high compared to three intervals, and thus leads to increase corrosion and fouling in the brine heater. Moreover, the result of this leads to increase blowdown brine temperature (Figure 8).

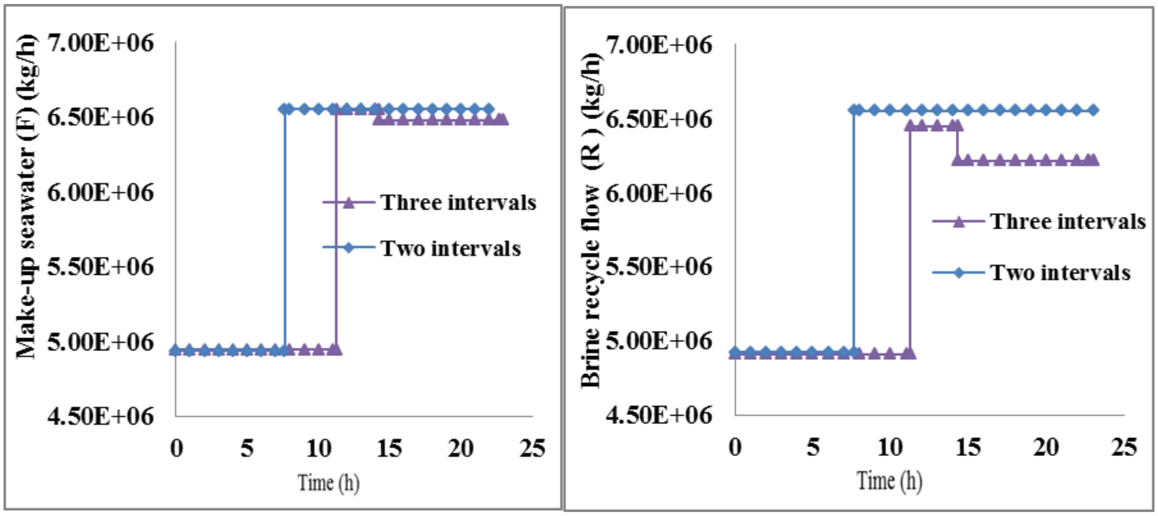


Figure 6 Optimal flowrate of seawater make up (F) and brine recycling rate (R) profiles in three and two time intervals

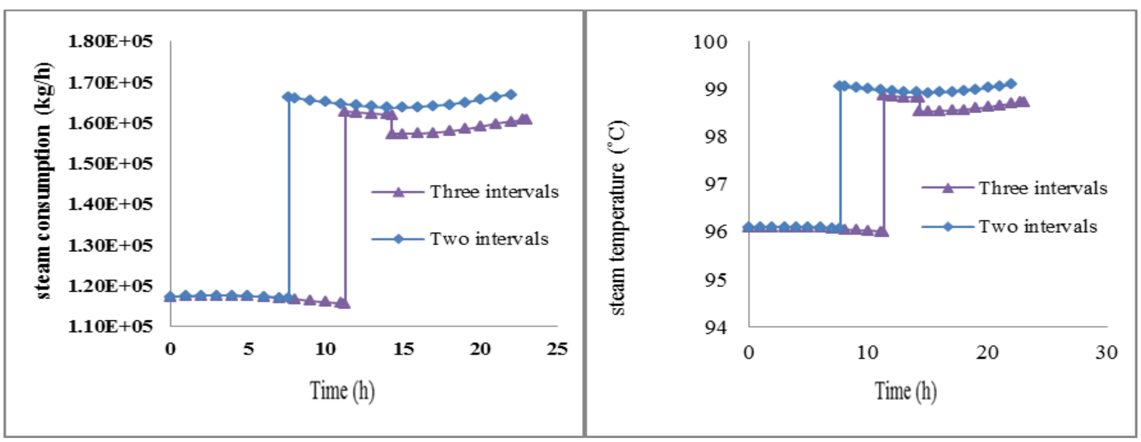


Figure 7 Changes in steam temperature and consumption profiles in two and three time intervals

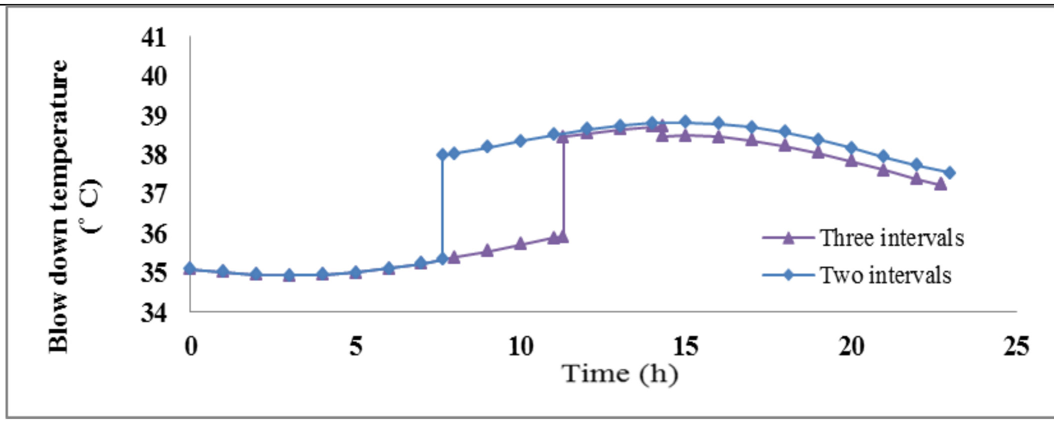


Figure 8 Variations of blowdown temperature profiles at three and two time intervals

Figure 9 presented the variations of freshwater consumption and MSF freshwater production by using two and three intervals during a day. It is clear from the results the control of the freshwater 'flow in' main supply (MSF) desalination process is performed by controls the operating parameters such as makeup and brine recycle flow rates at two and three discrete time intervals (Figure 6) based on storage tank level. Supply follows the consumption during the day to maintain storage tank levels and operating parameters of MSF process within normal operating ranges.

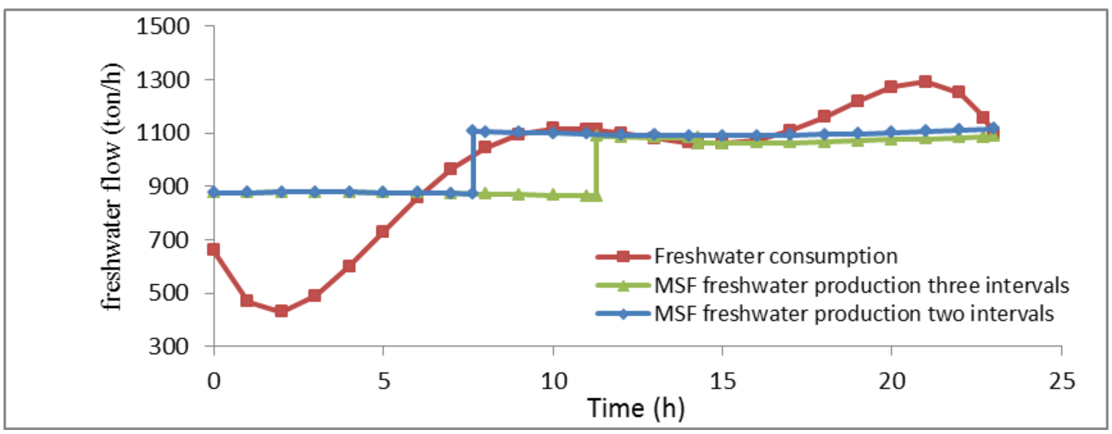


Figure 9 Freshwater consumption and production profile at different intervals

Table 2 summarizes the cost components and total operating cost for each interval on a daily basis. The optimization results showed that the total daily operating costs were reduced by approximately 7% using three intervals compared to the cost obtained within two. This is due to with increasing brine recycle and seawater make up flow rates using two time intervals (Figure 6), The brine flowrate that enters the brine heater (WR) will increase and then, will need to operate the MSF unit at a higher steam consumption and stem temperature to meet freshwater demand (Figure 7). This obviously demonstrates the utility of using 3 time intervals.

Table 2 Summary of optimization results using different intervals

| | CC1($/d) | CC2($/d) | CC3($/d) | CC4($/d) | CC5($/d) | TOC($/d) |
|---|---|---|---|---|---|---|
| One interval | ## | ## | ## | ## | ## | ## |
| Two intervals | 10103 | 602.82 | 2660.16 | 2001.71 | 2440.68 | 17808.38 |
| Three intervals | 9289.09 | 574.38 | 2534.30 | 1907.03 | 2325.21 | 16630.00 |

## No results obtained

## 6. Conclusion

A dynamic storage tank model coupled with steady state model for MSF operation was developed within the gPROMS modeling software. The total daily cost of MSF desalination process required was minimized while optimizing the operating parameter using single and multiple time intervals strategies. The MSF plant operated with single interval time was not sufficient to produce varying for fresh water, while interval strategies (two and three) have been found to produce variable demand for freshwater with a varying temperatures of seawater. The MSF desalination process has to be operated at higher rate of F, R, steam consumption and steam temperature using two intervals time compared to that obtained by using three time intervals, thus leads to increase corrosion and fouling in the brine heater. Furthermore, the total daily operating costs were reduced by approximately 7% using three intervals compared to the cost obtained within two intervals. Additionally, the effect on the marine environment will be higher when use two-time intervals due to a high discharge temperature.

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