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Minimise the Operation Schedule Time to Meet the Daily Fixed Water Demand of MSF Desalination

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Multi Stage Flash (MSF) desalination process is the largest sector in providing fresh water to the gulf region. The production of fresh water from an MSF process can vary with daily temperature variation of seawater producing more water during the night than during the day whereas the demand during the day is usually more than at night. In this work, a Dynamic Optimisation (DO) problem is formulated and solved within gPROMS based on Control Vector Parameterisation (CVP) where the minimum schedule time problem for fixed water demand is solved to achieve the optimal trajectories. The dynamic seawater temperature profile is considered to be piecewise constant or linear in each time zone.

1. Introduction

Steady and source of water supplies ensures quality of life for a community. Existing fresh water supplies are over exploited due to population growth, higher living standards and growth of both agriculture and industry (Patroklou et al. 2013). With almost 90% of the surface water being saline desalination is becoming one of the stable and sustainable source of freshwater around the world. MSF desalination process (Figure 1) is the oldest and is still leading in desalination industry (Alsadaie and Mujtaba, 2016). In the MSF process, vapour is formed from flashing of seawater in stages and condenses into freshwater.

When then design and the operation are fixed, the production of freshwater from an MSF is more in winter than in summer (Tanvir and Mujtaba, 2006). To maintain water production at the same level during both season, the common industrial practice is to operate the plant at higher temperature. However, this results in increased fouling and corrosion of heat exchanger (other plant equipment) leading to frequent shutdown of the plant interrupting the freshwater supply or resulting in the increased amount of antiscallant (Al-Hangary et al., 2007). Also note, the plant operation changes with time due to different uncertainty that originates from corrosion, equipment failure, raw material shortages, fluctuation in pricing, change in demand, change in weather condition, etc. Therefore, the short-term operational decision needs to be addressed to maintain the desired supply and expected profitability. Optimisation can help finding the short-term optimised plant operating schedule. Several works have been found in the literature considering dynamic and optimisation study of MSF desalination. Sowgath and Mujtaba (2015) presented DO framework to develop the real-time schedule and to maximize the performance while maintaining fixed water demand with daily variation of seawater temperature. They vary the steam temperature for discrete change of seawater temperature to offset its effect.

In this work, a number of DO problems are formulated to: (a) maximise the performance ratio (PR) for a given time to get to one steady state to other due to discrete change in seawater temperature (b) minimise the time between one steady state to other due to discrete change in seawater temperature and finally (c) minimise the time between one steady state to other due to continuous change in seawater temperature. In all cases, a fixed water demand is maintained optimum operation policies for in terms of brine heater steam temperature, recycled brine flowrate and rejected seawater flowrate are obtained. A set of Differential and Algebraic Equations (DAEs) that describe the transient behaviour of MSF process is incorporated in the DO problems.

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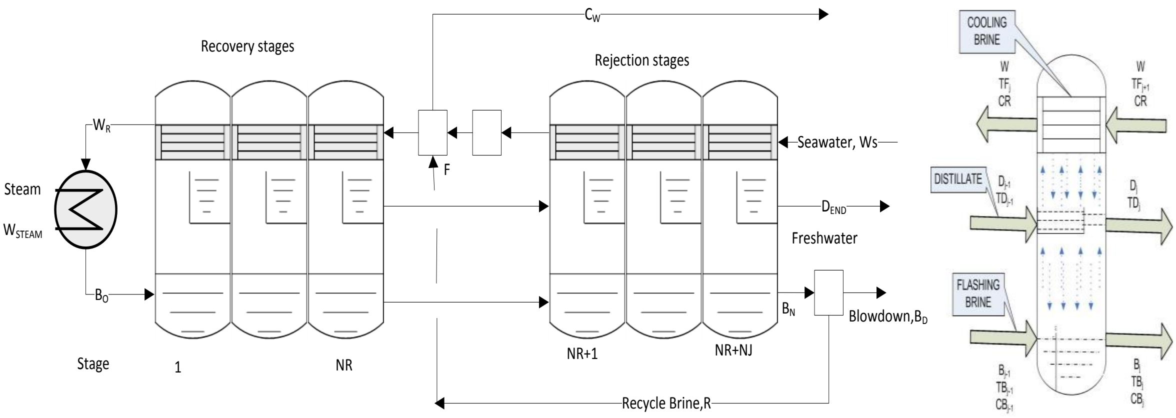

Figure 1: A typical MSF Process and Stage j.

2. Process model

Due to the availability of process engineering computational tools for model development and optimisation (e.g. Aspen Plus, Aspen Custom Modeler, gPROMS etc.), growing implementation of such tools in process design and operations over the past decades is observed. In gPROMS the "CVP_SS" solver act as a single solver manager for the solution of both dynamic and steady-state, continuous and mixed integer optimization problems. CVP technique can handle large Differential Algebraic Equation systems (DAE) of the dynamic process very faster than other methods. gPROMS enables user to construct the model in hierarchical structure.

Here, a dynamic model developed within gPROMS is taken from Sowgath and Mujtaba (2015) which is based on the work of Rosso et al. (1996), Hussain et al. (2003) and Mazzotti et al. (2000). Models for each unit operations such as flash chambers, brine heater, mixer, splitter and orifice are developed individually and connected according to the physical existence. The model equations for one recovery stage, one rejection stage, splitter, mixer, brine heater, etc. are written as unit models respectively. Note the number of stage is fixed. MSF dynamic model is constructed in hierarchical structure where lower hierarchy includes flashing stages, brine heater, mixers, splitter and physical properties models while higher hierarchy combines them in a process flowsheet model. Sowgath and Mujtaba (2015) validated the model using steady state data from Rosso et al. (1996) which showed a good agreement.

3. Optimization problem formulation and constraints

3.1 Optimization Problem 1 (*OP1*)

The optimization problem is described as:

Given: Fixed water demand throughout the year, fixed number of rejection stages, fixed amount of seawater flow, heat exchanger areas in stages, design specifications of each stages

Optimise: The number of recovery stages, steam temperature, recycled brine flowrate, rejected seawater flowrate while there is a step change in seawater temperature

So as to Maximise: Performance ratio (PR) ($10^3 \times amount\ of\ freshwater / energy\ consumption$)

Subject to: Process constraints: Equality constraints such as process model, Inequality constraints such as linear bounds on optimisation variables and other parameters.

The optimization problem (*OP1*) can be described mathematically by:

$$\underset{R, C_w, T_{Steam}}{Max} \quad PR$$

$$f\left(t, x(t), \dot{x}(t), x(t), v\right) = 0, [t_0, t_f] \quad \text{Model}$$

$$D_{\text{END}} = D^*_{END}$$

$$(93^{o}\mathrm{C})\ T_{steam}^{L} \le T_{steam} \le T_{steam}^{U} (97^{o}C)$$
$$(4.7\times10^{6})\ R_{L} \le R \le R^{U} (7.85\times10^{6})$$
$$(4.1\times10^{6})\ C_{w}^{L} \le C_{w} \le C_{w}^{U} (5.9\times10^{6})$$
$$W_{s} = 1.13\times10^{7}, SeawaterConcentrration = 5.7wt\%$$
$$T_{seawater} = X1\ \ (t=0,t_{1}), T_{seawater} = X2\ \ (t_{1},t_{2}),$$
$$2 \le t_{2} \le 10$$

D_{END} is the total amount of fresh water produced and D_{END}^{*} is the fixed water demand (= kg/hr). T_{steam} is the steam temperature. *TBT* is the Top Brine Temperature. *R* is the Recycle flowrate; C_{W} is the Rejected seawater flow rate. Subscripts/superscripts L and U refer to lower and upper bounds of the parameters. The bounds of the parameters are shown in brackets above. Water demand D_{END}^{*} is fixed over schedule time. X1 and X2 are seawater temperatures in the first (t_1) and second interval (t_2). The minimum and maximum value of (t_1) are 1 and 5 seconds respectively and the minimum and maximum value of second interval (t_2) is 5 and 10 seconds respectively.

3.2 Optimization Problem 2 (*OP2*)

The optimization minimum time problem (*OP2*) can be described mathematically by:
For fixed water demand Minimum time problem (*OP2*) can be expressed as.

$$\underset{R,C_w,T_{Steam}}{Min} \qquad t_f$$
$$f\left(t, x(t), \dot{x}(t), x(t), v\right) = 0, [t_0, t_f] \qquad \text{Model}$$
$$\text{Other Constraints are same as } OP1$$

4. Results

The results of the first two optimisation problems (*OP1* and *OP2*) are presented in Table 1. In Table 1, the MSF process is assumed to be at steady-state condition at $T_{seawater}$ = 33°C. An external disturbance of seawater temperature is considered where it increases from 33°C to 35°C. The optimizer reaches the steady state again in 35°C in both *OP1* and *OP*2 where the fixed water demand is maintained from $D^{end} = 10\times10^{5}$ to $D^{end} = 8.5\times10^{5}$ for different case studies (1-4). For case 1, the objective is to minimize schedule time for fixed water demand for operation schedule time. For case 2, the objective is to maximise *PR* for fixed water demand for operation schedule time. For *OP1*, operation schedule time hits the upper bound 9 except the water demand $D^{end} = D^{*} = 8.5\times10^{5}$, while for *OP2*, except the water demand $D^{end} = D^{*} = 10\times10^{5}$, operation schedule time hit the lower bound of the controller time horizon. In Case 2, the step changes are minimum to go for stable operation. It is interesting to note that water production per unit energy is increased with decrease of water demand for both *OP1* and *OP2*.

For *OP1*, with decrease in fixed water demand Reject seawater *Cw*, top brine temperature *TBT* is increase, while recycle flowrate *R,* Amount of steam *Wsteam* also decrease to maintain the fixed water demand for increase in seawater temperature. For *OP1*, T_{steam} hits the higher bound while for OP2, it decreases with decrease of water demand.

For *OP1*, it is found that PR is increased at the cost of more time to reach stable operation and larger step of manipulated variable is found. From the Table 1, it can be concluded that the minimum time problem (*OP2*) leads to the smaller step changes and optimum steady condition reaches for lesser time than maximum problem (*OP1*). Therefore minimum time optimisation is more desirable with respect to operation of the process.

Table 1: Comparison of the Results for different fixed water demand for Case 1 and Case 2

		$T_{seawater}$	T_{steam}	TBT	R	C_w	W_{STEAM}	PR	t_2
OP1									
Case 1	$D^{end} = D^* = 10\times10^5$	33	94.41	84.59	7.14E+06	4.10E+06	1.49E+05	***10.3***	9
		35	97.00	87.07	7.23E+06	4.10E+06	1.51E+05	***10.4***	
Case 2	$D^{end} = D^* = 9.5\times10^5$	33	97.00	89.07	4.70E+06	4.10E+06	1.25E+05	***11.5***	8.80
		35	97.00	88.20	5.94E+06	4.10E+06	1.36E+05	***10.9***	
Case 3	$D^{end} = D^* = 9\times10^5$	33	93.00	86.91	4.70E+06	5.90E+06	1.00E+05	***12.1***	9.0
		35	97.00	89.21	4.80E+06	4.10E+06	1.23E+05	***11.5***	
Case 4	$D^{end} = D^* = 8.5\times10^5$	33	94.66	88.01	4.76E+06	5.45E+06	1.08E+05	***12.0***	8.30
		35	97.00	90.06	4.70E+06	5.02E+06	1.12E+05	***11.9***	
OP2									
Case 1	$D^{end} = D^* = 10\times10^5$	33	93.00	84.64	6.35E+06	4.89E+06	1.30E+05	10.9	***4.5***
		35	95.32	85.20	7.85E+06	4.25E+06	1.53E+05	10.1	
Case 2	$D^{end} = D^* = 9.5\times10^5$	33	93.00	84.64	6.35E+06	4.89E+06	1.30E+05	10.9	***1.0***
		35	94.33	84.78	7.85E+06	4.85E+06	1.45E+05	10.3	
Case 3	$D^{end} = D^* = 9\times10^5$	33	93.00	84.64	6.35E+06	4.89E+06	1.30E+05	10.9	***1.0***
		35	93.53	84.88	7.30E+06	5.30E+06	1.34E+05	10.6	
Case 4	$D^{end} = D^* = 8.5\times10^5$	33	93.00	84.64	6.35E+06	4.89E+06	1.30E+05	10.9	***1.0***
		35	93.09	85.37	6.50E+06	5.57E+06	1.21E+05	11.0	

Objective function values are in bold & italic

Based on the Kuwait the daily seawater temperature profile of October 27, 2016 (timeanddate, 2017), seawater temperature discrete profile is divided into several zones (Figure 2). Seawater temperature increases from 23°C (at 2:00 am) to 35°C (at 1:00 pm noon) and again decreases form 35°C to until 23°C (at midnight). As before in Table 1, the MSF process is assumed to be at steady-state condition for at the beginning of time horizon and an external disturbance of seawater temperature is considered piecewise constant where it increases or decreases 2°C increment for each time horizon (Figure 2). The optimizer reaches the steady state for different temperature change during the day where the fixed water demand is maintained. A minimum schedule operation time for different time horizon of that particular day without compromising the freshwater demand is studied where the optimum operation policies is obtained which will offset the change in seawater.

The results for optimum operation schedule time for particular day are presented in the Table 2. For the simplicity, the steam temperature is kept constant. The operation schedule time value hit the lower bound of control time horizon. *R* and W_{steam} increase while *PR*, *TBT* and C_w are decrease with increase of seawater temperature from 2:00 am to 1:00pm. The opposite trends is observed with decrease of seawater temperature form 1 pm to midnight.

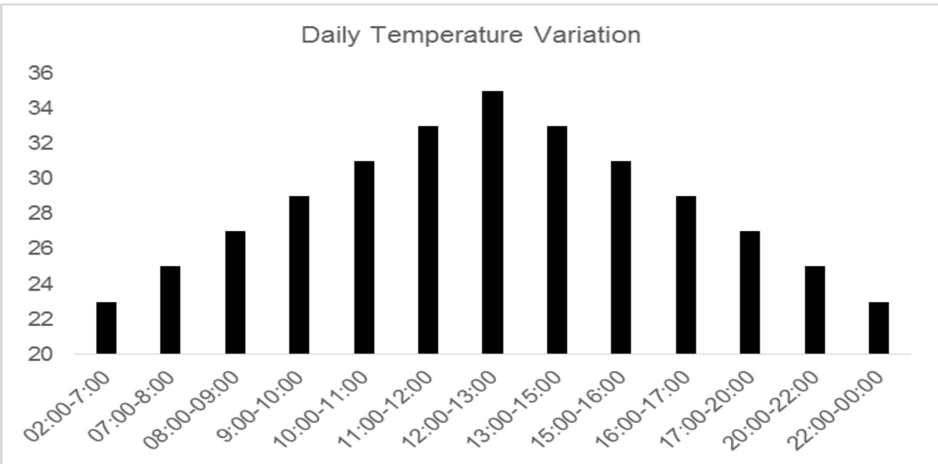

Figure 2: Discrete Seawater Temperature Profile during the Day assuming temperature as piecewise constant

Table 2: Summary of the optimum operation for fixed water demand D_{END}=9x10^{5}

Tseawater	*Tsteam*	*TBT*	*R*	*C_w*	*W_{STEAM}*	*PR*	*t_2*
23	93	85.85	4.70E+06	5.79E+06	1.17E+05	12.1	*1*
25	93	85.64	5.19E+06	5.88E+06	1.20E+05	11.8	
25	93	85.64	5.19E+06	5.88E+06	1.20E+05	11.8	*1*
27	93	85.41	5.63E+06	5.86E+06	1.22E+05	11.6	
27	93	85.40	5.63E+06	5.86E+06	1.22E+05	11.6	*1*
29	93	85.16	6.00E+06	5.74E+06	1.25E+05	11.4	
29	93	85.17	6.00E+06	5.74E+06	1.25E+05	11.4	*1*
31	93	84.89	6.42E+06	5.60E+06	1.28E+05	11.1	
31	93	84.90	6.42E+06	5.60E+06	1.27E+05	11.1	*1*
33	93	84.58	6.91E+06	5.43E+06	1.31E+05	10.8	
33	93	84.58	6.91E+06	5.43E+06	1.31E+05	10.8	*1*
35	93	84.23	7.47E+06	5.24E+06	1.35E+05	10.5	
35	93	84.23	7.47E+06	5.24E+06	1.35E+05	10.5	*1*
33	93	84.58	6.91E+06	5.43E+06	1.31E+05	10.8	
33	93	84.58	6.91E+06	5.43E+06	1.31E+05	10.8	*1*
31	93	84.89	6.42E+06	5.60E+06	1.28E+05	11.1	
31	93	84.90	6.42E+06	5.60E+06	1.27E+05	11.1	*1*
29	93	85.17	5.99E+06	5.72E+06	1.25E+05	11.4	
29	93	85.17	6.00E+06	5.74E+06	1.25E+05	11.4	*1*
27	93	85.41	5.63E+06	5.86E+06	1.22E+05	11.6	
27	93	85.40	5.63E+06	5.86E+06	1.22E+05	11.6	*1*
25	93	85.64	5.19E+06	5.88E+06	1.20E+05	11.8	
25	93	85.64	5.19E+06	5.88E+06	1.20E+05	11.8	*1*
23	93	85.85	4.70E+06	5.79E+06	1.17E+05	12.1	

Objective function values are in italic.

The optimised *TBT* temperature profile is shown in Figure 3. Recycle flow rate and Reject seawater flowrate offset the seawater temperature change.

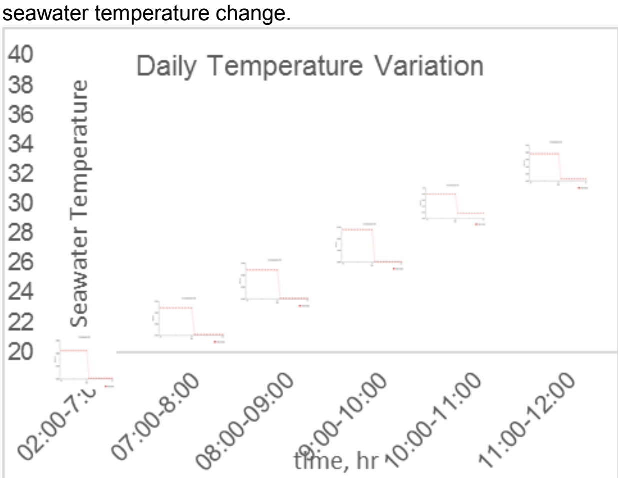

Figure 3: TBT Response of the Optimised Profile

5. Conclusions

The objective is to improve in design, operation and control of the MSF desalination process to ensure the quality of water at a cheaper rate. Firstly, series of maximum problem and minimum time problem is solved. Since the maximum problem leads to the larger step changes. It optimum steady condition reaches for longer time. Secondly, the different operation policies have been studied for MSF process by a series of minimum time interval problem for fixed water demand for particular day. Thirdly, in the daily temperature variation is varied in linearly (timeanddate, 2017), seawater temperature changes linearly and its effects are compared with piecewise constant step changes. Operational policies obtained can be implemented by designing an appropriate controllers.

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