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Enhancement of Feed Forward Multi Effect Evaporator Performance for Water Desalination Using PI Control

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ABSTRACT

The increasing of population needs safe, reliable and consistent supply of water had made many manufacturing industries and water treatment plants to look for efficient desalination plants.There are two major types of desalination technologies around the world, namely membrane desalination and thermal desalination . MEE is one of the types of thermal desalination. MED process operates in a series of evaporator condenser vessels called effects and uses the principle of reducing the ambient pressurein the various effects. A novel algorithm to solve the steady state analysis problem of three effects feed forward multi effect evaporator (FF MEE) for water desalination is investigated. A dynamic model is derived for MEE. FF MEE dynamic model is controlled using a Proportional-Integral (PI) controller that designed to improve its performance against the variation of the cold water temperature. Simulation results show the effectiveness of the proposed design and calculation has been presented using MATLAB®.

Keywords: *Feed forward multi effect evaporator- Water desalination-Steady state analysis-Dynamic model-PI controller*

1. INTRODUCTION

Shortage of fresh water is a major problem affecting many countries. One of the ways to get an additional source of drinking water in places where there are much seawater resources is seawater desalination plants[1]. Population growth and industrial development have caused water shortage as a comprehensive crisis in many countries especially in the Middle East and North Africa [2]. Seawater desalination is very important technology to efficiently produce water for human use and irrigation from wastewater and seawater. Main desalination techniques are currently Multistage Flash Distillation (MSF), Multi-effect Distillation (MED) and Reverse osmosis(RO) [3]. Multi-effect desalination (MED) is the common technique that provides considerable quantity of potable water. This type of thermal desalination methods has been used recently because of its advantages such as low capital requirements, low operating costs, simple operating and maintenance procedures, thermal efficiency, heat transfer coefficient, lower energy used and good performance ratio that is higher than other thermal desalination techniques like MSF[2] .

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There are four different possible configurations for the MEE desalting systems, which differ in the flow directions of the heating steam and the evaporating brine, backward feed (BF), forward feed (FF), parallel feed (PF) and parallel/cross feed (PCF)[4]Transient modeling for different feed multi-effect evaporator (MEE)was investigated by a few researchers. For example, Miranda and Simpson [5] described a stationary and dynamic lumped model of backward feed MEE for tomato concentration. Tonelli et al. [6] presented an open-loop dynamic response model of triple effect evaporatorsfor apple juice concentrators with backward feed configuration.

Kumar et al. [7] modeled transient characteristics of mixed feed MEEsystem for paper industry based on the work in [8]. Their results showthat the effects temperature has a faster response compared to the solid concentration. The dynamic behavior of four effects parallel/cross MEDsystems was done by Aly and Marwan [8] which allowed the study ofsystem start-up, shutdown and load changes using lumped model ofmass, energy and salt balance equations. El-Nashar and Qamhiyeh [9]. The backward feed arrangement is not suitable for application in sea water desalination. The parallel feed layout is by no means the most economical and is efficient only when the feed brine is nearly saturated to boil inside the effects. The salt concentration reaches the maximum permissible value in all effects [10]. The aim of this paper is developing a dynamic modeling of MEE and improving its performance by using PI controller to eliminate the effect of disturbance.

2. SYSTEM DESCRIPTION

MED process operates in a series of evaporator condenser vessels called effects and uses the principle of reducing the ambient pressure in the various effects[2] . Sea water is fed to condenser then it is preheated to required temperature and then is forwarded to two streams; portion of the heated water is used as feed of evaporators and the other as cooling seawater is rejected back to the sea. The feed seawater is entered to the first effect and the steam also does that as a source of energy.

Part of the feed is evaporated and the produced vapor is used to evaporate feed in the next effect, the un-evaporated brine is fed to the next effect [11].Same change occurs in the 2nd evaporator. Also, the process is repeated in 3rd evaporator as shown in figure 1.

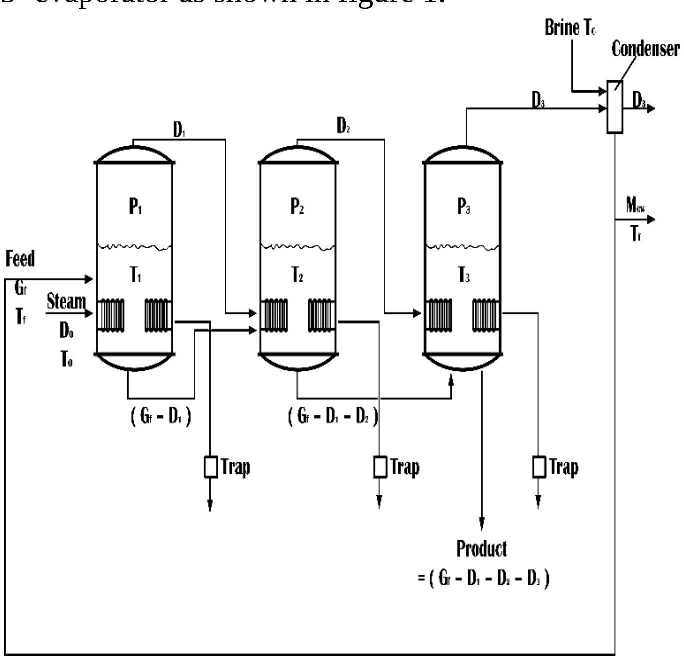

Figure 1: Three Effect Feed Forward MEE

3. STEADY STATE ANALYSIS

Brine solution has a boiling point greater than pure water depending in salt content and the difference between these two boiling points is called the Boiling Point Elevation (BPE). The variation of the boiling of saline solution with sodium chloride concentration can be estimated by an approximate relation

$$T_b = T + aX \quad (1)$$

Where,

$\boldsymbol{T_b}$: Boiling temperature of brine.

$\boldsymbol{T}$: Boiling temperature of water (Given in steam tables)

$\boldsymbol{X}$: Salt concentration in percent %. (kg/kg)

$\boldsymbol{a}$: Coefficient = 0.05 [12]

A recent formula for the saturation pressure of steam is given by [13] and results is shown in in figure 2.

$$P = P_0 \, exp\left[\frac{(A - BT + CT^2)T}{T+273}\right] (2)$$

Where $\boldsymbol{T}$ is temperature in °C with parameters $\boldsymbol{A}$ =19.846, $\boldsymbol{B}$ =8.97×10^{-3}, $\boldsymbol{C}$ =1.248×10^{-5} and $\boldsymbol{P_0}$ = 611.21 MPa for temperature range from 0 °C to 110 °C.

A formula for latent heat of vaporization of water as a function of temperature is given by [14] and results is shown in in figure 4.

$$\lambda = l - mT \quad (3)$$

$$l = 2500.82 \ \frac{\text{KJ}}{\text{Kg}}, \qquad m = 2.358$$

$\boldsymbol{T}$ is temperature in °C.

This equation is valid for 0 °C to 50 °C but we shall use it up to 120 °C with negligible error (15/2200)*100 % less than 1% as obtained from Figure 4. Table 1 gives the variation of saturation pressure and latent heat with temperature.

The effect of salt concentration $\boldsymbol{X}$ on $\boldsymbol{P}$ and latent heat was neglected. The partial derivatives of $\boldsymbol{T_b}$, $\boldsymbol{P}$ and $\boldsymbol{\lambda}$ are

$$\frac{\partial Tb}{\partial T} = 1, \qquad \frac{\partial Tb}{\partial X} = a$$

$$\frac{\partial P}{\partial T} = P_t = P\,\frac{(A - 2BT + 3CT^2)(T + 273) - (A - BT + CT^2)T}{(T + 273)^2}$$

$$\frac{\partial \lambda}{\partial T} = \lambda_t = -m$$

The vapor density ρ_v is calculated from pressure and temeprature by

$$\rho_v = \frac{p}{RT} \qquad (4)$$

where P is calcualed from Eq. (2) and R_w is the gas constant for steam (= 461.52 J/kg/K). The partial deriavtive of ρ_v is

$$\rho_t = \frac{\partial \rho_v}{\partial T} = \frac{P_t}{R_w T} - \frac{P}{R_w T^2}$$

Maximum error <1% at 120°C for three evaporators arranged as shown in Figure (4).
where the temperatures and pressures are T_1, T_2, T_3, and P_1, P_2, P_3 respectively, in each effect, if brine has noboiling point rise, then the heat transmitted per unit time across each effect is:

Effect 1:

$Q_1 = U_1A_1\Delta T_1$, where $\Delta T_1 = (T_0 - T_1)$,

Effect 2:

$Q_2 = U_2A_2\Delta T_2$, where $\Delta T_2 = (T_1 - T_2)$,

Effect 3:

$Q_3 = U_3A_3\Delta T_3$, where $\Delta T_3 = (T_2 - T_3)$,

Neglecting the heat required to heat the feed from T_f to T_1, the heat Q_1 transferred across A_1, assuming that the heat transferred is equal So :
$Q_1 = Q_2 = Q_3$
So that: $U_1A_1\Delta T_1 = U_2A_2\Delta T_2 = U_3A_3\Delta T_3$.
If, as commonly the case, the individual effects are identical, $A_1 = A_2 = A_3$, and:
$U_1\Delta T_1 = U_2\Delta T_2 = U_3\Delta T_3$
The water evaporated in each effect is proportional to Q, since the latent heat is approximately constant. Thus the total capacity is:
$Q = Q_1 + Q_2 + Q_3$
$= U_1A_1\Delta T_1 + U_2A_2\Delta T_2 + U_3A_3\Delta T_3$
If an average value of the coefficients U_{av} is taken, then:
$Q = U_{av}(\Delta T_1 + \Delta T_2 + \Delta T_3)A$
Assuming the area of each effect is the same. At a pressure of P_3 kN/m^2 , the boiling point of water is T_3 K, so that the total temperature difference
$\Sigma \Delta T = T_0 - T_3$ K.

The latent heats λ_0, λ_1, λ_2 and λ_3, are givenin steam tables where :
λ_0 KJ/Kgis the latent heat at T_0
λ_1KJ/Kgis the latent heat at T_1
λ_2 KJ/Kgis the latent heat at T_2
λ_3 KJ/Kgis the latent heat at T_3
Assuming that the condensate leaves at the steam temperature, and then heat balances across each effect may be made as follows:

Effect 1:

$D_0\lambda_0 = G_fC_p(T_1 - T_f) + D_1\lambda_1$

Effect 2:

$D_1\lambda_1 + (G_f - D_1)C_p(T_1 - T_2) = D_2\lambda_2$,

Effect 3:

$D_2\lambda_2 + (G_f - D_1 - D_2)C_p(T_2 - T_3) = D_3\lambda_3$,

Where G_f is the mass flow rate of brine fed to the system, and C_p is the specific heat capacity of the liquid, which is assumed to be constant.
The material balance of sodium chloride gives
$G_fX_f = (G_f - D_1 - D_2 - D_3)X_3$
That can put in the following matrix form:

$$\begin{bmatrix} U_1 & -U_2 & 0 \\ 0 & U_2 & -U_3 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \Delta T_1 \\ \Delta T_2 \\ \Delta T_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ T_0 - T_3 \end{bmatrix} \qquad (5)$$

$$\begin{bmatrix} \lambda_0 & -\lambda 1 & 0 & 0 \\ 0 & \lambda_1 - C_p(T_1 - T_2) & -\lambda_2 & 0 \\ 0 & -C_p(T_2 - T_3) & \lambda_2 - C_p(T_2 - T_3) & -\lambda_3 \\ 0 & X_3 & X_3 & X_3 \end{bmatrix}$$

$$\begin{bmatrix} D_0 \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} G_f C_p(T_1 - T_f) \\ -G_f C_p(T_1 - T_2) \\ -G_f C_p(T_2 - T_3) \\ G_f(X_3 - X_f) \end{bmatrix}$$

First matrix equation gives ΔT_1, ΔT_2, and ΔT_3 from which
$T_1 = T_0 - \Delta T_1$, $T_2 = T_1 - \Delta T_2$ and $T_3 = T_2 - \Delta T_3$
The second matrix equation gives D_0, D_1, D_2 and D_3
To find X_1 and X_2 make material balance at the first effect and at the first and second effect respectively
$G_fX_f = (G_f - D_1)X_1$
$G_fX_f = (G_f - D_1 - D_2)X_2$
The heat balance at the condenser is:
$D_3\lambda_3 = (G_f + M_{cw})C_p(T_f - T_c)$
Having obtained X_2 and X_3 update the brine temperatures T_{b3}, T_{b2} and T_{b1}

$$T_{b3} = T_3 + aX_3$$
$$T_{b2} = T_2 + aX_2 T_{b1} = T_1 + aX_1$$

As a check to the assumption of equal heat transfer area calculate

$A_1 = D_0\lambda_0 / U_1 \Delta T_1,$

$A_2 = D_1\lambda_1 / U_2 \Delta T_2$

$A_3 = D_2\lambda_2 / U_3 \Delta T_3$

In the first iteration use $\boldsymbol{T_1}$, $\boldsymbol{T_2}$ and $\boldsymbol{T_3}$ in the second matrix Eq. In the subsequent iterations use $\boldsymbol{Tb_1}$, $\boldsymbol{Tb_2}$ and $\boldsymbol{Tb_3}$ in the second matrix Eq. Iterations are necessary to force $A_1=A_2=A_3$ approximately. $\boldsymbol{T_o}$ update $\boldsymbol{\Delta T_1}$, $\boldsymbol{\Delta T_2}$, and $\boldsymbol{\Delta T_3}$ as follows

$$\Delta T_{(1)} = \Delta T_{(1)} + (A_1 - A_2)/g$$
$$\Delta T_{(2)} = \Delta T_{(2)} + (A_2 - A_3)/g \quad (7)$$
$$\Delta T_{(3)} = \Delta T_{(3)} + (A_3 - A_1)/g$$

Where$\boldsymbol{g}$ is an adjustable parameter dependent on $\boldsymbol{X_f}$ and $\boldsymbol{X_3}$. The sum of $\boldsymbol{\Delta T_1}$, $\boldsymbol{\Delta T_2}$, and $\boldsymbol{\Delta T_3}$ is $\boldsymbol{T_0}$ -$\boldsymbol{T_3}$ .Also no change in $\boldsymbol{\Delta T_1}$, $\boldsymbol{\Delta T_2}$, and $\boldsymbol{\Delta T_3}$ occurs when $\boldsymbol{A_1=A_2=A_3}$.

Pressures $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$ are calculated using Eq. 2. The performance of the three effects MEE is the ratio between the output steam to the input steam.

$$J = \frac{D_1 + D_2 + D_3}{D_0} \quad (8)$$

To calculate the brine rejected $\boldsymbol{M_{cw}}$. Carry out energy balance at the condenser

$$M_{cw} = D_3\,\lambda_3 / C_p(T_f - T_c) - G_f$$

The input data are $\boldsymbol{P_0}$, $\boldsymbol{T_0}$, $\boldsymbol{P_3}$, $\boldsymbol{T_f}$, $\boldsymbol{T_c}$, $\boldsymbol{G_f}$, $\boldsymbol{X_f}$, and $\boldsymbol{X_3}$ (brine concentration in the third effect).

Table 1: Saturation steam pressure and latent heat from steam table

T °C	P MPa	λ KJ/Kg	V_g m^3/Kg	ρ_v Kg/m^3
20	0.002339	2453.5	57.76	0.0173
25	0.003170	2441.7	43.34	0.0231
30	0.004247	2429.8	32.88	0.0304
35	0.005629	2417.9	25.21	0.0397
40	0.007385	2406.0	19.52	0.0512
45	0.009595	2394.0	15.25	0.0656
50	0.01235	2382.0	12.03	0.0831
55	0.01576	2369.8	9.564	0.1046
60	0.01995	2357.6	7.667	0.1304
65	0.02504	2345.4	6.194	0.1614
70	0.03120	2333.0	5.040	0.1984
75	0.03860	2320.6	4.129	0.2422
80	0.04741	2308.0	3.405	0.2937
85	0.05787	2295.3	2.826	0.3539
90	0.07018	2282.5	2.359	0.4239
95	0.08461	2269.5	1.981	0.5048
100	0.1014	2256.4	1.672	0.5981
110	0.1434	2229.7	1.209	0.8271
120	0.1987	2202.1	0.8912	1.1221

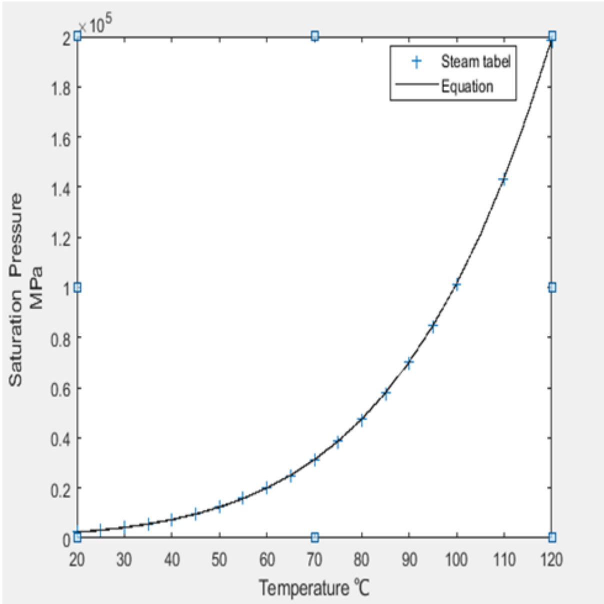

Figure 2: Variation of the Saturation Pressure with Temperature Eq. (2) and Measurements from Table (1)

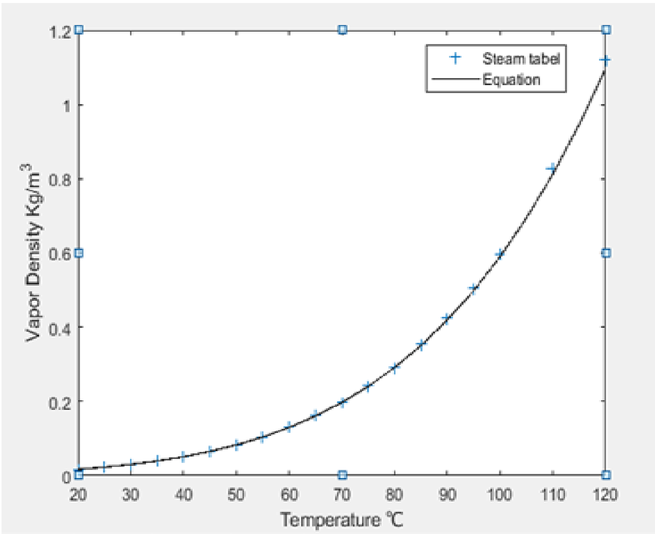

Figure 3: Measured and Calulated Vapor Density Eq. (4)

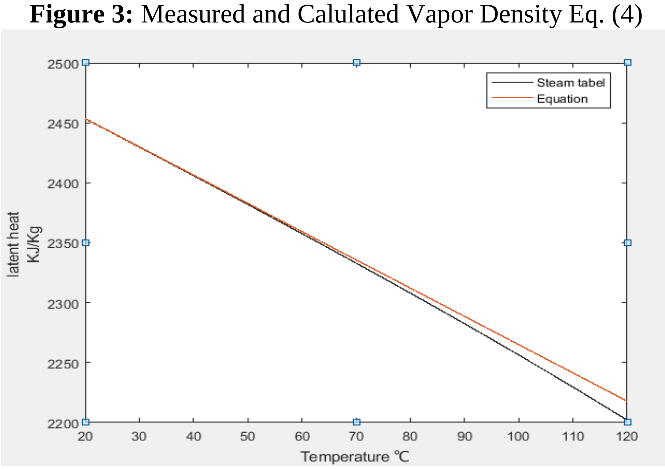

Figure 4: Latent Heat Variation with Temperature Eq. (3) and Calculations from Table (1)

4. DYNAMIC MODEL OF THREE EFFECTS FEED FORWARD MEE

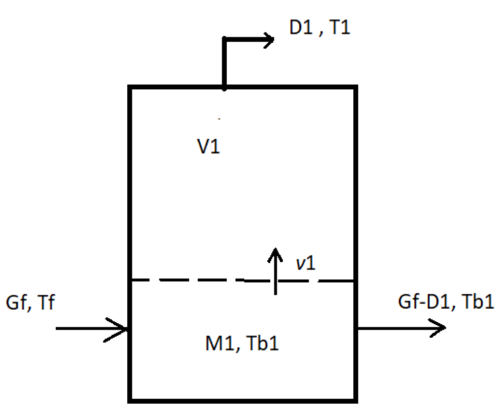

Figure 5: Fluid Components of First Effect

$\boldsymbol{M_1}$ **:** Brine mass in effect 1 $M_1 = \rho_1 L_1 \alpha$

$\boldsymbol{v_1}$ **:** Vapor mass in from $\boldsymbol{M_1}$ to $\boldsymbol{V_1}$ effect 1

$\boldsymbol{V_1}$**:** vapor mass in effect 1 $V_1 = \rho_{v1}(L - L_1)\alpha$

$\boldsymbol{L}$**:** is the length of the effect

$\boldsymbol{\alpha}$**:**is the effective area of the effect

$\boldsymbol{L_1}$**:** is the brine level in the effect

The enthalpy of $\boldsymbol{M_1}$ **:**is$\rho_1 L_1 \alpha C_p(T_{b1} - T_R)$

The enthalpy of $\boldsymbol{V_1}$ **:** is $\rho_{v1}(L - L_1)\alpha(C_p(T_{b1} - T_R) + \lambda_1)$

$\boldsymbol{T_R}$**:** is a reference temperature

$\boldsymbol{c_l}$coefficient of liquid discharge due to difference in liquid height

Material and Energy balance of the first effect

<u>Liquid:</u>

$$\frac{dM_1}{dt} = \frac{d(\rho_1 L_1 \alpha)}{dt} = G_f - v_f - (G_f - D_1) - c_l(L_1 - L_2)$$

<u>Vapor:</u>

$$\frac{dV_1}{dt} = \frac{d(\rho_{v1}(L - L_1)\alpha)}{dt} = v_1 - D_1$$

<u>Salt:</u>

$$\frac{dX_1 M_1}{dt} = \frac{d\,X_1 \rho_1 L_1 \alpha}{dt} = X_f G_f - X_1(G_f - D_1):$$

<u>Energy</u>

$$\frac{d\left(\rho_1 L_1 \alpha C_p(T_{b1} - T_R) + \rho_{v1}(L - L_1)\alpha\left(C_p(T_{b1} - T_R) + \lambda_1\right)\right)}{dt} = D_0\lambda_0 - D_1\lambda_1 - C_p(G_f - D_1)(T_{b1} - T_f)$$

Adding first and second equations

$$\frac{d(\alpha\rho_1 L_1 + \alpha\rho_{v1}(L - L_1))}{dt} = -c_l(L_1 - L_2)$$

Where $\frac{d\rho_{v1}}{dt} = \frac{\rho_{t1} dT_1}{dt}$

$$(\rho_1 - \rho_{v1})\alpha\frac{dL_1}{dt} + \rho_{t1}\alpha(L - L_1)\frac{dT_1}{dt} = -c_l(L_1 - L_2)$$

Third Eq.

$$\rho_1 X_1 \alpha\frac{dL_1}{dt} + \rho_1 L_1 \alpha\frac{dX_1}{dt} = X_f G_f - X_1(G_f - D_1)$$

Fourth Eq.

$$\{(\rho_1 - \rho_{v1})C_p(T_{b1} - T_R) + \rho_{v1}\lambda_1\}\alpha\frac{dL_1}{dt} +$$

$$\{(\rho_1 L_1 + \rho_{v1}(L - L_1))C_p\ \alpha\}\alpha\frac{dX_1}{dt} +$$

$$\{ (\rho_1 L_1 + \rho_{v1}(L - L_1))C_p + (L - L_1)C_p(T_{b1} - T_R)\rho_{t1} - \rho_{v1}(L - L_1)m\}\alpha \frac{dT_1}{dt} = D_0\lambda_0 - D_1\lambda_1 - C_p(G_f - D_1)(T_{b1} - T_f)$$

In matrix form

$$\begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} \frac{dL_1}{dt} \\ \frac{dX_1}{dt} \\ \frac{dT_1}{dt} \end{bmatrix} = \begin{bmatrix} -c_l(L_1 - L_2) \\ X_f G_f - X_1(G_f - D_1) \\ D_0\lambda_0 - D_1\lambda_1 - C_p(G_f - D_1)(T_{b1} - T_f) \end{bmatrix}$$

$c_{11} = (\rho_1 - \rho_{v1})\alpha$
$c_{12} = 0$
$c_{13} = (L - L_1)\ \alpha\ \rho_{t1}$
$c_{21} = X_1\rho_1\alpha,$
$c_{22} = \rho_1 L_1\alpha$
$c_{23} = 0.$
$c_{31} = (\rho_1 - \rho_{v1})C_p(T_{b1} - T_R)\alpha - \rho_{v1}\lambda_1\alpha,$
$c_{32} = (\rho_1 L_1 + \rho_{v1}(L - L_1))\alpha * C_p * a,$
$c_{33} = ((\rho_1 L_1 + \rho_{v1}(L - L_1))\alpha C_p + (L - L_1)C_p\alpha(T_{b1} - T_R)\rho_{t1} - (\alpha\rho_{v1}(L - L_1)m$

Calculated at T_{1ss} (steady state Temperature of first effect)

Eq. Can be written as

$$E_1 \begin{bmatrix} \frac{dL_1}{dt} \\ \frac{dX_1}{dt} \\ \frac{dT_1}{dt} \end{bmatrix} = F_1$$

Similarly for the second effect

$$\begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} \frac{dL_2}{dt} \\ \frac{dX_2}{dt} \\ \frac{dT_2}{dt} \end{bmatrix} =$$

$$\begin{bmatrix} c_l(L_1 - L_2) - c_l(L_2 - L_3) \\ X_1(G_f - D_1) - X_2(G_f - D_1 - D_2) \\ D_1\lambda_1 - D_2\lambda_2 - C_p(G_f - D_1 - D_2)(T_{b2} - T_{b1}) \end{bmatrix} \quad (10)$$

$c_{11},\ldots c_{33}$ are the same as in Eqs.(9) but calculated at T_{2ss} (steady state Temperature of second effect)

For the third effect

$$\begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} \frac{dL_3}{dt} \\ \frac{dX_3}{dt} \\ \frac{dT_3}{dt} \end{bmatrix} =$$

$$\begin{bmatrix} c_l(L_2 - L_3) - c_l L_3 \\ X_2(G_f - D_1 - D_2) - X_3(G_f - D_1 - D_2 - D_3) \\ D_2\lambda_2 - D_3\lambda_3 - C_p(G_f - D_1 - D_2 - D_3)(T_{b3} - T_{b2}) \end{bmatrix} \quad (11)$$

$c_{11},\ldots c_{33}$ are the same as above but calculated at T_{3ss}(steady state Temperature of third effect).

Condenser dynamics

$$C_p\rho_f V_c \frac{dT_f}{dt} = D_3\lambda_3 - (G_f + M_{cw})(T_f - T_c) \quad (12)$$

V_c, P_c are the condenser volume and pressure respectively. Eq.(9) Can be written as

$$E_1 \begin{bmatrix} \frac{dL_1}{dt} \\ \frac{dX_1}{dt} \\ \frac{dT_1}{dt} \end{bmatrix} = F_1$$

Similarly for Eq. (10) and Eq. (11)

Let

$$X^T = [L_1 - L_{1s}X_1 - X_{1s}T_1 - T_{1s}\ \ L_2 - L_{2s}X_2 - X_{2s}\ \ T_2 - T_{2s}L_3 - L_{3s}X_3 - X_{3s}T_3 - T_{3s}T_f - T_{fs}]$$

A relationship between D_1, D_2 and D_3 and the temperatures T_1, T_2, T_3

$$D_1 = \gamma_1(P_1 - P_2), D_2 = \gamma_2(P_2 - P_3), D_3 = \gamma_3(P_3 - P_c)$$

Pc is the condenser pressure andG_f and X_f are constant. To find γ_1

$$\gamma_1 = \frac{D_{1s}}{P_{1s} - P_{2s}}$$

$$\dot{x} = Ax + bu + bd \quad (13)$$

d: Disturbance; change of $\boldsymbol{T_c}$ from steady state
$d=T_c-T_{cs}$

$$A=\begin{bmatrix} E_1^{-1} & 0 & 0 & 0 \\ 0 & E_2^{-1} & 0 & 0 \\ 0 & 0 & E_3^{-1} & 0 \\ 0 & 0 & 0 & (C_p\rho_f V_c)^{-1} \end{bmatrix}\times$$

$$\begin{bmatrix} -C_l & 0 & 0 & C_l & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & D_{1s}-G_f & \gamma_1 X_{1s}P_{t1} & 0 & 0 & -\gamma_1 X_{1s}P_{t2} & 0 & 0 & 0 & 0 \\ 0 & -C_p a * (G_f-D_{1s}) & -\gamma_1 P_{t1}[\lambda_{1s}-C_p(T_{b1s}-T_{fs})] + D_{1s}m - C_p(G_f-D_{1s}) & 0 & 0 & 0 & 0 & 0 & 0 & C_p(G_f-D_{1s}) \\ C_l & 0 & 0 & -2C_l & 0 & 0 & c_l & 0 & 0 & 0 \\ 0 & G_f-D_{1s} & \gamma_1(X_{2s}-X_{1s})P_{t1} & 0 & D_{1s}+D_{2s}-G_f & P_{t2}*(\gamma_1 X_{1s}-\gamma_1 X_{2s}+\gamma_2 X_{2s}) & 0 & 0 & \gamma_2 X_{2s}*P_{t3} & 0 \\ 0 & f_{62} & f_{63} & 0 & f_{65} & f_{66} & 0 & 0 & f_{69} & 0 \\ 0 & 0 & 0 & C_l & 0 & 0 & -2c_l & 0 & 0 & 0 \\ 0 & 0 & \gamma_1(X_{3s}-X_{2s})P_{t1} & C_l & (G_f-D_{1s}-D_{2s}) & P_{t2}*(\gamma_1 X_{2s}-\gamma_1 X_{3s}+\gamma_2 X_{3s}-\gamma_2 X_{2s}) & 0 & D_{1s}+D_{2s}+D_{3s}-G_f & P_{t3}*(\gamma_3 X_{3s}-\gamma_2 X_{3s}+\gamma_2 X_{2s}) & 0 \\ 0 & 0 & f_{93} & 0 & f_{95} & f_{96} & 0 & f_{98} & f_{99} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -m & -G_f-M_{cws} \end{bmatrix}$$

$$f_{62}=C_p(G_f-D_{1s}-D_{2s})a$$
$$f_{63}=-D_{1s}m+(\lambda_{1s}+\ C_p(T_{b2}-T_{b1})\gamma_1 P_{t1} + C_p(G_f-D_{1s}-D_{2s})$$
$$f_{65}=\ -f_{62}$$
$$f_{66}=\ D_{2s}m-C_p(G_f-D_{1s}-D_{2s}) + \left(-\lambda_{1s}-C_p(T_{b2}-T_{b1})\right)\gamma_1 - \left(\lambda_{2s}-C_p(T_{b2}-T_{b1}\right)\gamma_2 P_{t2}$$
$$f_{69}=\left(\lambda_{2s}-C_p(T_{b2}-T_{b1})\right)\gamma_2 P_{t3}$$
$$f_{93}=C_p(T_{b3}-T_{b2})\gamma_1 P_{t1}$$
$$f_{95}=C_p(G_f-D_{1s}-D_{2s}-D_{3s})a$$
$$f_{96}=-D_{2s}m+C_p\left(G_f-D_{1s}-D_{2s}-D_{3s}\right) + \left(\lambda_{2s}+C_p(T_{b3s}-T_{b2s})\right)\gamma_2 - C_p(T_{b3s}-T_{b2s})\gamma_1)P_{t2}$$
$$f_{98}=-f_{95}$$
$$f_{99}=D_{3s}m-C_p\left(G_f-D_{1s}-D_{2s}-D_{3s}\right) +(-\gamma_3\lambda_3 +\left(C_p(T_{b3s}-T_{b2s})\gamma_2\right)P_{t3}$$

$$b=\begin{bmatrix} E_1^{-1} & 0 & 0 & 0 \\ 0 & E_2^{-1} & 0 & 0 \\ 0 & 0 & E_3^{-1} & 0 \\ 0 & 0 & 0 & (C_p\rho_f V_c)^{-1} \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ .. \\ 0 \\ 0 \\ T_{fs}-T_{cs} \end{bmatrix} \quad (15)$$

5. PERFORMANCE ENHACEMENT USING PI CONTROL

A state feedback PI controller is used to eliminate the effect of disturbance $\boldsymbol{d}(=T_{cws}-T_{cw})$ Choose an output of the system as the pressure of third effect $y=P_3$

$$y=Cx$$
$$C=[0\quad 0\quad 0\quad 0\quad 0\quad 0\quad 0\quad 0\quad P_{t3}\quad 0],$$

The third effect pressure $\boldsymbol{P_3}$ is affected by the u $(u=M_{cw}-M_{cws})$.$\boldsymbol{D}$ is selected as a small number. Let $y_R=P_{3R}$ be desired pressure of third effect

$$p=\int (P_3-P_{3R})\,dt=\int (y-y_R)\,dt$$

Hence

$$\dot{p}=Cx-y_R$$
$$\begin{bmatrix}\dot{x}\\ \dot{p}\end{bmatrix}=\begin{bmatrix}A & 0\\ C & 0\end{bmatrix}\begin{bmatrix}x\\ p\end{bmatrix}+\begin{bmatrix}b\\ 0\end{bmatrix}u+\begin{bmatrix}b & 0\\ 0 & -1\end{bmatrix}\begin{bmatrix}d\\ y_R\end{bmatrix}$$

At steady state $\dot{x}=\dot{p}=0$

$$0=\begin{bmatrix}A & 0\\ C & 0\end{bmatrix}\begin{bmatrix}x_s\\ p_s\end{bmatrix}+\begin{bmatrix}b\\ 0\end{bmatrix}u_s+\begin{bmatrix}b & 0\\ 0 & -1\end{bmatrix}\begin{bmatrix}d\\ y_R\end{bmatrix}$$

Subtract these two equations

$$\begin{bmatrix}\dot{x}\\ \dot{p}\end{bmatrix}=\begin{bmatrix}A & 0\\ C & 0\end{bmatrix}\begin{bmatrix}x-x_s\\ p-p_s\end{bmatrix}+\begin{bmatrix}b\\ D\end{bmatrix}(u-u_s)$$

Let

$$u-u_s=-k_1(x-x_s)-k_2(p-p_s)$$

$\boldsymbol{k_1}$ and $\boldsymbol{k_2}$ are selected to make the closed loop matrix have negative eigenvalues

$$\begin{bmatrix}A & 0\\ C & 0\end{bmatrix}-\begin{bmatrix}b\\ 0\end{bmatrix}[k_1\quad k_2]$$

The gain $[k_1\ k_2]$ can be obtained using lqr command The steady state terms in Eq. cancel and can be written as

$$u=-k_1x-k_2p=-k_1x-k_2\int (y-y_R)\,dt \quad (16)$$

Which is PI controller. Use lqr MATLAB command to design feedback controller.

6. SIMULATION RESULTS

Two sub sections (static analysis section and closed loop analysis with feedback controller section) are considered here. In static analysis the design point that necessary to study the effect of deviation of the external input (e.g. *Tc*) on the performance is calculated. This is carried out in subsection 2. Subsection 3 shows how the feedback Controller restores the performance using feedback control.

a) Static analysis

Table 2: The flowing data are used

T_0 K	T_f K	P_3 KN/m^2	U_1 KW/m^{2}K	U_2 KW/m^{2}K
394	**294**	**13**	**3.1**	**2**
U_3 KW/m^{2}K	X_f %	X_3 %	C_p KJ/Kg K	G_f Kg/s
1.1	**10**	**50**	**4.18**	**4**

T_1: is saturation temperature at P_3=13 kN/m^2 which equals 325 K
Solving Eq. (1) with $T_0 - T_3 = 394 – 325 = 69$ K,
Results of first iteration
$\Delta T_1 = 12.8535$, $\Delta T_2 = 19.9229$, $\Delta T_3 = 36.2235$
$A_1 = 91.7003$, $A_2 = 55.1322$, $A3 = 61.4478$
Results of the 4th iteration
A_1= 63.7015, A_2= 65.1540, A_3 = 66.5189
The vapor flow rates are
D_0 =1.6275, D_1= 0.9914,
D_2 = 1.0680, D_3 = 1.1406,
D_1 =0.9782
D_2=1.0679
D_3=1.1539
The performance is J= 1.9662
A_1 = 91.7003, A_2= 55.1322, A_3 = 61.4478
Since areas are not equal increase $\Delta T_1$and decrease ΔT_2 and ΔT_3. To calculate the brine rejected M_{cw} for T_c= 288, =104.1583
Another run
G_f= 4; T_f= 320; T_0= 394; T_3= 325; T_c= 298
A_1= 61.9185, A_2= 63.1129, A_3= 64.1984
ΔT_1= 16.6170, ΔT_2=17.6679, ΔT_3=34.7151
D_0=1.4397, D_1= 0.9891, D_2=1.0676, D_3= 1.1433
J = 2.2227, M_{cw}=25.5674

b) Closed Loop Performance

The closed loop gain is obtained using lqr command of MATLAB®. Figure (6) shows the closed loop response for step input. The output is chosen to be the pressure of the third effect.

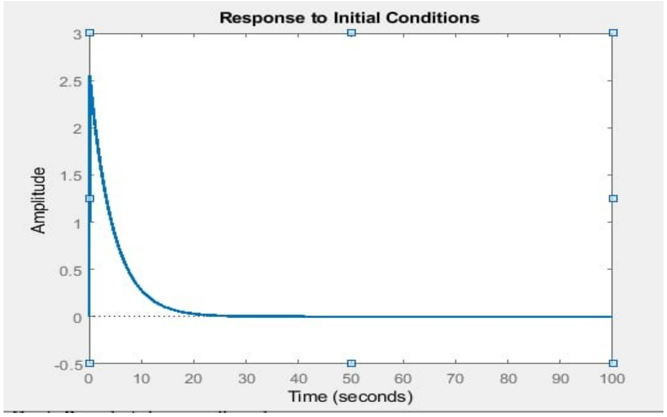

Figure ٦: Closed Loop Response with Output Pressure of the Third Effect

7. CONCLUSION

Novel algorithm for steady state calculation has been presented using MATLAB. At steady state, it was known the temperatures, pressures and flow rates of the three effects and performance of them. A dynamic model is derived for single effect then for MEE. PI controller has been designed to reject the effect of disturbance due to cold water temperature variation which degrades the performance of MEE system. Simulation part contains results of static analysis and feedback controller which restores the performance of the system.

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Appendix A MATLAB script for steadystate

```
clc

clear all

% data file name staticbasmaFF

Gf=4;Tf=294;T0=394;T3=325;Cp=4.18;l=2500.82;m
=2.358;
U1=3.1;U2=2.0;U3=1.1;a=0.05;X3=50;Xf=10;
M1=[U1 -U2 0;0 U2 -U3;1 1 1];B1=[0;0;T0-T3];
dT=inv(M1)*B1;

% first iteration

T1=T0-dT(1);T2=T1-dT(2);T3=T2-dT(3);
lt0=l-m*(T0-273);lt1=l-m*(T1-273);lt2=l-m*(T2-
273);lt3=l-m*(T3-273);
M2=[lt0 -lt1 0 0;0 lt1-Cp*(T1-T2) -lt2 0;
   0 -Cp*(T2-T3) lt2-Cp*(T2-T3) -lt3;0 X3X3 X3];
B2=[Gf*Cp*(T1-Tf);-Gf*Cp*(T1-T2);-Gf*Cp*(T2-
T3);Gf*(X3-Xf)];
D=inv(M2)*B2;D0=D(1);D1=D(2);D2=D(3);D3=D(4);
X1=Gf*Xf/(Gf-D1);X2=Gf*Xf/(Gf-D1-D2);
Tb1=T1+a*X1;Tb2=T2+a*X2;Tb3=T3+a*X3;
dT;
J=(D1+D2+D3)/D0;
 A1=D0*lt0/U1/dT(1),A2=D1*lt1/U2/dT(2),A3=D2*lt2/
  U3/dT(3)

%loop iteration

fori=1:3
   g=10;
dT(1)=dT(1)+(A1-A2)/g;dT(2)=dT(2)+(A2-A3)/g
;dT(3)=dT(3)+(A3-A1)/g;
T1=T0-dT(1);T2=T1-dT(2);T3=T2-dT(3);
lt0=l-m*(T0-273);lt1=l-m*(T1-273);lt2=l-m*(T2-
273);lt3=l-m*(T3-273);
0M2=[lt0 -lt1 0 0;0 lt1-Cp*(Tb1-Tb2) -lt2 0; 0 -
Cp*(Tb2-Tb3) lt2-Cp*(Tb2-Tb3) -lt3;0 X3X3 X3];
B2=[Gf*Cp*(T1-Tf);-Gf*Cp*(Tb1-Tb2);-Gf*Cp*(Tb2-
Tb3);Gf*(X3-Xf)];
D=inv(M2)*B2;D0=D(1);D1=D(2);D2=D(3);D3=D(4);
X1=Gf*Xf/(Gf-D1);X2=Gf*Xf/(Gf-D1-D2);
Tb1=T1+a*X1;Tb2=T2+a*X2;Tb3=T3+a*X3;
dT;
J=(D1+D2+D3)/D0;
 A1=D0*lt0/U1/dT(1),A2=D1*lt1/U2/dT(2),A3=D2*lt2/
 U3/dT(3),
end
```

تحسين الأداء لنظام متعدد مراحل المبخرات لتحلية المياه باستخدام نظام التحكم PI

الملخص:

نظرا لما يواجهه العالم من ندرة المياه الصالحة للشرب خصوصا هذة الأيام فقد أصبحت تحلية المياه من العمليات الضرورية والملحة مما دفع الكثير من الدول الى البحث عن طرق لتحلية المياه وتطويرها .

وقد تم دراسة عمل نظام المبخر المتعدد المراحل في عملية تحلية المياه نظرا لكفاءته العالية وسهولة صيانته . وقد تمت دراسة النظام جيدا ومعرفة المؤثرات التي تؤدي الي التقليل من كفاءته وبالتالي معرفة كيفية التغلب على هذه المؤثرات وذلك بتصميم نظام تحكم PI يمنع أن يتأثر النظام بأى متغيرات خارجية تؤدي الي التأثير على كفاءته مثل درجة حرارة المياه المالحة الداخلة أول العملية عن طريق ضبط معدل تدفق المياه المالحة التي يتم التخلص منها اول العملية مما يؤدى الى ضبط ضغط المبخر الثالث مما يؤدى الى استعادة الكفاءة وبالتالي تم الغاء تأثير هذا المؤثر واخضاع العملية لنظام التحكم المصمم لها قد اظهر كفاءة عالية فى تحسين الادائية.

تم الاستعانة ببرنامج MATLAB® للتمكن من حل المعادلات التي تمثل النظام سواء في الحالة الاستاتيكية او الديناميكية للتمكن من تصميم نظام التحكم PI وعمل محاكاة والتمكن من الحصول على كفاءة عالية والتخلص من مسببات احتمالية قلة الادائية والرجوع بالنظام الى الحالة المستقرة

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