Volume Reduction of Industrial Effluent in Multiple Effect Evaporator through Model-Based Control Schemes

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ABSTRACT: *Multi Effect Evaporator (MEE) is an important unit operation in industrial waste effluent treatment where water recovered from MEE can be reused for industrial operations thus reducing fresh water demand of the industry leading to Zero Liquid Discharge (ZLD) and environmental sustainability. Economically, multi-effect evaporators in many industries are used to improve the steam economy and cut down the waste handling cost. In this study, a dynamic mathematical model for a seven-effect evaporator has been developed and the model is validated against the real-time data collected from an industrial evaporator available in the Common Effluent Treatment Plant (CETP) located at Pallavaram, Chennai, India. Parametric sensitivity analysis is carried out to study the effect of various input parameters on the concentration of the output stream. Parametric studies reveal that input parameters namely heat transfer coefficient and steam flow rate have more influence on the concentration of the output. Lyapunov-based MPC (LMPC) scheme is implemented to achieve important performance characteristics like a low salt concentration in the water discharge, disturbance rejection, and stability. The disturbance rejection efficiency of LMPC is tested by adding 1% positive disturbance in feed concentration. Also, stability is assessed by introducing an additional delay of 2 seconds in the process. The performance of LMPC is compared with other controllers like IMC-PID and MPC. The closed-loop performance of all the proposed controllers for MEE is evaluated using error criteria and settling time. In LMPC, ISE, IAE value, and settling time are drastically reduced by 68.15%, 88.39%, and 21.79% respectively with respect to MPC. Thus better setpoint tracking, quicker settling time and better stabilization of product concentration will pave the way for ZLD and improved water quality of the recycled water.*

KEYWORDS: *Multi-effect evaporator; Model-based control scheme; Effluent treatment; IMC-PID and Lyapunov MPC.*

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INTRODUCTION

Due to increased population, there is an increased need to discharge the wastewater after minimal treatment from industries. The findings of different studies indicate that tannery wastes affect the environment severely, causing ecological imbalance and the spreading of different kinds of fatal and contagious disease among the tannery workers and other individuals [12]. The negative impact of tannery waste on water quality index is comprehensively discussed [15]. Mathematical models representing steady-state are available for Multi Effect Evaporator. However, the detailed work on dynamic behaviour of MEE is not available in literature [1, 5]. Some of the prominent efforts on forming static model for MEE were made by researchers. *Hisham El-Dessouky et al.* [9] explained the steady state analysis using correlation for various parameters and their effect on product. *Miranda* and *Simpson* [11] studied a phenomenological, stationary and dynamic model of five effect evaporator (tomato concentrate) for simulation and control purposes. Rigorous mathematical model namely digital twin was proposed by *Rafael et al.* [13] to represent a four-stage multi-effect evaporation train from an industrial sugar-cane processing unit. The dynamic model behaviour of two or three multi effect evaporator systems in process industries like sugar, food, desalination, paper etc. is also studied. Model based on Mixed Integer Nonlinear Programming (MILP) is developed for optimization purpose [6]. Apart from conventional control schemes, adaptive feedforward controller is also proposed. [8]. Three types of model-based linear approaches namely the Generalized Predictive Control (GPC) Scheme, The Linear Quadratic Gaussian (LQG) and the Internal Model Control (IMC) scheme are applied to five effect evaporators used in sugar industry [7]. However, MILP has its own limitations. *Christofides et al.* [3] describe the design and implementation of Lyapunov MPC for processes. *David Muñoz de la Peña et al.* [4] has suggested that Lyapunov-based Model Predictive Control (LMPC) Scheme Gives Better Stability For The Non- Linear process, fault tolerant control scheme and switched system. In general, MPC plays a prominent role in controlling non-linear systems [10]. When there exists a data loss, actuators make use of predicted evolution of the system to update the input. In order to guarantee the stability of the closed loop system many approaches were formulated. Among them, LMPC gives an explicit characterization of the stability region for the closed-loop system [14]. *Wang et al.* [16] propose a control scheme that combines a feedforward compensation part based on disturbance observer and a feedback regulation part using MPC.

Andréa O.S. Costa et al. [2] have proposed controlling strategies using the combination of phenomenological and neural network approaches based on real-time industrial data. Though various processes were considered for implementing LMPC scheme, evaporators were not extensively chosen due to its energy-consuming performance and its computational complexities. The authors opine that to the best of their knowledge, the proposed LMPC control scheme is the first of its kind on multiple effect evaporator. The evaporator under study is used for concentrating the discharge stream ejected from Reverse Osmosis (RO) of a typical Common Effluent Treatment Plant (CETP).

In this work, a dynamic model representing the transient behaviour of the evaporator is formulated and validated using the real-time data obtained from CETP. LMPC scheme for multi-effect evaporator is designed for controlling temperature and maintaining the stability of the process. With this motivation, the rest of the paper is organized as follows: The Theoretical Section discusses the development of the model. The model validation against plant data is also presented in this section. Open loop results and sensitivity analysis are presented in Results and Discussion. Section 4 describes the design of control schemes and their implementation.

THEORETICAL SECTION

Mathematical model of multieffect evaporator

In a multi-effect evaporator, vapours are reused making the required temperature differences to a lower value. Each effect or evaporator is integrated to another such that the vapour from one effect enters the other as a heating medium. The first effect/stage is fed with raw steam where pressure and vapour space are more. In the last effect, vapour space is minimal. In each effect, the temperature drop across the heating surface corresponds to a pressure drop in that effect. The concentration of the final product is maintained by adjusting the feed flow rate.

The multiple-effect evaporator system considered in this work a seven-effect evaporator is used for the concentration of the salt solution from the Reverse Osmosis (RO)

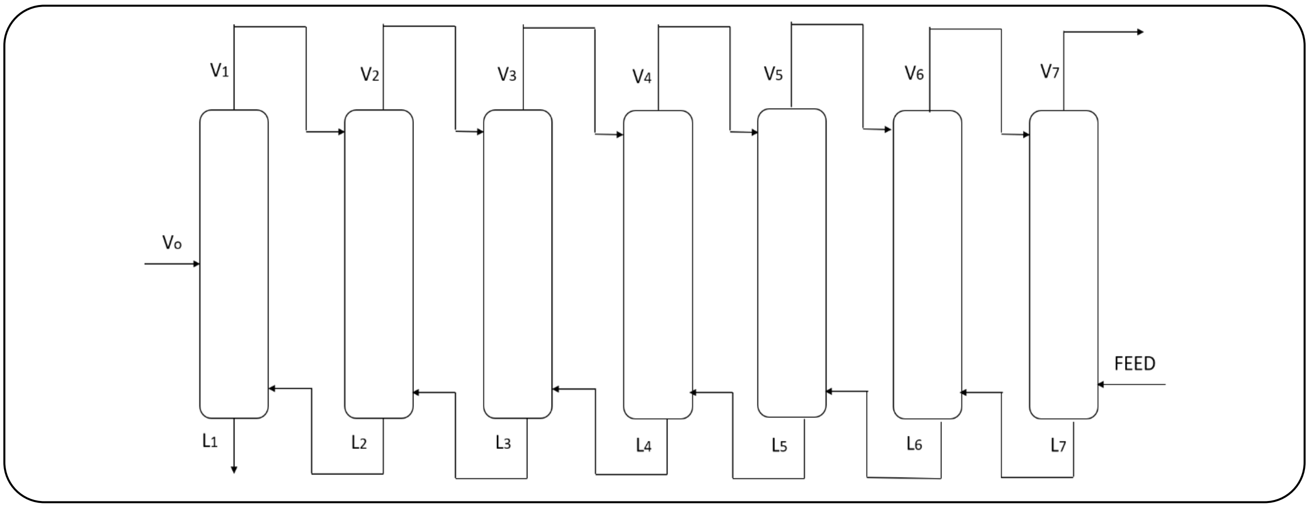

Fig. 1: Process flow diagram of Multi Effect Evaporator.

unit in a Common Effluent Treatment Plant (CETP) at Pallavaram in Chennai. In a CETP, effluents from several process-industries, producing similar products, are collected and are subjected to different unit operations (one of which is reverse osmosis) to treat the effluent. It gives rise to a tedious problem in disposing RO rejects (concentrated brine solutions). Reuse of these RO rejects in original process give rises to quality control problems. Hence, as an alternative, salts from brine are separated in evaporator followed by centrifuge. During the treatment, salts containing in the effluents are concentrated in MEE for further use in different purposes. The feed flow sequence of the considered process is backward and the steam flow is forward which means that live-steam is supplied to first effect. Vapour thus formed as a result of steam passage through the first stage is fed as steam input to next stage and a part of vapour coming out from the stage is used to preheat the liquor entering the vapour forming stage in order to improve the overall steam economy of the system. The process flow diagram of multi effect evaporator is shown in Fig. 1.

The following are the assumptions made to formulate the model

- The heat loss to the surroundings in each effect is negligible.
- The latent heat of vaporization and condensation carry temperature dependence, whereas enthalpy of discharge stream depends both on temperature and liquor concentration.
- The discharge stream and vapour produced at each effect are in phase equilibrium

Mass and energy balance equation

Mass and energy balance equations for each effect of MEE are as given below.

Material balance of liquor in the i^{th} effect

$$\frac{dM_i}{dt} = L_{i+1} - L_i - V_i \tag{1}$$

Total component balance for first effect

$$\frac{d(M_1 X_1)}{dt} = L_2 x_2 - L_1 x_1 \tag{2}$$

On differentiating equation (2) with respect to time and simplifying, we get

$$\frac{d(X_1)}{dt} = \frac{L_2(x_2 - x_1) - x_1(V_1)}{M_1} \tag{3}$$

Thus the generalized equation for component balance for each effect can be given by

$$\frac{d(X_i)}{dt} = \frac{L_{i+1}(x_{i+1} - x_i) - x_i(V_i)}{M_i} \tag{4}$$

and the generalized form for steam flow rate is

$$V_i = \frac{U_i A_i (T_{i-1} - T_i)}{\lambda_{i-1}} \tag{5}$$

Energy balance equation for the first effect is represented as

$$\frac{d(T_1)}{dt} = \frac{L_2[h(T_2, x_2) - h(T_1, x_1)] + U_1 A_1 (T_s - T_1) - V_1[H(T_1) - h(T_1, x_1)]}{M_1(4.187 - 2.26098 x_1} \tag{6}$$

For second to sixth effect, the generalised temperature equation is given by

$$\frac{dT_{i+1}}{dt} = \frac{L_{i+1}[h(T_{i+1}x_{i+1}) - h(T_i, x_i)] + U_iA_i(T_{i-1} - T_i) - V_i[H(T_i) - h(T_i, x_i)] - 2.261T_i[L_i(x_i - x_i) + V_ix_i}{M_7(4.187 - 2.26098x_i)} \quad (7)$$

Energy balance equation for the seventh effect is given by

$$\frac{dT_7}{dt} = \frac{L_f[h(T_fx_f) - h(T_7, x_7)] + U_7A_7(T_6 - T_7) - V_7[H(T_7) - h(T_7, x_7)] - 2.261T_7[L_f(x_f - x_7) + V_7x_7}{M_7(4.187 - 2.26098x_7)} \quad (8)$$

The dynamic model for MEE consists of a set of fourteen Differential-Algebraic Equations (DAEs) which are obtained after applying the first principle laws and empirical correlations of physico-thermal parameters namely: enthalpy of discharge stream (h_l), vapour (H) and condensate (h_c), and latent heat of vaporization (λ_i). The empirical correlation of enthalpy of liquor, enthalpy of vapour and latent heat of vaporisation with respect to temperature and product concentration are given in equation (9-12).

$$\lambda_i = -0.003857T_i^2 - 2.069T_i + 2497 \approx -2.069T_i + 2497 \quad (9)$$

$$H_i = -0.0002045T_i^2 - 1.677T_i + 2507 \approx -1.677T_i + 2507 \quad (10)$$

$$h_{li} = (4.187 - 2.26098x_i)T_{li} \quad (11)$$

$$h_{ci} = 0.001364T_i^2 + 4.15T_i - 2.24 \quad (12)$$

Model validation with real time plant

Validation of open loop response with the real time data of product concentration obtained from CETP is also performed and is shown in Fig. 2.

It is observed that the first principle model gives similar trend as that of real time data. Their similarities are computed by evaluating the error between them, using root mean square. The root mean square error between the predicted graph and real time data is 1.5292. States space matrices were formed for the seven stage evaporator by considering temperature and concentration of liquor in each effect as states. As we have seven effects, it totally gives 14 states.

Open loop studies

Open loop studies were carried out by simulating the above equations pertaining to all effects in MATLAB Simulink. The operating parameters used for the MEE are given in Table 1.

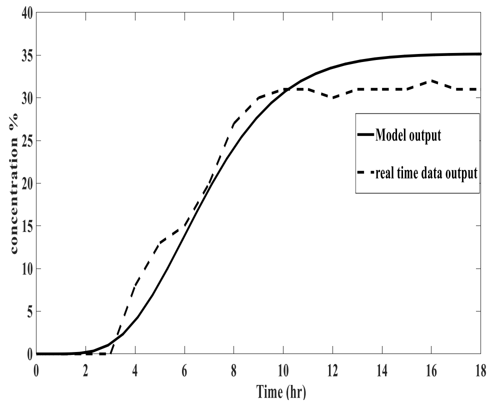

Fig. 2: Validation of open loop response with real time data obtained from the effluent treatment plant.

The steady state values and the nominal values of physico thermal parameters of multi effect evaporator are given in Table 2 and Table 3 respectively.

Parametric sensitivity analysis

In order to study the effect of parameters on the overall performance of the process, the sensitivity of the system to variations in input parameters is tested. The sensitivity of the MEE's behaviour to variations in withhold mass per effect, latent heat of vaporization, heat transfer coefficient and enthalpy is analysed. While maintaining the other parameters at the nominal value, variation of ±10% from nominal value was given in each of the above input parameters. The corresponding change in the product concentration is determined and is presented quantitatively in Table 4 and qualitatively in Fig. 3.

From the Table 4 and Fig. 3, it is observed that product concentration does not change for change in withhold mass per effect while it decreases for increase in latent heat of vaporization. Likewise, the concentration increases for increase in heat transfer coefficient and for increase in specific heat. The graphical response of parametric sensitivity analysis is given in Fig. 4.

Thus, from the sensitivity analysis, it is found that 'heat transfer coefficient' has more influence on the product concentration whereas variation in 'withhold mass per effect' shows no effect. The other parameters namely enthalpy has least effect on the product concentration while variations in latent heat of vaporization decreases

Table 1: Operating parameters of the multi effect evaporator.

S.No	Parameters	Values
1	Total number of effects	7
2	Number of effects supplied to live steam	1
3	Sequence of feed	Backward
4	Sequence of steam	Forward
5	Cross sectional Area of each effect	2357 m^2
6	Feed concentration	3%
7	Output concentration	35%
8	Feed flow rate	5.28 kg/s
9	Temperature of last effect	67^{o}C
10	Inlet steam temperature	110^{o}C

Table 2: Steady State Values of multi effect evaporator.

Amount of change given	Steady state value of the variable considered	Product Concentration (Fraction)	Product Concentration (%)
Parameter: Withhold mass per effect			
Nominal value	90.19 kg	0.3582	35.82
Increase of 10%	99.21 kg	0.3582	35.82
Decrease of 10%	81.17 kg	0.3582	35.82
Parameter: Latent heat of vaporization			
Nominal value	2311.6 ^{o}C	0.3582	35.82
Increase of 10%	2521.2 ^{o}C	0.3402	34.02
Decrease of 10%	2062.8 ^{o}C	0.383	38.3
Parameter: Heat transfer coefficient			
Nominal value	1.44 kW/m^2 ^{0}C	0.3582	35.82
Increase of 10%	1.584 kW/m^2 ^{0}C	0.3803	38.03
Decrease of 10%	1.296 kW/m^2 ^{0}C	0.3385	33.85
Parameter: Specific Heat (Through Enthalpy)			
Nominal value	242.57 kJ/kg	0.3582	35.82
Increase of 10%	266.83 kJ/kg	0.3655	36.55
Decrease of 10%	218.31 kJ/kg	0.3492	34.92

Table 3: Nominal values of physico thermal parameters of multi effect evaporator.

Effect	Concentration (%)	Boiling point Elevation (ºC)	Output Temperature (ºC)	Vapour Temperature (ºC)	Density (kg/m^3)
1	35	1.3849	90	88.6150	1188.6
2	32.86	1.2564	89	87.7436	1175.8
3	24.03	0.7868	85	84.2132	1122.8
4	13.47	0.3526	83	82.643	1057.3
5	7.40	0.1658	79	78.8342	1021.2
6	4.65	0.0961	62	61.9039	1012.6
7	3.45	0.0688	58	57.9312	1006.9

Table 4: Effect of input parameters on product concentration of the final product.

Amount of change given	Steady state value of the variable considered	Concentration (Fraction)	Product Concentration (%)	Percentage Change
Parameter: Withhold mass per effect				
Nominal value	90.19 kg	0.3582	35.82	-
Increase of 10%	99.21 kg	0.3582	35.82	0%
Decrease of 10%	81.17 kg	0.3582	35.82	0%
Parameter: Latent heat of vaporization				
Nominal value	2311.6 ºC	0.3582	35.82	-
Increase of 10%	2521.2 ºC	0.3402	34.02	0.05%
Decrease of 10%	2062.8 ºC	0.3759	37.59	-0.05%
Parameter: Heat transfer coefficient				
Nominal value	1.44 kW/m^2 ^{0}C	0.3582	35.82	-
Increase of 10%	1.584 kW/m^2 ^{0}C	0.3803	38.03	-0.06%
Decrease of 10%	1.296 kW/m^2 ^{0}C	0.3365	33.65	0.06%
Parameter: Specific Heat (Through Enthalpy)				
Nominal value	242.57 kJ/kg	0.3582	35.82	-
Increase of 10%	266.83 kJ/kg	0.3655	36.55	-0.02%
Decrease of 10%	218.31 kJ/kg	0.3509	35.09	0.02%

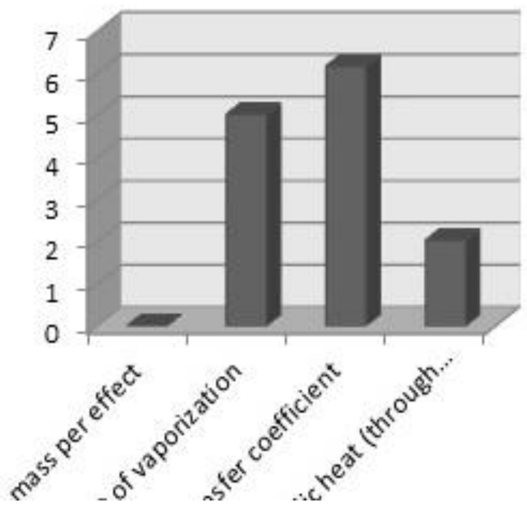

Fig.3: Effect of input parameters on product concentration.

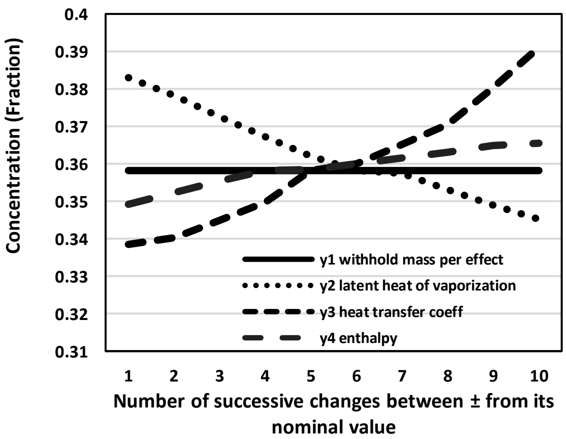

Fig.4: Response of Parametric sensitivity analysis.

the product concentration. Similarly, to analyse the effect of input variables on product concentration, ±10% step change is given to steam flow rate, feed flow rate and feed concentration. The corresponding changes in product concentration were observed and shown graphically in Figs. 5, 6, 7 and quantitatively in Table 5. From the analysis, it is observed that variations in steam flow rate has greater influence on product concentration while variations in feed flow rate and feed concentration does not influence much.

The quantitative results of the analysis carried out is given in Table 5. From the analysis, it is observed that variations in steam flow rate has greater influence on product concentration while variations in feed flow rate and feed concentration does not influence much. Open loop simulation studies of the MEE was performed by simulating the dynamic equations of concentration and temperature. The open loop response obtained are shown in Fig. 8. It is clear that concentration increases as it passes on from seventh to first effect since the feed is backwards. Also it is observed that, temperature at first effect is higher than that of other effects in the evaporator. This is because of the reason that live steam is given at the first effect.

Closed loop studies

Design of IMC-PID control scheme

Although design of Internal Model Control scheme cannot be implemented practically since most industries still uses the PID controller. So the IMC structure can be modified and rearranged to the form of a standard feedback control diagram or Conventional PID structure. The controller settings thus obtained are presented in Table 6.

For stable processes with a time delay the IMC-based PID procedure will not give exactly the same performance as IMC, because a Padé approximation for deadtime is used in the controller design. From the Fig. 9, it is clear that there exists an offset. In order to overcome these issues, advanced control schemes namely MPC is designed.

Model predictive control scheme

Model Predictive Control (MPC) is one of the advanced control scheme which is widely used in many processing industries. MPC method is mostly preferred for the time lag process. The major feature of this control is that it can handle input, output and state constraints well. While designing MPC, objective function must be chosen in such a way that it should minimize the tracking error and control effort. The objective function is a "sum of squares" of the predicted errors (differences between the set points and the model-predicted outputs) and the control moves (changes in control action from step to step). MPC scheme was implemented in MATLAB software using MPC toolbox where the considered prediction horizons are 50 and control horizons are 7 with control interval of 0.4. Feed flow rate of inlet dilute solution at effect seven is considered as disturbance. Fig. 10 shows the MPC scheme result for servo operations. With reduced time, MPC scheme offers better performance without any overshoot.

Table 5: Effect of input variables on product concentration.

Effect	Mass flow of liquor (kg/s)	Mass flow of Vapour (kg/s)	Enthalpy of liquor (kJ/kg)	Enthalpy of Vapour (kJ/kg)	Heat transfer coefficient (kW/m^2 ^{o}C)	Mass hold up (kg)
1	0.4529	0.0295	376.73	2659.08	6.7	5.08
2	0.482	0.1772	372.529	2657.84	3.367	9.648
3	0.6596	0.5169	355.72	2651.64	2.15	13.19
4	1.1765	0.9650	347.31	2646.98	3.306	30.7
5	2.1414	1.2666	330.52	2641.94	2.130	42.84
6	3.4081	1.1823	259.32	2613.207	1.992	68.16
7	4.5900	0.6896	242.57	2606.33	1.44	90.19

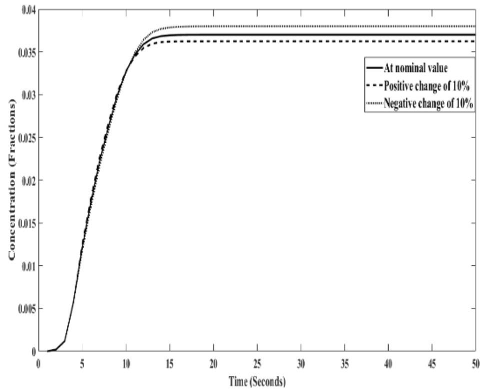

Fig. 5: Variation in product concentration for ± 10% change in feed flow rate from the nominal value.

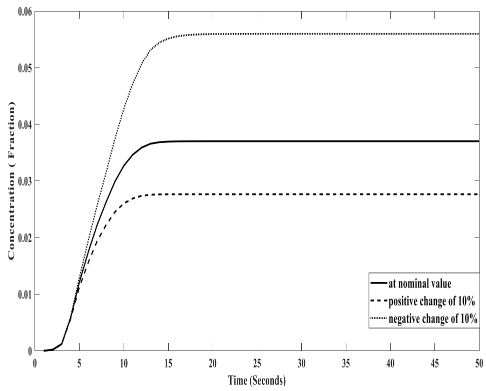

Fig. 7: Variation in product concentration for ±10% change in steam flow rate from the nominal value.

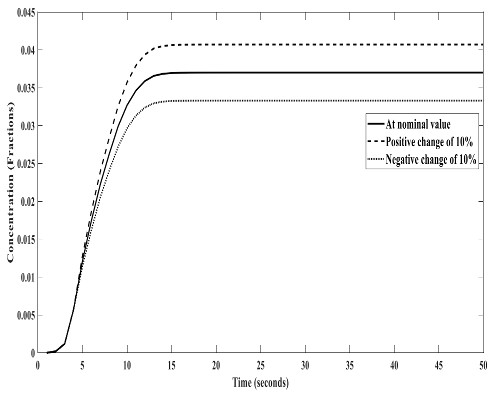

Fig. 6: Variation in product concentration for ±10% change in feed concentration from the nominal value.

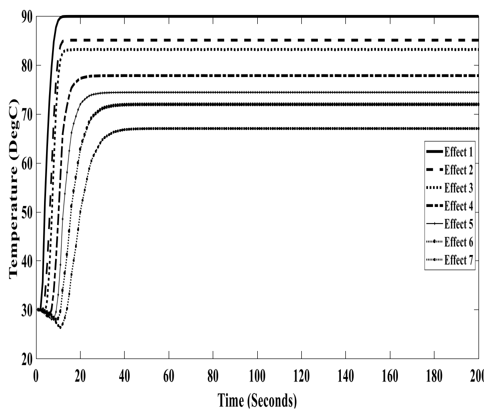

Fig. 8: Open loop responses for temperature at each effect.

Lyapunov based model predictive control scheme

To guarantee the stability of MPC scheme, lyapunov based non-linear controller design is proposed. The stability properties of Lyapunov based Model Predictive Control (LMPC) scheme are inherited due to the presence of non-linear control law. First a controller is designed that makes the time-derivative of a Lyapunov function along the closed-loop system trajectory negative definite around the equilibrium point; then, an estimate of the set where the time derivative is negative is computed, and finally,

Table 6: PID Controller settings for IMC PID.

Controller Parameters	K_c	τ_i	τ_d	τ_f
Value	301.74	117.11	0	0.85

a level set (ideally the largest) of lyapunov function embedded in the set where time derivative is negative, is computed. From this approach, we can ensure that the level set is a guaranteed closed-loop stability set.

Let the generalized non-linear process be

$$\dot{x}(t) = f[x(t)] + g[x(t)]u(t) + w(x(t)) \quad (13)$$

Consider the lyapunov function

$$V(x) = x^T P x \quad (14)$$

Where, x^T= [T-T_s C- C_s] is the state and P is the positive definite symmetric matrix that satisfies the Riccati equation

Let the Riccati equation be

$$A^T P + PA - P B^T B P = -Q \quad (15)$$

Design a non-linear control H(x) as a Lyapunov – based feedback law using following method,

$$H(x) = \left\{ -\frac{L_f V + \sqrt{(L_f V)^2 + (L_g V)^{\wedge}(4)}}{(L_g V)} \right\} \quad (16)$$

if $(L_g V) \neq 0$

if $(L_g V) = 0$

Where $(L_f V)$= $\frac{\partial V(x)}{\partial x}$f(x) and$(L_g V)$= $\frac{\partial V(x)}{\partial x}$ g(x) be the Lie derivatives of the scalar function V with respect to the vector fields f and g. Heat transfer coefficient (U) is considered to be a non-linear term as given in equation 17 since, it varies with steam temperature (T_s). Correlation between U and T_s is as follows,

$$U = 1961.9 + 12.6T_s - (9.6 * 10^{-2} {T_s}^2) + (3.16 * 10^{-4} {T_s}^3) \quad (17)$$

Conditions to be satisfied for the stability in the closed loop system

The following conditions have to be satisfied for designing feedback non-linear control law which maintains effective temperature of the process by varying steam flow rate so as to get rid of instability in the response

$\frac{\partial V(x((t_k))}{\partial x}$ f(x((t_k) , u(t_k), 0) ≤ $\frac{\partial V(x((t_k))}{\partial x}$ f(x((t_k) , H(x(t_k)), 0)

$\frac{dV}{dt} < 0$

From above conditions, it is clear that the time derivative of the lyapunov function V(x) at time (t_k) should be smaller than or equal to the value obtained in u = h(x) and V(x) should lies in the stability region considered based on the product concentration and temperature of the process at (t_k).

LMPC scheme can be used only for maintaining stability of the process in case of data losses or asynchronous measurement. If any data loss occurs in a system between controller and process, system starts to run in open loop. Hence, it is important to maintain the stablity of the process. Thus, non- linear feedback control law takes the process input in order to sustain the stability of the process based on process outputs (product concentration and temperature) at ((t_{k-1}) instant.

Procedure for designing Lyapunov based MPC scheme

The implementation strategy the LMPC for systems subject to time-varying measurement delays is as follows.

1. When a measurement x(t_k −d_k) is available at t_k, the LMPC checks whether the measurement provides new information.

If (t_k −d_k) >$\max_{l<t}$(t_l − d_l)), go to Step2. Else the measurement does not contain new information and is discarded, go to Step 5.

2. The LMPC estimates the current state of the system *x*(t_k*)* and computes the optimal input trajectory of *u* based on *x*(t_k*)*, for *t* ∈ [(t_k, (t_k +NΔ).

3. The LMPC sends the entire optimal input trajectory to the actuators.

4. The actuators implement the input trajectory until a new measurement is received at time (t_k+1).

5. When a new measurement is received (k←k +1), go to Step 1.

Quantitatve compression of closed loop performances

A seven stage multieffect evaporator is modelled using differential equations and is validated using the real time data obtained from the industry. Parametric sensitivity is carried out to study the effect of different parameters on product concentration. It is observed that steam flow rate has more effect on product concentration while variations in feed flow rate and feed concentration does not influence much.

With the objective of achieving disturbance rejection and stability, controllers namely IMC-PID, MPC and LMPC is implemented and their closed loop performance is compared. The controllers are tested for disturbance rejection by introducing disturbance of 1% in the feed concentration. In order to test the stability, an additional delay of 2 secs is introduced. Fig. 11 shows the regulatory response of IMC-PID, MPC and LMPC on multieffect evaporator. When there is no delay or loss in the process link, lyapunov based control law remain inactive. But when an additional delay of 2 Secs is introduced into the process, yet lyapunov based MPC scheme provides better stability of the process.

The quantitative comparison of closed loop performance of various control schemes is presented in Table 7. From Table 7, it is observed that Lyapunov MPC scheme gives better results compared to other control schemes in terms of time domain features like ISE, IAE and settling time. It is also found that LMPC provides better disturbance rejection and good stability for the instability of process caused due to process delay.

Relative to IMC-PID, it is observed that ISE value and IAE value in LMPC has drastically reduced by 47.47% and 63.64% respectively. Similarly, relative to MPC, LMPC shows ISE and IAE value reduced by 68.15% and 88.39% respectively. The settling time in LMPC is reduced by 11.17% with respect to IMC-PID and 21.79% with respect to MPC.

Table 7: Performance measure for various control schemes.

Controller	ISE	IAE	Settling time (s)
IMC-PID	378.42	23.94	173.6
MPC	263.607	17.236	89
LMPC	179.637	15.236	19.4

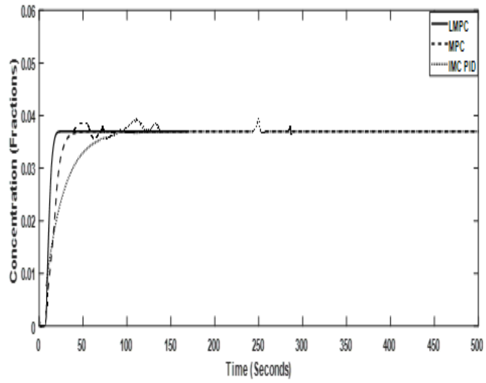

Fig. 11: Closed loop response of LMPC scheme.

CONCLUSIONS

In this work, the dynamic model of a seven effect Multi Effect Evaporator (MEE) is formulated using first principle method. The model is validated against the real time data obtained from a typical industrial MEE used in local Common Effluent Treatment Plant (CETP). It was found that the Root Mean Square Error (RMSE) between the real evaporator temperature and that of the simulated model is lesser confirming a close agreement of the formulated model with the realtime data. Sensitivity study on input parameters like withhold mass per effect, latent heat of vaporization, heat transfer coefficient and enthalpy to study their effect on product concentration is carried out. Also effect of steam flow rate, feed flow rate and feed concentration on the product concentration is also studied to optimally select the appropriate manipulated variable for controller design. It was found that the product concentration is more sensitive towards changes in heat transfer coefficient and steam flow rate. In order to effectively control the product concentration and also achieve disturbance rejection, control schemes namely IMC-PID and MPC is implemented. Disturbance rejection by the controllers is assessed by introducing a positive disturbance of 1% in feed concentration. Also in order to guarantee the stability of the MEE, lyapunov based control law has been implemented by considering the combination of product concentration and temperature as lyapunov function. The performance of the LMPC scheme is assessed by introducing an additional delay of 2 seconds in the process and it is observed that LMPC scheme still can capture the dynamics of the plant variables. The performance of the proposed control schemes are evaluated quantitatively in terms of ISE, IAE and settling time.

ISE, IAE value and settling time is drastically reduced by 68.15% , 88.39% and 21.79% respectively with respect to MPC. Thus LMPC proves to be a robust controller achieving setpoint tracking, disturbance rejection and process stability. Future research direction on multieffect evaporator can be in the areas of multiobjective optimization where evaporation parameters namely feed temperature, feed flow rate and steam flow rate can been optimized for achieving energy minimization and quality control.

Numenclatures

i	Effect number
L_i	Mass flow rate of i^{th} effect
V_i	Vapour flow rate of i^{th} effect
M_i	Mass hold up in i^{th} effect
U_i	Heat transfer co-efficient of i^{th} effect
A_i	Area of i^{th} effect
T_i	Temperature of i^{th} effect
λ_i	Latent heat of vaporisation of i^{th} effect
H_i	Enthalpy of vapour in i^{th} effect
H	Enthalpy of brine in i^{th} effect
S	Steam flow rate
L_f	Flow rate of feed
x_f	Feed concentration
B_{pe_i}	Boiling point elevation of i^{th} effect
X_p	Product concentration
L_p	Mass flow rate of the product
K	Total number of effect
$\mathbf{T_s}$	Steam temperature
T_k	Time at an instant k
D	Delay time

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