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Simulation and control of evaporator: caustic soda concentrate

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Abstract

The presented work examines the dynamic model as well as the control related to the multiple-effect evaporator through conducting 3 control strategy types for the evaporation of the caustic soda solution. Neural, fuzzy, and PID are the control techniques in this work, while the results specified that excellent enhancement for caustic soda system was done in the case when a fuzzy logic with 7 functions of membership and neural predictive control was utilized, since such approaches were more adequate, less integral absolute error, less offset value and low overshoot.

Introduction:

The dynamic behaviour related to multiple-effect evaporators was examined via generating 4 disturbance types such as feed concentration, rate of the feed flow, feed temperature, and the rate of the steam flow (Kumar, Kumar, and Singh, 2012). Because of the increase in applications of multiple-effect evaporators in the industry of food, the precise modelling regarding such procedures was significant. Due to the large process disturbances and time delays, the precise control related to product temperature is considered to be complicated (Karimi, and Jahanmiri, 2006). A study conducted by Simpson and Miranda (2004) indicated a dynamic, stationary, and phenomenological model of the evaporator of multiple-effects for purposes of control and simulation.

In such a process, the major parameters were the latent heat of vaporization and the global heat transfer coefficient. A study carried out via Riehl and Vlassov (2007) provided an LHP (i.e. loop heat pipe) mathematical model. The researchers specified that the mathematical model has an ability for predicting a transient behaviour related to LHP with integrated reservoirs, while a paper conducted via William and José (2011) examined developing a simulation and mathematical model of the multiple-effect evaporation.

This model performed has shown an acceptable type of dynamic conduct of evaporation process. A study conducted by Shah (2012) specified a model of the steady-state regarding multiple-effect evaporator types for purposes of simulations. The system is showing that the outcomes were acquired for the steam economy by 3.5%. A paper via Kumar et al. (2012) developed the unsteady-state model with regard to the system of multi-effect evaporator of the paper industries for obtaining the system's dynamic responses. The researchers specified that steady-state can be quickly obtained for the temperature compared to the solid concentrations and all responses converging in a smooth way.

Controlling the temperature of the evaporator is one of the significant aspects in evaporation system control since it is directly affecting the safety and effectiveness of the system (Zhu, Zheng, and Wu, 2000). A study conducted by Bakker et al. (2004) developed a cascade controller for the purpose of controlling the concentration of product in 2 effects falling film evaporators. In addition, the control related to concentrates total solids that exited the multi-effect and the multi-pass falling film evaporators might be improved via using cascade architecture. A study conducted by Jahanmiri and Farsi (2009) examined simulation and non-linear dynamic modelling regarding 3-effect falling film evaporator, while the obtained results were put to comparison with the results of traditional PID control. A study carried out via Atuonwu et al. (2010) utilized an RNN-based NMPC (i.e. non-linear model predictive control) system in a parallel manner with the control loops of the PI, which have been created for the model of the simulation regarding 5-stage industrial-scale evaporators.

In addition, results are showing considerable enhancements in the control performance through a new parallel NMPC PI control system. Zhang et. al. (2011) developed a fuzzy sliding model controller for the purpose of controlling the evaporator's superheat in waste heat using the system. The suggested controller was utilized for controlling the evaporator's outlet temperature, while the results of the simulation specified that fuzzy mechanism of inference might be reducing chattering, also the performance of the system of the closed-loop is good. A study conducted by Chai et. al. (2012) created a mathematical framework that has been related to the system of the evaporation as a model of the state-space with several of the time delays, while the research of the simulation specified that results that have been acquired via optimum control were better than the ones acquired via a level controller utilized in the present practice as well as model predictive control (MPC).

The system studied:

A simulated feed forward 4-effect evaporator which is related to caustic soda is indicated in Fig1. The raw solution's evaporations should be conducted in a range of pressure which is less than the atmospheric pressure as pumps are controlling pressure externally, every effect's temperature has been set via vapor temperature from the former effect as well as head pressure, that is set for meeting the specifications of solid contents. The steam enters system at concentrator in the 1st phase. Furthermore, the concentrate levels for each one of the effects were regulated for the purpose of avoiding low levels as well as getting a suitable global heat transfer coefficient.

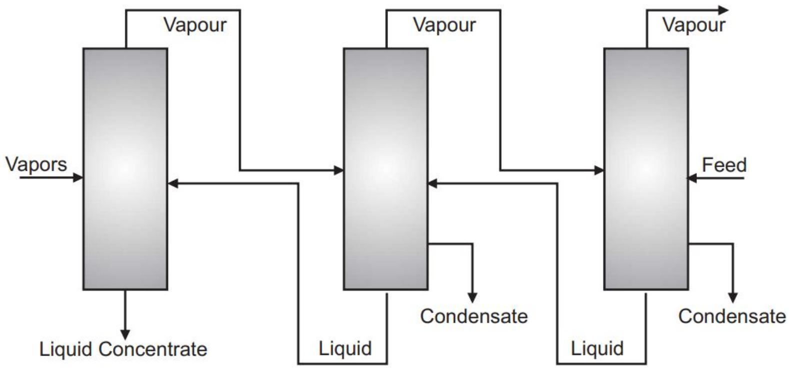

Fig. 1 *Multiple-effect evaporation equipment.*

Evaporator's Mathematical Modelling:

The temperature and composition in every one of the evaporators were homogenous, the solution density and solution level evaporator has been constant, thermos-dynamic equilibrium (liquid-vapor) with regard to the entire modelled system as well as a process of evaporation was within atmospheric pressure. The evaporator's modelling involves the formulation related to component balances and total mass along with the balance of the energy.

The evaporator has been simulated according to the formulas of the model:

Total balance of the mass at the unsteady states

$$\frac{dM}{dt} = m_{in} - m - m_{vap} \qquad (1)$$

-The mass balance of the component, which has been based on the soluble solid types.

$$\frac{d(c_s(t)M)}{dt} = m_{in}c_{s,in}(t) - m\ c_s(t) \qquad (2)$$

Eq. (2) may be expressed as:

$$\frac{d(c_s(t)\ M)}{dt} = c_s(t)\ \frac{dm}{dt} + M\ \frac{dc_s(t)}{dt} \qquad (3)$$

The substitution of Eqs (1) & (2) in Eq3 will give:

$$M\ \frac{dc_s(t)}{dt} = c_{s,in}(t)m_{in} - c_s(t)\left(m_{in} - m_{vap}\right) \quad (4)$$

Re-arranging eq4 will give:

$$M\ \frac{dc_s(t)}{dt} + c_s(t)\left(m_{in} - m_{vap}\right) = c_{s,in}(t)\ m_{in} \qquad (5)$$

Dividing eq5 by $(\dot{m}_{in} - \dot{m}_{vap})$ gives:

$$\frac{M}{\left(\dot{m}_{in} - \dot{m}_{vap}\right)}\ \frac{dc_s(t)}{dt} + c_s(t) = \frac{m_{in}}{\left(m_{in} - m_{vap}\right)}\ c_{s,in}(t)$$

Putting:

$$\tau_1 = \frac{M}{(m_{in} - m_{vap})}\ , k_1 = \frac{m_{in}}{(m_{in} - m_{vap})}$$

$$\tau_1\ \frac{dc_s(t)}{dt} + c_s(t) = k_1\ c_{s,in}(t) \qquad (6)$$

Taking the Laplace transform of equation (6):

$$\tau_1 s\ c_s(s) + c_s(s) = k_1\ c_{s,in}(s)$$

So:

$$c_s(s) = \frac{k_1}{\tau_1 s+1}\ c_{s,in}(s) \qquad (7)$$

Lastly, the system's transfer function might be characterized via 1st-order system:

$$G(s) = \frac{c_s(s)}{c_{s,in}(s)} = \frac{k_1}{\tau_1 s+1} \qquad (8)$$

Total balance of the energy at the unsteady states

$$\frac{d(MH)}{dt} = m_{in}\ H_{in} - m\ H - m_{vap}\ H_{vap} + \dot{Q}_{steam} \qquad (9)$$

$\dot{Q}_{steam}$ represents the steam that generates in power plant:

$$\dot{Q}_s = \dot{m}_s\ (H_s - H_c) \qquad (10)$$

and product concentration enthalpy:

$$H = cpT \qquad (11)$$

$$cp = 4.1868 + 2.261c_S \qquad (12)$$

Substitute Eqs (10, 11 & 12) in (Eq9) will give:

$$M\ cp\ \frac{dT}{dt} = -T(t)\ \left[m_{in}\ cp - m_{vap}\ cp\ - m\ \ B\ \left(c_s(t) - c_{s,in}(t)\right)\right] + m_{in}\ cp_{in}\ T_{in}(t) + \dot{m_s}\ (t)(\ H_s -\ H_c\ ) \qquad (13)$$

Rearranging of equation (13):

$$M\ cp\ \frac{dT}{dt} + T(t)\ \left[m_{in}\ cp - m_{vap}\ cp\ - m\ \ B\ \left(c_s(t) - c_{s,in}(t)\right)\right] = m_{in}\ cp_{in}\ T_{in}(t) +\ m_s\ (t)(\ H_s - H_c\ ) \qquad (14)$$

The division of eq. (15) by $\left[m_{in}\ cp - m_{vap}\ cp\ - m\ \ B\ \left(c_s(t) - c_{s,in}(t)\right)\right]$ and putting:

$$\tau_2 = \frac{M\ cp}{m_{in}\ cp - m_{vap}\ cp\ - m\ \ B\left(c_s(t) - c_{s,in}(t)\right)}$$

$$k_2 = \frac{m_{in}\ cp_{in}}{m_{in}\ cp - m_{vap}\ cp\ - m\ \ B\left(c_s(t) - c_{s,in}(t)\right)}$$

$$k_3 = \frac{(\ H_s - H_c\ )}{m_{in}\ cp - m_{vap}\ cp\ - m\ \ B\left(c_s(t) - c_{s,in}(t)\right)}$$

$$\tau_2 \frac{dT}{dt} + T(t) = k_2\ T_{in}(t) + k_3 \dot{m_s}(t) \qquad (15)$$

Taking Laplace transformation of the eq15:

$$\tau_2 s\ T(s) + T(s) = k_2\ T_{in}(s)\ \ + k_3 \dot{m_s}(s)$$

So:

$$T(s) = \frac{k_2}{\tau_2 s+1}\ T_{in}(s) + \frac{k_3}{\tau_2 s+1}\ \dot{m_s}(s) \qquad (16)$$

At the steady-state of T_{in}, Eq. (16) will be:

$$G(s) = \frac{T(s)}{\dot{m_s}(s)} = \frac{k_3}{\tau_2 s+1} \qquad (17)$$

Control techniques of the evaporator:

The Fuzzy, as well as the neural-network control approach, were utilized and put to comparison with the PID technique.

Fuzzy logic controller

In control engineering, one of the significant methods is Fuzzy logic control, while the Fuzzy Control Systems are exploring a major research area that involves fuzzy set theory. (Mendel 1995). The design of fuzzy logic system doesn't depend upon the process's mathematical framework, while fuzzy controller types are developed utilizing fuzzy logic which has implemented the human reasoning that has been programmed in the functions of membership, rule interpretation, and fuzzy rules (Mehmet & Erhan 2010).

In this presented work, an input into the fuzzy control was evaporator's temperature of the outlet and the results of control action have indicated that there has been a change in steam's inlet flow rates. The MF (i.e. the membership function) can be defined as a curve defining the way that each one of the points in input space was mapped to the value of the membership (or membership degree) from 0 to 1, as can be seen in Fig. (2). In the presented work, there are 5 triangular membership functions used for 1 input: Negative Small (NS), Negative Big (NB), Positive Small (PS) Zero(Z), and Positive Big(PB) as well as 5 MFs utilized for fuzzy controller output: Negative Small (NS), Negative Big(NB), Positive Small (PS), Zero (Z) and Positive Big (PB); along with 7 triangular MFs used for 1 input: Negative (N), Negative Big (NB), Zero (Z), Negative Small (NS) and Positive Small (PS), Positive Big(PB) and Positive(P), as well, 7 MFs utilized for fuzzy controller's output: Negative (N), Negative Big (NB), Zero (Z), Negative Small (NS), Positive (P), Positive Small (PS) and Positive Big (PB). MF for output and input is shown in the figures below:

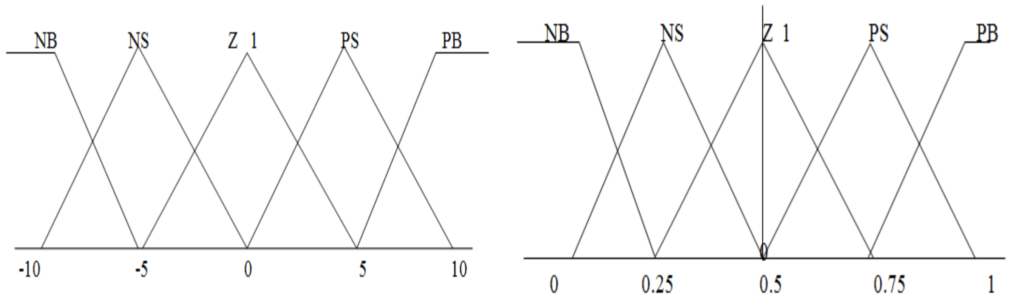

Fig. 2 *MF for Input and MF for Output.*

Neural network controller

Neural networks (NNs) were successfully utilized in identifying and controlling the dynamic systems. In the presented work, multi-layer feed-forward NN has been utilized to evaporator with 4 of the input neurons, 9 of the output neurons from a hidden layer as well as 1 output neuron from the output layer as well as (Tan Sigmoid transfer function) function of the activation in the hidden output, also (the function of the Linear transfer) activation function in the output of the network, as can be seen from Fig 3.

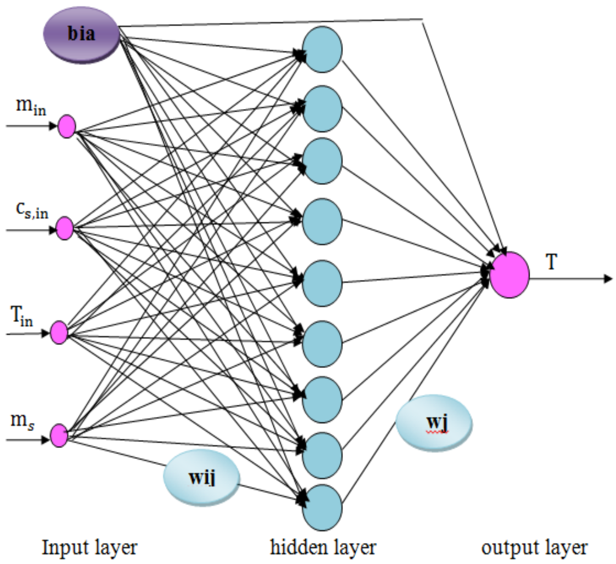

Fig. 3 *The structure of NN for the evaporator.*

Operating parameters with regard to the caustic soda system indicated as follows:

Table1: Operating parameter values.

Parameters	**Values**
Feed Flow rate (min), kg/hr	10000
Steam Flow rate (m_s), °C	100
Inlet concentrations of caustic soda (c_s,in) , kg_solid/kg_solution	0.050
Temperature of the Feed (T in),°C	75

This research attempted to examine the various approaches where multi-layer networks were utilized in the control systems, there are 2 major NN controllers will be considered: model predictive control and model reference control, such controllers were representing the many approaches where multi-layer networks were utilized in a control system as can be seen in the two fig. (4 & 5):

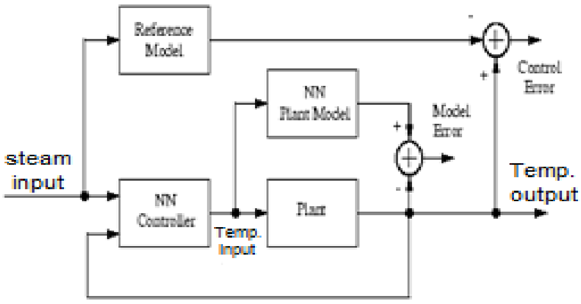

Fig. 4 A typical Reference Control system.

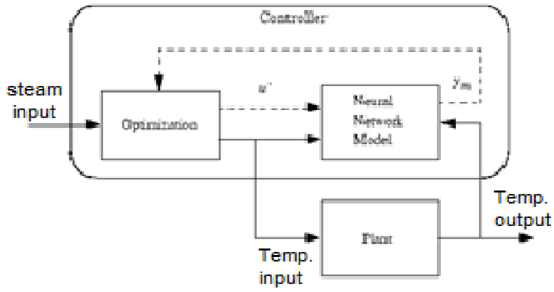

Fig. 5 ANN typical predictive control system.

Simulation work:

A simulation program has been developed for the evaporator with the use of MATLAB/Simulink V.R 2011-a from (Math-works) that has been considered as a software modelling dynamical systems and used for analysis and simulations, nonlinear and linear and depends on the systems of modelling in continuous and constant times. With the use of Simulink, one might develop models from the start of an amendment to current models and it is used for studying the properties of control as well as the dynamic situations.

The mathematical framework has been developed for evaporator as a set of systems, every one of the system components with a group of the sub-systems representing the evaporator's equations of the mathematical model. Also, the results of the simulation, which show qualitatively good behaviours in terms of all the systems, while the model includes algebraic and differential equations verified with the use of parameter sensitivities technique which is using the data that has been obtained in an industrial plant.

Open-loop system simulation

The simulation runs of the unsteady step-change have been carried out via providing flow rates of steam, a flow rate of the feed, feed concentration, and temperature to the first evaporator as well as evaluating all evaporator's output temperature, as can be seen in Fig. (6 & 7):

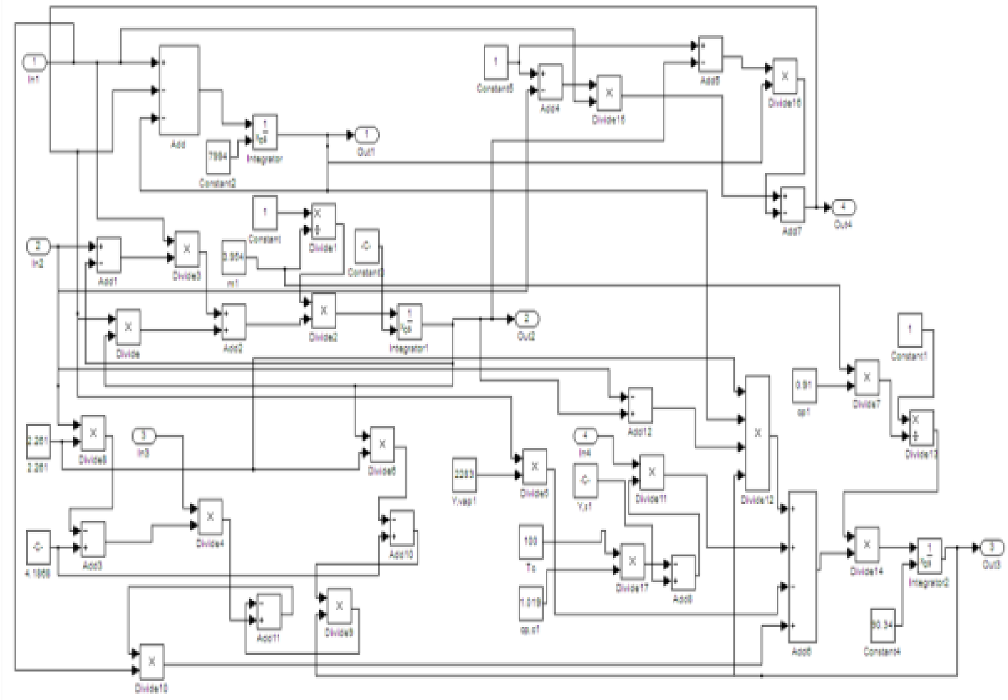

Fig.6 *Simulation work related to caustic soda solution sub-system.*

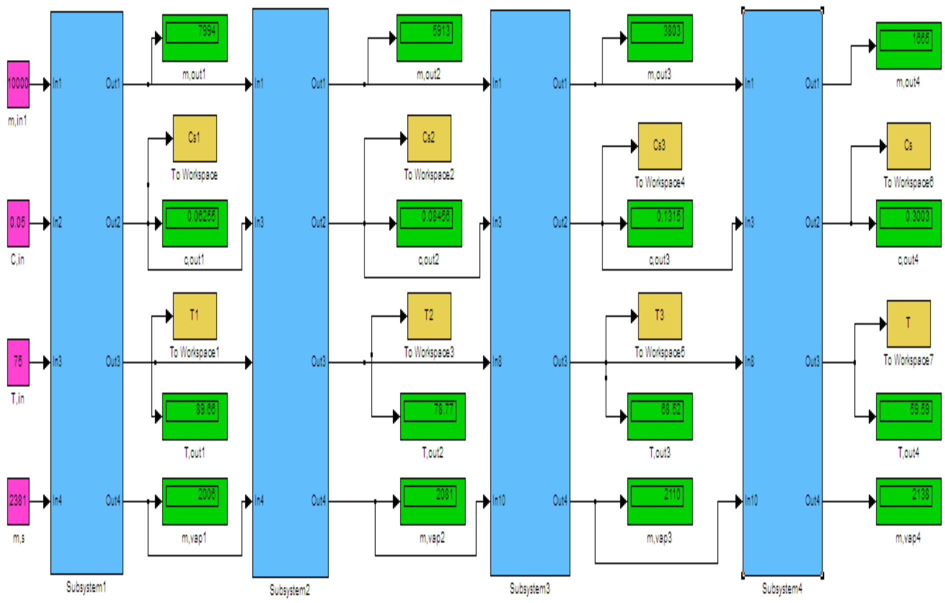

Fig.7 *Simulation work related to caustic soda solution system.*

Simulation of a fuzzy control system

Following running a dynamic model which was created utilizing Simulink as well as specifying the amount of system response to a few changes, then the control system was developed for such model by means of fuzzy control technique (Fuzzy logic), as can be seen in Fig. 8:

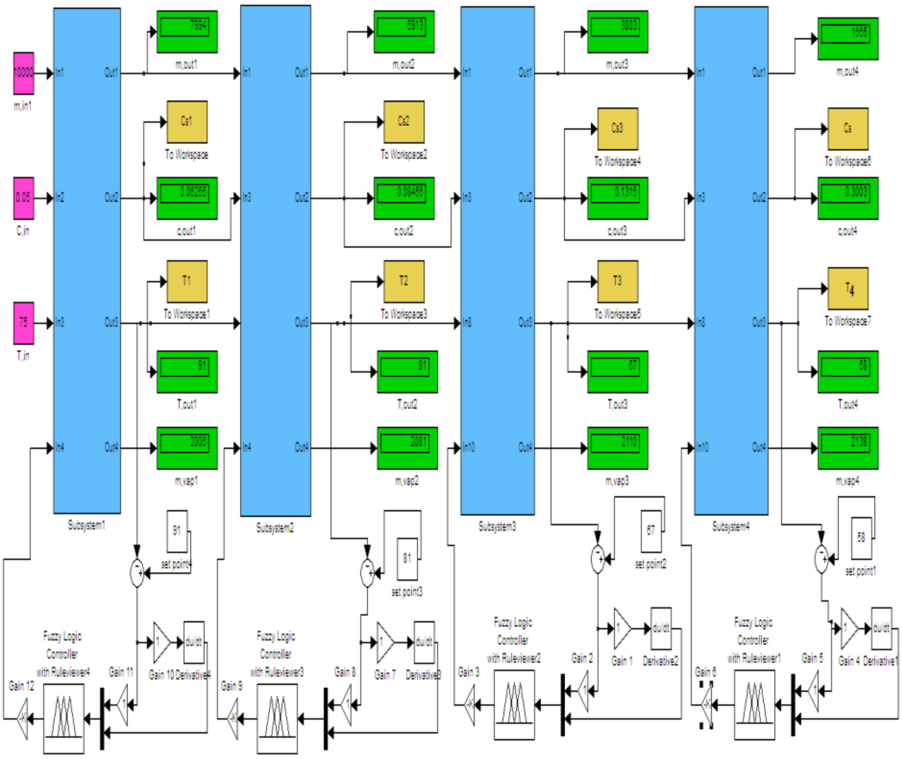

Fig.9 *Fuzzy logic control for each one of the evaporators in the caustic soda system.*

Simulation of neural control system

Following running a dynamic model which was built with the use of Simulink and specifying the amount of the response of the system to a few variations, this system was developed for such model with the use of neural control technique (neural predictive and reference models), as can be seen in Fig. (10 & 11):

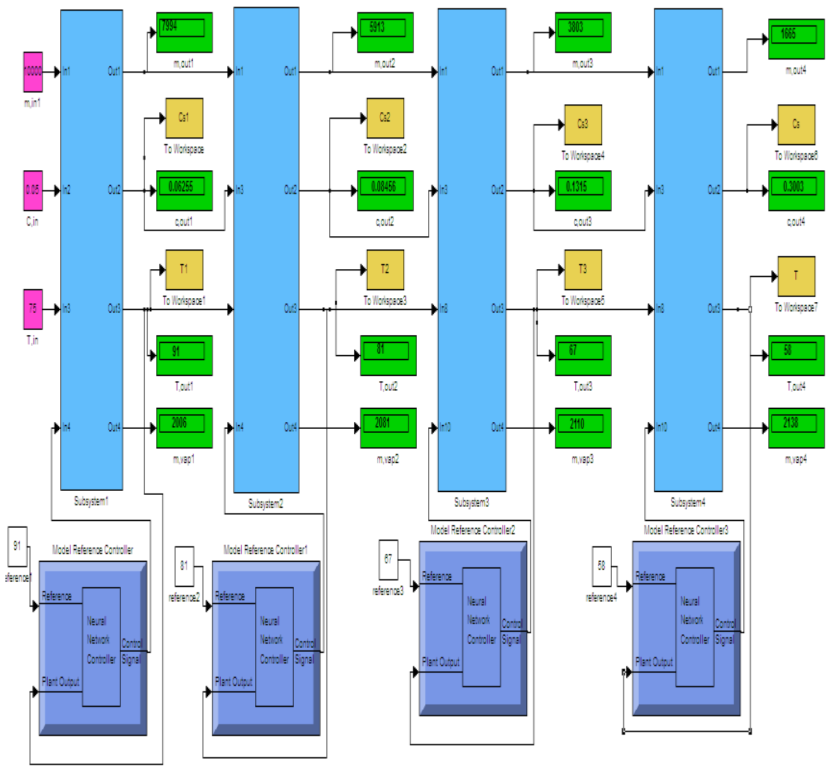

Fig. 10 *Neural Model Reference Control for caustic soda system.*

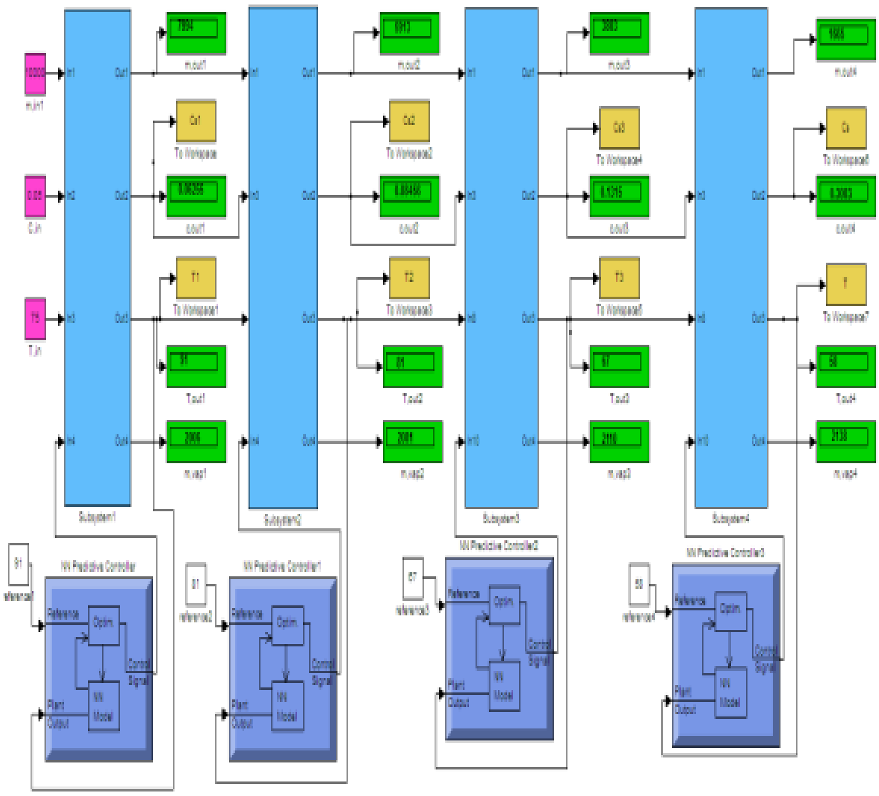

Fig. 11 *Neural Predictive Control for caustic soda system.*

Simulation of a PID control system

Following running a dynamic model which was built utilizing Simulink and specifying the amount of system responses to a few alterations, the control system that has been developed for such model with the use of conventional control (PID), as can be seen in Fig. (12):

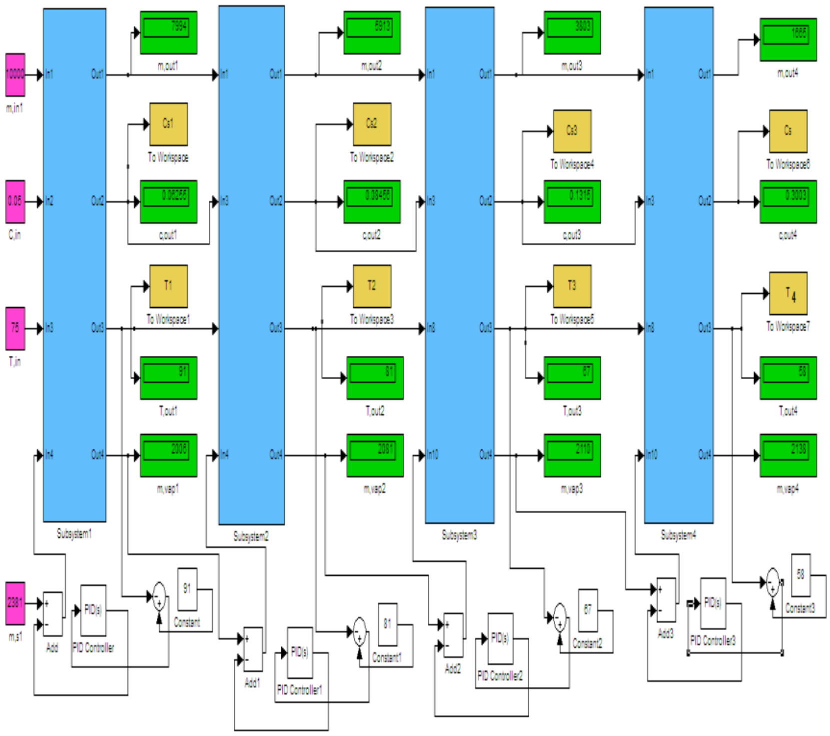

Fig. 12 *PID control for each one of the evaporators in the caustic soda system.*

Result and Discussions:

Evaporator Dynamics

The results of the simulations in terms of temperature of evaporator response for many step variations in the flow rate of steam, the flow rate of the feed, feed concentration, as well as temperature have been acquired in simulation.

Impact of Steam Flow Rate

The evaporator's outlet temperature was subjected to an increase via the increase in the steam flow rate in the system since increased heating happens with the increase in steam flow rate. It has been indicated from the curves of the temperature response, that 3rd effect evaporator was put to comparison with the 1st and 2nd effect evaporators reaching a new condition of the steady-state and more delays in the time, while the responses related to third and fourth evaporators showed more time delay in comparison with first as well as second evaporator. In addition, when analysing the parameter of the transfer function, it has been specified that the constant of time is decreased with the increase in the rate of the steam flow, as can be seen from Fig. 13

The approximate transfer function might be specified as the first-order system and often the combination regarding 2 elements in the series, the time delay element, and the first-order element. The next simulation transfer functions were acquired for step changes in the flow rate of steam in the system:

$$G(s) = \frac{T1(s)}{m_s 1(s)} = \frac{15.41}{1.51\ s+1}$$

$$G(s) = \frac{T2(s)}{m_s 2(s)} = \frac{14.79e^{-0.16\ s}}{1.96\ s+1}$$

$$G(s) = \frac{T3(s)}{m_s 3(s)} = \frac{15.44\ e^{-0.21\ s}}{2.43\ s+1}$$

$$G(s) = \frac{T4(s)}{m_s 4(s)} = \frac{42.9\ e^{-0.32\ s}}{3.57\ s+1}$$

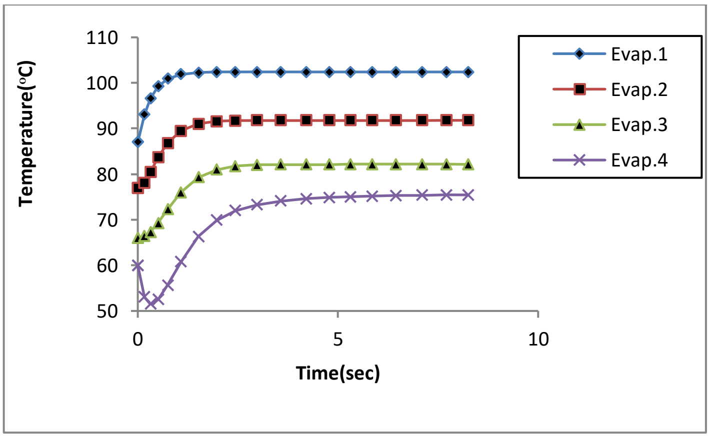

Fig. 13 *Evaporators' temperature response to the step-changes in flow rates of the steam between 2,381 and 2,619kg/hr.*

Impact of Feed Flow Rate

The flow rate of the feed is a major cause of current evaporation disturbances. The time constant related to the 3rd evaporator was large compared to the 1st and 2nd evaporators. Fig. (14) showing the responses regarding the temperature of the outlet of the multi-effect evaporator for the caustic soda systems. Furthermore, it is specified that there is a decrease in temperature and a fast response appears due to the fact that the evaporator's time constant was small. The following simulation transfer functions are obtained for step-change in feed flow rate for the system:

$$G(s) = \frac{T1(s)}{m_s 1(s)} = \frac{-2.25}{1.33\ s+1}$$

$$G(s) = \frac{T2(s)}{m_s 2(s)} = \frac{-12.31}{1.79s+1}$$

$$G(s) = \frac{T3(s)}{m_s 3(s)} = \frac{-16}{2.35\ s+1}$$

$$G(s) = \frac{T4(s)}{m_s 4(s)} = \frac{-8.61e^{-0.24\ s}}{3.01\ s+1}$$

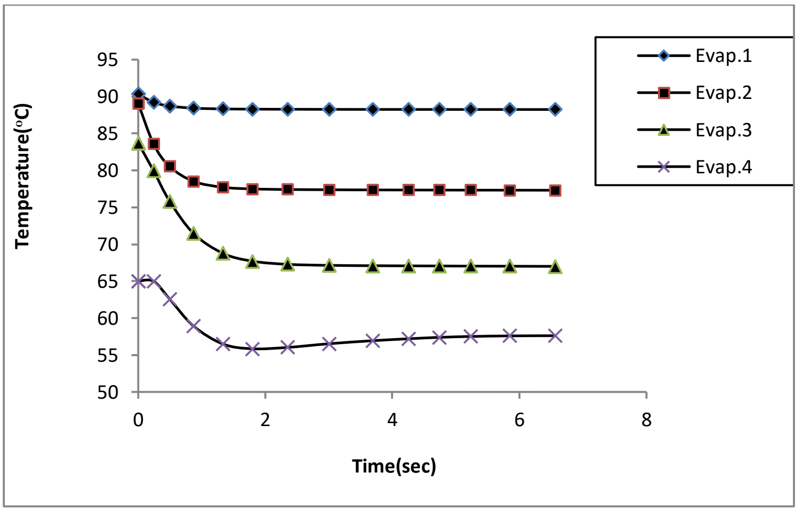

Fig.14 *evaporators of the temperature responses to the step-changes in the feed flow rate between 10,000 and 11,000kg/hr.*

Impact of Feed Temperature

The outlet caustic soda temperatures have been subjected to an increase via the increase in temperature feed. It was identified from the temperature response 3rd and 4rth effects evaporator in comparison to 1st and 2nd effects evaporator reaching new steady-state conditions with further time delays. When analysing the transfer function parameter, it is specified that there is a decrease in time constant with the increase in temperature of the feed, as can be seen in Fig (15).

The next simulation transfer functions acquired for step-change in the flow rate of the feed in the system:

$$G(s) = \frac{T1(s)}{m_s 1(s)} = \frac{9.78}{1.45\ s+1}$$

$$G(s) = \frac{T2(s)}{m_s 2(s)} = \frac{9.11}{2.63s+1}$$

$$G(s) = \frac{T3(s)}{m_s 3(s)} = \frac{4.34\ e^{-0.39\ s}}{3.11\ s+1}$$

$$G(s) = \frac{T4(s)}{m_s 4(s)} = \frac{7.23e^{-0.67\ s}}{4.88\ s+1}$$

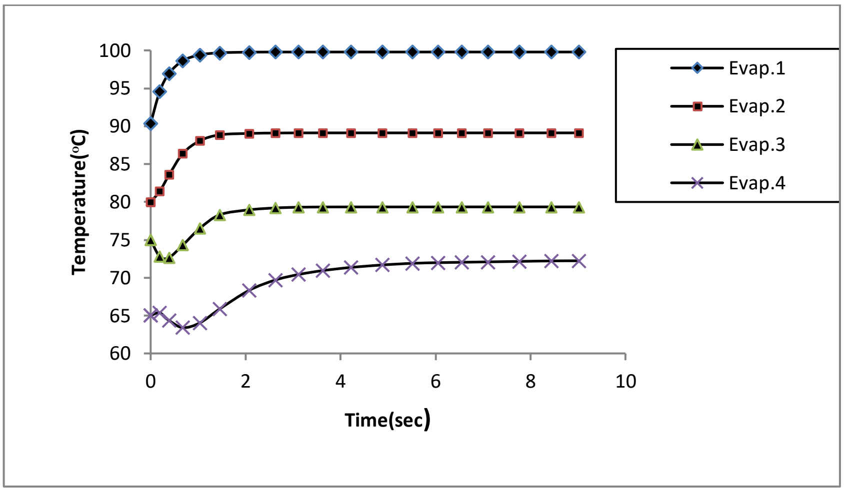

Fig. 15 *The temperature response evaporators to the step-changes in the feed of temperature between 75°C to 85°C.*

Impact of Feed concentricity

The temperature values of the outlet have specified that temperature was majorly constant or of low-effects in the case where there was a disturbance in feed concentration. Results have indicated that a 50% increase in feed material concentration didn't have a strong impact on the temperature of the evaporator, as can be seen in Fig (16).

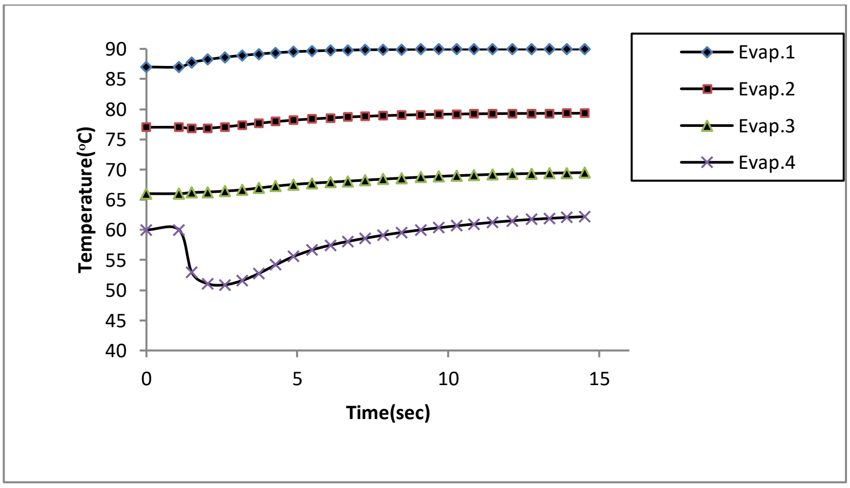

Fig. (16) *The evaporators of the temperature response to the step changes in concentration feed between 0.05 and 0.06 kgsolid/kgsolution.*

Control of Evaporator

PID Controller

A process reaction curve technique created via Cohen-Coon approach was utilized to determine the values related to controller parameters needed transient response for evaporator's outlet temperatures to the step-changes in the feed flow rate and step changes in feed temperatures. Table2 show the efforts to tune PID controller parameters.

Table2: Cohen-Coon Parameter Values for PID Controllers.

No.	Variables of step-changes	Values of step-change	Kc	τI	τD
1	Rate of the Feed flow (kg/h)	10,000 – 11,000	0.30	0.20	0.030
2	Feed Temperature (°C)	75 – 85	0.440	0.150	0.022

The response related to temperatures for the evaporator with the use of PID feed-back controller to the step-changes in feed flow rates and step changes in feed temperatures have been conducted on a simulation program with regard to PID controller, as can be seen in Fig (17).

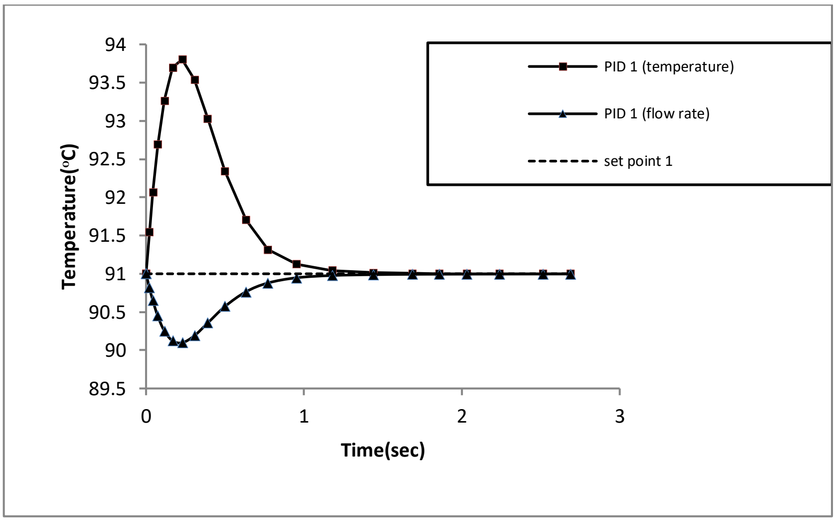

Fig. 17 *responses of temperature of 1st evaporator for the PID controller to a step-change in feed flow rates between 10,000 and 11,000kg/hr and step changes in feed temperatures between 75°C and 85°C at set point which is equal to 91°C.*

Fuzzy Logic Controllers

In the presented work, rule bases with a group of the rule forms. The output and input were associated through (25) rules (Table 3), each one of the rule outputs was specified via "MIN-MAX" inferences, also the output and input output were associated by (47) rules (Table 4), each one of the rule outputs was specified via "MIN-MAX" inference.

Table (3): Fuzzy Logic Controller (5 MF) Rules.

E / CE	**NB**	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NB	NS	Z
NS	NB	NS	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PS	PB
PB	Z	PS	PB	PB	PB

Table (4): Rules of Fuzzy Logic Controller (7MF).

E/CE	**NB**	**N**	**NS**	**Z**	**PS**	**P**	**PB**
NB	NB	NB	NB	NB	N	N	Z
N	NB	N	N	N	NS	Z	P
NS	NB	N	NS	NS	Z	PS	P
Z	NB	N	NS	Z	PS	P	PB
PS	N	NS	Z	PS	PS	P	PB
P	N	Z	PS	P	P	P	PB
PB	Z	P	P	PB	PB	PB	PB

Evaporator's outlet temperature via utilizing simulated fuzzy logic controllers to the step disturbance levels in the feed temperature and feed flow rate, as can be seen in the two fig. (18 & 19). IAE for such 2 controllers was provided in Table (5). Also, it might be indicated that there is excellent performance with regard to the fuzzy logic controller in comparison to PID controller since the fuzzy controller is reaching the required value fast in comparison to PID controllers with minimum (IAE) value, such advantage was due to the fact that fuzzy controller has been developed on logical functions providing output actions which are consistent with input error, such functions resulted in rapid responses. Yet, over shots above the required value as well as simple fluctuation levels occur in the fuzzy controllers.

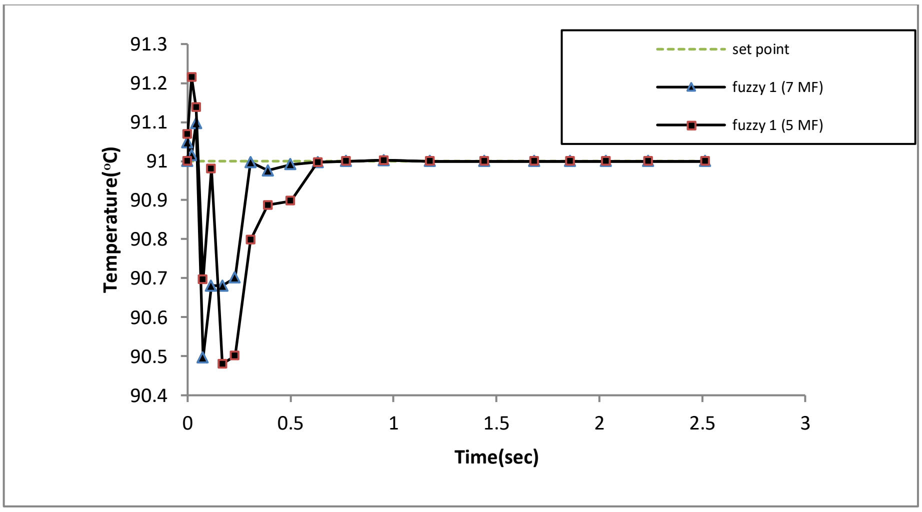

Fig. 18 *responses of Temperature that are related to 1st evaporator under 5 & 7 MFs fuzzy logic controller to the step-changes feed flow rates between 10,000 and 11,000kg/hr. at the set point =91°C.*

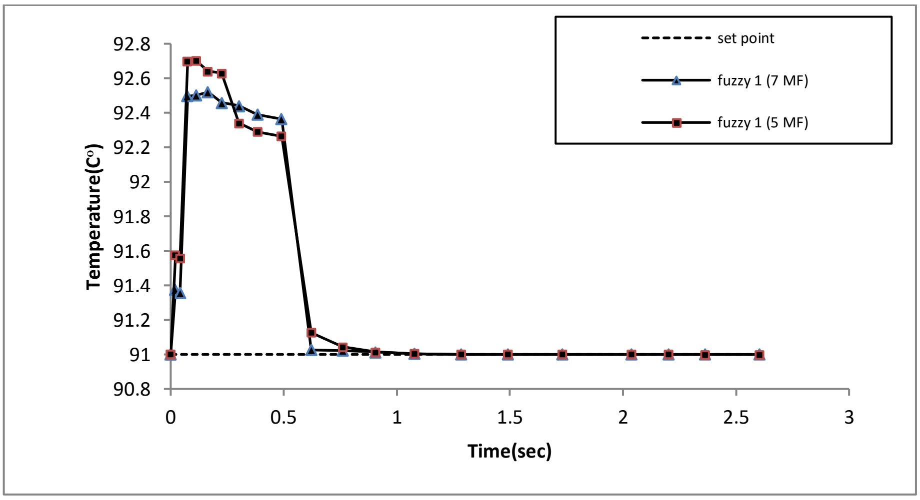

Fig.19 *responses of Temperature that are associated with the 1st evaporator under 5 & 7 MFs fuzzy logic controllers to the step changes in the temperatures of the feed between 75°C – 85°C at the set point =86°C.*

Neural Network Controller

The evaporator's temperature via utilizing simulated NN controller to step disturbance levels in the feed and temperature flow rate. As can be seen from Fig. (20 & 21). IAE for those 3 controllers have been listed in Table5. It was specified that the neural controller has been of excellent performance and giving more sufficient results compared to the PID controllers, due to the fact that neural controllers have a smaller value of the offset, the neural controllers are more appropriate, the response of the temperature can reach steady-state values faster and the neural controllers have a smaller value of the over-shoot.

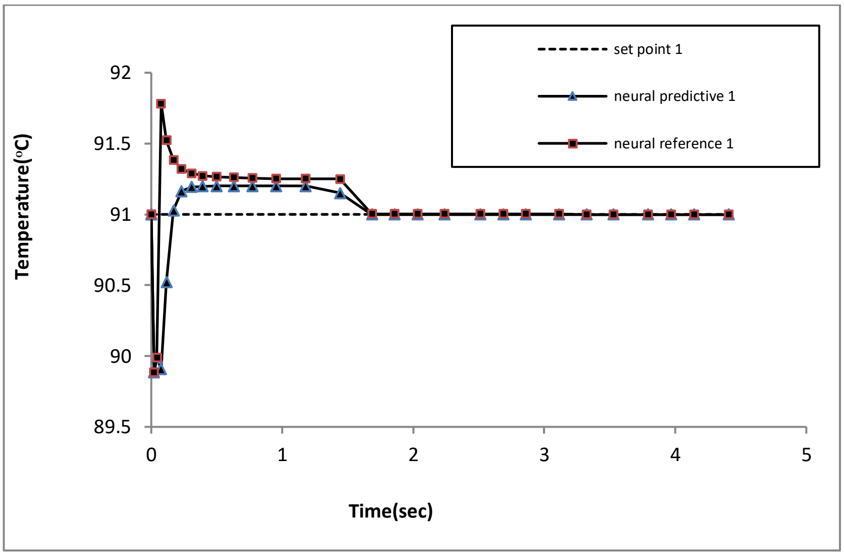

Fig. 20 *responses of the Temperature, which are related to 1st evaporator under the neural predictive and neural reference controllers to the step changes in the feed flow rate between 10,000 and 11,000kg/hr at 91°C set point.*

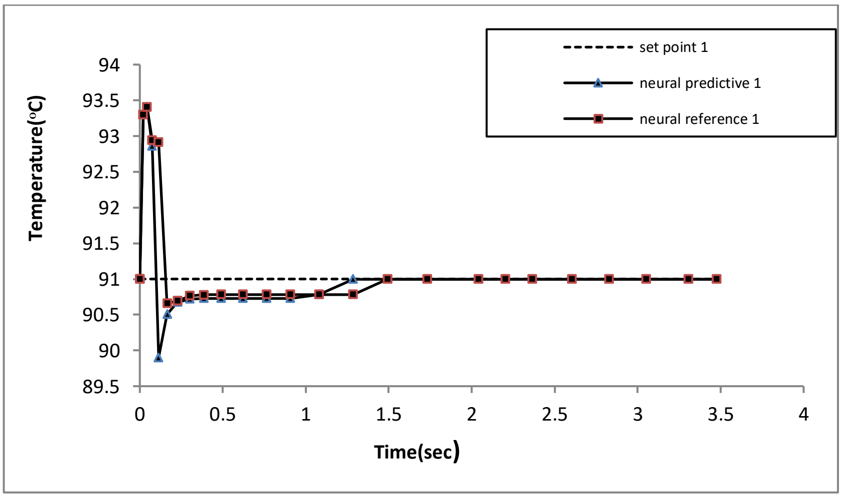

Fig. 21 *responses of the Temperature that are related to 1st evaporator under the neural predictive and neural reference controllers to the step-changes in the feed temperatures between 75°C – 85°C at 91°C set point.*

Comparing the evaporator temperature control between 3 approaches

The quantitative values of performance, IAE, for fuzzy, neural and PID, controller types have been provided in table5. The evaporator temperatures' control with the use of the PID is insignificantly worse compared to that of the utilization of the NN and fuzzy logic. A control which is related to this process utilizing PIDs shows a degradation in performance as can be seen in the following figures. From PID efficiency, it might be specified that temperature has extreme nonlinear dynamics depending on the system of evaporation.

Neural and fuzzy controllers are responding as fast as PID, indicating that the neural and fuzzy are providing better and smooth control performance compared to PID controllers with small values of the IAE errors, in the case where the disturbances were provided to systems. In addition, the figures showing that neural and fuzzy strategies brought the temperature of the evaporator to set points via gradually increasing the flow rate that is providing a smooth response of the control. As a result, PID controls have brought the temperature of evaporator to setpoint through rigorous adjustment related to flow rate resulting in over-shoot in system response with longer time of the response, indicating that the neural and fuzzy controllers are providing fewer errors and offering excellent results of the control. The adequate performance was because of the full representation related to the evaporator's non-linear dynamics through NN and fuzzy logic models. Putting to comparison such areas of results showing considerable enhancement of controllers with the use of NN and fuzzy logic model types over the controller of the PID, as can be seen from Fig (22) through Fig (25).

Table (5): IAE for control approaches.

control methods	**Variable of a step-change**	**IAE (Integral Absolute Error)**			
		Evap1	**Evap2**	**Evap3**	**Evap4**
PID controller	Feed flow rate (kg/hr)	0.4777	0.2966	0.7174	0.8329
	Temp. of feed (C^o)	1.3867	0.4918	00.7738	0.8212
Fuzzy logic controller (5MF)	Feed flow rate (kg/hr)	00.1377	00.0823	00.7024	00.1377
	Temp. of feed (C^o)	00.8488	00.2172	00.4538	00.8488
Fuzzy logic controller (7MF)	Feed flow rate (kg/hr)	00.0897	00.0578	00.5308	00.6302
	Temp. of feed (C^o)	00.8135	00.1787	00.3544	00.3051
Neural Network controller (Reference)	Feed flow rate (kg/hr)	00.7668	00.1965	00.5605	00.6537
	Temp. of feed (C^o)	00.9667	00.9051	00.3181	00.6967
Neural Network controller (Predictive)	Feed flow rate (kg/hr)	00.5283	00.1664	00.3512	00.4339
	Temp. of feed (C^o)	00.7563	00.6281	00.1901	00.5763

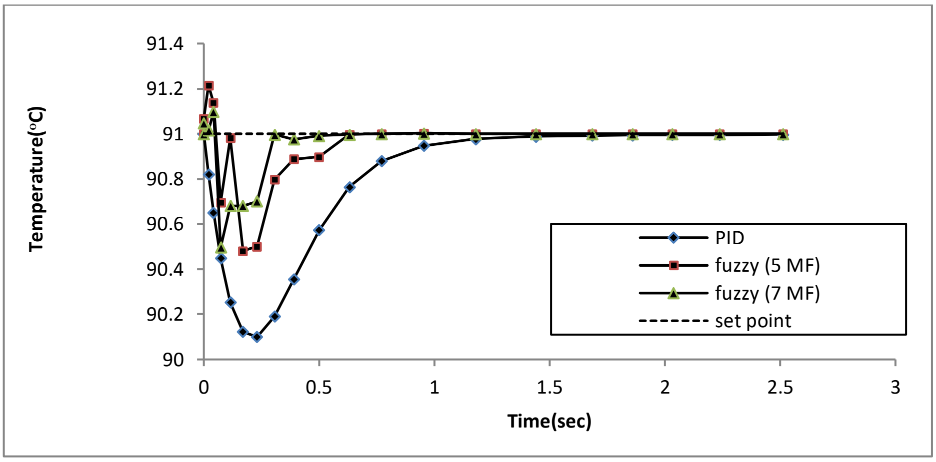

Fig. 22 *Comparing PIDs with the fuzzy logic (5 & 7 MFs) controllers in 1st evaporator to the step-changes in the flow rates of the feeds between 10,000 and 11,000kg/hr. at 91°C set point for the caustic system of the soda.*

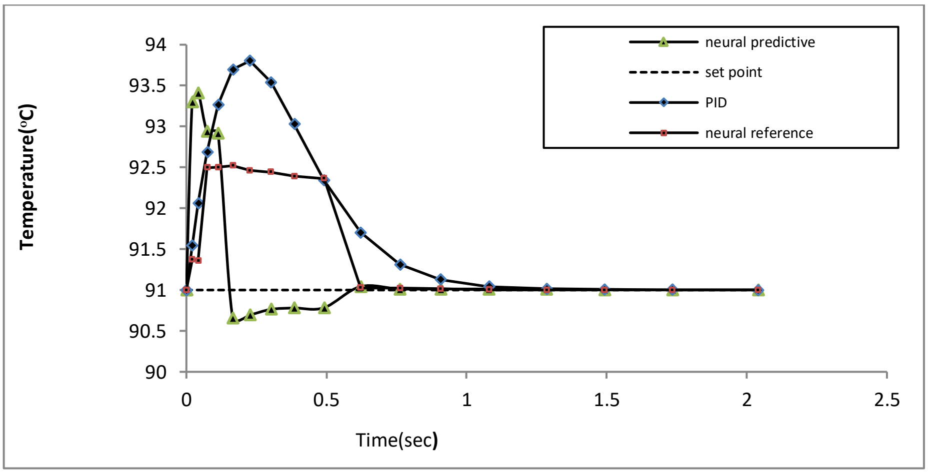

Fig. 23 *Comparing PID and neural network (predictive and reference) controllers 1st evaporator to step-changes in the feed temperature from 75°C to 85°C at a setpoint value of 91°C in the case of the caustic soda systems.*

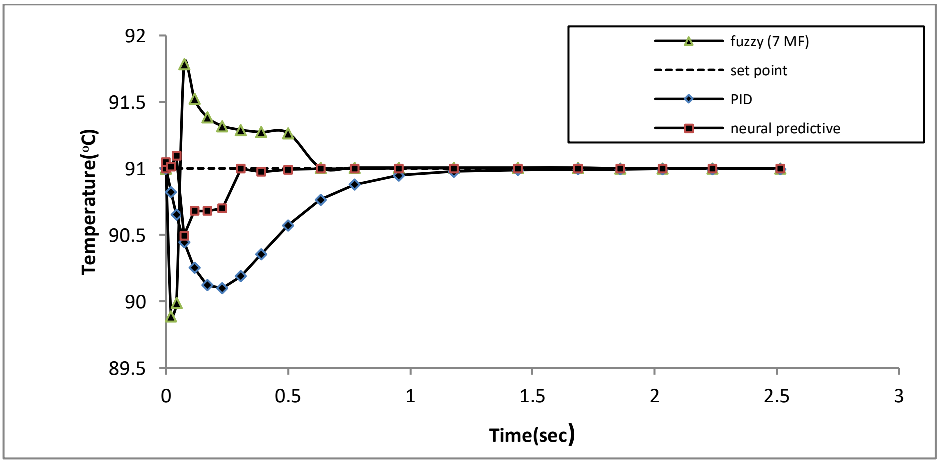

Fig. 24 *Comparing PID, NN (predictive), and fuzzy logic (7 MFs functions) in 1st evaporator to step-changes in flow rates of the feed between 10,000 & 11,000kg/hr at 91°C set point for the caustic system of the soda.*

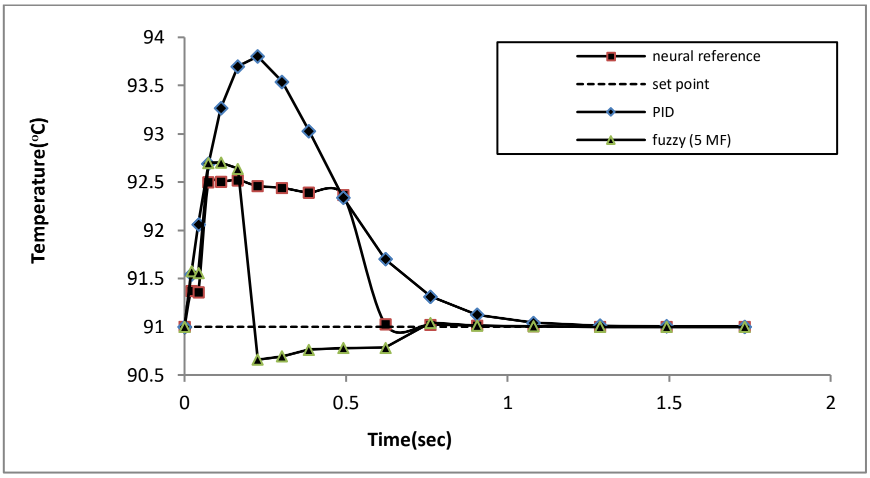

Fig. 25 *Comparing between NN (reference), PID, and fuzzy logic (5 MFs) in the 1st evaporator to step-changes in the feed temperature between 75°C – 85°C at 91°C set point for caustic soda system.*

Conclusions:

From the presented work, the next conclusions are obtained in terms of dynamic behavior as well as the control of multiple-effect evaporators. Also, the identification process utilizing reaction curve techniques specified that in the majority of cases, the system might be indicated as 1st order lag with dead time.

The results showed a priority related to NN (model predictive) controller in the caustic soda system providing less offset value, also the response of the temperature has reached a steady-state value faster and with low over-shoots in comparison to the PID controller. The PID controller's performance was oscillator. It might be indicated that the performance regarding PID simulation required long periods for reaching a steady state.

Nomenclature:

$c_{s,in}$	represents the soluble solids' mass fraction in the feed
C_P	Specific heat capacity, (kJ/kg. °c)
$c_{l,in}$	mass fraction of the liquid in the feed
c_s	represents soluble solids' mass fraction in product
A, B	Constant
c_l	mass fraction of the liquid in the product
H	enthalpy of the product (kJ/kg)
G	Transfer function
H_{in}	enthalpy of feed (kJ/kg)
H_c	enthalpy of condensate (kJ/kg)
H_{vap}	enthalpy of saturated vapor (kJ/kg)
H_s	enthalpy of steam (kJ/kg)
m	Mass flow rate of the product, (kg/sec)
m	Mass holdup, (kg)
$m_{\cdot s}$, $m_{\cdot c}$	Mass flow rate of steam and condensate, (kg/sec)
m_{in}	Mass flow rate of feed, (kg/sec)
Q_{steam}	heat transfer (kJ/sec)
s	Laplace transform
m_{vap}	vapor Mass flow rate, (kg/sec)
T	Temperature product (°c)
t	Time, (sec)
T_{in}	Temperature feed (°c)

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