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Multiloop Control of Continuous Stirred Tank Reactor Using Biggest Log Modulus Method

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***Abstract* - A majority of the chemical processes are naturally a Multi Input Multi Output (MIMO) system because of the existence of many loops where the interactions between the loops are high. In a Single Input Single Output (SISO) control, the primary objective is to maintain only one variable nearer to its set point, though several measured variables are involved. In contrast to SISO system, the MIMO control involves maintaining several controlled variables at their relevant setpoints simultaneously, Cha et al. (2002). For controlling MIMO systems, a single loop tuned controller design procedure cannot be directly applied because of the heavy interaction among the loops.. A Continuous Stirred Tank Reactor (CSTR) is one of the versatile reactors which find its application in many chemical and petrochemical industries, exhibiting reasonably high non-linear behaviour. The control of CSTR throws a challenge to the control engineers to design a well-suited controller for its smooth operation. The interaction in the CSTR is phenomenal and hence in this present work, the Biggest Log modulus Tuning (BLT) is designed for the CSTR and performances are evaluated under various operating conditions through simulation.**
***Keywords*: CSTR, MIMO, SISO, BLT, Multiloop**

I. INTRODUCTION

Many chemical reactors found in the industries are usually Multi Input and Multi output (MIMO) systems. In a SISO control, the primary objective is to maintain a single process variable nearer to the setpoint, though several measured variables are involved. Usually, the interactions among those variables are ignored in the control design. This leads to the increased use of energy and hence the running cost of the plant. In contrast to SISO, MIMO control objective is elaborated little more to maintain several controlled variables at their setpoints simultaneously. For controlling MIMO systems, single loop tuned controller design procedure cannot be directly applied because of heavy interaction among the loops and impose complexity in the design of control systems. There exist two types of control system design for a MIMO system. In a multivariable control approach, a single control algorithm governs the control of all the interacting loops in the system hence the fail-safe design is more complicated. On the other hand, the multiloop control is a sort of multiloop control of each loop which shows a natural immunity to the loop failure and hence results in a simple and effective fail-safe design. . The interaction in the CSTR is phenomenal and hence in this present work, Biggest Log modulus Tuning (BLT) is implemented and the performance of the system is analysed through simulation

II. MATHEMATICAL MODELING OF CSTR

The first step in the study of the dynamic behaviour and control of CSTR is to develop a mathematical model depending on mass and energy balances that can be considered as the gateway for all works. The high non-linearity is the inherent characteristics of any CSTR found in chemical industries. A first order irreversible exothermic reaction ($A \rightarrow B$) in a CSTR as shown in the Fig. 1 is considered. The Heat generated by the reaction is removed using cooling jacket surrounding the reactor. Perfect mixing is assumed in CSTR and change in volume due to reaction is negligible. The jacket water is assumed to be perfectly mixed, the mass of the metal walls is considered as negligible, and there exists a constant hold up of the water in the jacket. The first principle model of the CSTR at the corresponding operating points given in Table3.1 cited from Albertos and Sala, (2008) has been considered for the simulation studies.

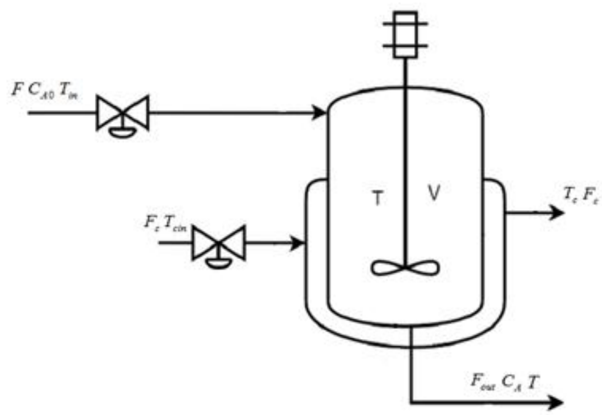

Fig. 1 Continuous Stirred Tank Reactor

The overall Reactor Mass Balance can be obtained as:

— (1)

where, F_{in} is the feed flow rate; is the product (effluent) flow rate; V is the volume of the reactor.
Since the volume of the reactor is constant, therefore:

$$F_{in} = F_{out} = F \qquad (2)$$

The component (A) Mass Balance is given by

$$\frac{dVC_A}{dt} = F_{in}C_{A0} - F_{out}C_A - Vr_A \qquad (3)$$

where, C_A is the Concentration of component A in outlet stream (effluent); C_{A0} is the Feed concentration of component A; r_A is the rate of reaction per unit volume. Since, the first order reaction is considered; the following Arrhenius expression is used.

$$r_A = C_A K_0 e^{(-E/RT)} \qquad (4)$$

where, K_0 is the Pre-exponential factor; E is the Activation energy ; R is the Universal gas constant ; T is the Temperature of the reactants in the reactor.
Substituting equation (4) in (3) and since V is constant; from equation (2), equation (3) becomes

$$\frac{dC_A}{dt} = \frac{F}{V}C_{A0} - \frac{F}{V}C_A - C_A K_0 e^{(-E/RT)} \qquad (5)$$

The heat balance inside the reactor is obtained as

$$\rho\frac{dVC_pT}{dt} = \rho C_p F_{in} T_{in} - \rho C_p F_{out} T - H_r V C_A K_0 e^{(-E/RT)} - UA(T - T_c) \qquad (6)$$

where, ρ is the density of the inlet and outlet stream; C_p the heat capacity of the inlet and outlet stream ; T_{in} the inlet stream temperature; H_r the Heat of reaction; UA is the heat transfer term and T_c is the temperature of the coolant water in the jacket.
Since volume (V) of the reactor is constant, the specific heat (C_p) is not a function of temperature, and from equation (2), equation (6) becomes:

$$\frac{dT}{dt} = \frac{F}{V}T_{in} - \frac{F}{V}T - \frac{H_r C_A K_0 e^{\left(-\frac{E}{RT}\right)}}{\rho C_p} - \frac{UA}{\rho C_p V}(T - T_c) \qquad (7)$$

The heat balance on the Jacket is given by

$$\rho_c V_c C_{p_c}\frac{dT_c}{dt} = F_c C_{p_c}\rho_c(T_{cin} - T_c) - \rho C_p F_{out} T \quad \frac{UA}{\rho C_p V}(T - T_c) \qquad (8)$$

where, $\rho_c$is the density of the coolant water in the jacket; V_c is the volume of the jacket; C_{p_c} the heat capacity of the coolant water in the jacket and T_{cin} is the temperature of the inlet coolant water in the jacket.
After simplification, equation (8) becomes:

$$\frac{dT_c}{dt} = \frac{F_c}{V_c}(T_{cin} - T_c) + \frac{UA}{\rho_c V_c C_{p_c}}(T - T_c) \qquad (9)$$

The equations (5), (7) and (9) represent the mass balance and heat balance around the reactor and jacket respectively.

It is evident from the modelling equations of CSTR, the process variables C_A, T and T_c are of a nonlinear function. Also, they are interactive in nature and cannot be solved independently. Table I shows the steady state operating parameters of the CSTR considered in this work.

TABLE I VARIABLES AND NOMINAL CSTR PARAMETER VALUES

Variable	Description	Nominal operating Values
V	Reactor volume (l)	50
F_{in}	Inlet volumetric flow rate to the reactor (l/min)	50
F_{out}	Outlet volumetric flow rate from the reactor (l/min)	50
C_A	Concentration of component A in outlet stream (mole/l)	-
C_{A0}	Feed concentration of component A (mole/l)	1
K_0	Pre-exponential factor (l/min)	7.8^*10^{10}
E	Activation energy in the Arrhenius equation (Cal/mole)	E/R=8567
R	Universal gas constant (Cal/mole. K)	
ρ	Density of the inlet and outlet stream (g/l)	900
C_p	Heat capacity of inlet and outlet stream (Cal/g.K)	0.329
T	Temperature of the reactants in the reactor (K)	-
T_{in}	Inlet stream temperature (K)	350
H_r	Heat of reaction (Cal/mole)	-5^*10^4
UA	Heat transfer term (Cal/min. K)	5^*10^4
T_c	Temperature of the coolant water in the jacket (K)	-
ρ_c	Density of the coolant water in the jacket (g/l)	1000

A. Step response model of the CSTR as MIMO system

A step change in the input variables F and F_c from the nominal operating points are given at three different operating regions. The response of the output variables C_A and T are recorded including interaction effect of one variable on another. This chunks the dynamics of the whole system and hence serves to design a controller for a MIMO system. The Table 3.6 displays the transfer function obtained at three different operating conditions of the CSTR.

TABLE II TRANSFER FUNCTION MODEL OF CSTR AS A MIMO SYSTEM

Operating Regions	F_c (l/min)	F (l/min)	C_A (mol/l)
Lower	55	65	$G(s)=\begin{bmatrix} \frac{1.26e^{-0.2s}}{0.3s+1} & \frac{-0.58e^{-0.2s}}{0.6s+1} \\ \frac{-0.0061e^{-0.45s}}{0.15s+1} & \frac{0.0046e^{-0.4s}}{0.6s+1} \end{bmatrix}$
Middle	31	99	$G(s)=\begin{bmatrix} \frac{0.5e^{-0.1s}}{1.2s+1} & \frac{-0.2e^{-0.05s}}{1.35s+1} \\ \frac{-0.0025e^{-2.05s}}{1.35s+1} & \frac{0.0039e^{-1.35s}}{1.65s+1} \end{bmatrix}$
Higher	25	115	$G(s)=\begin{bmatrix} \frac{0.48e^{-0.1s}}{0.9s+1} & \frac{-0.04e^{-0.4s}}{0.6s+1} \\ \frac{-0.00068e^{-3.3s}}{1.2s+1} & \frac{0.00056e^{-0.9s}}{1.8s+1} \end{bmatrix}$

III. MULTILOOP CONTROL OF CSTR

A multivariable system is one, which has several interacting control loops with multiple control variables and multiple manipulated variables as shown in Fig. 3.1. Such systems have several inputs and several outputs that are often interacting, that means a change in any one input cause a change in some or all the outputs.

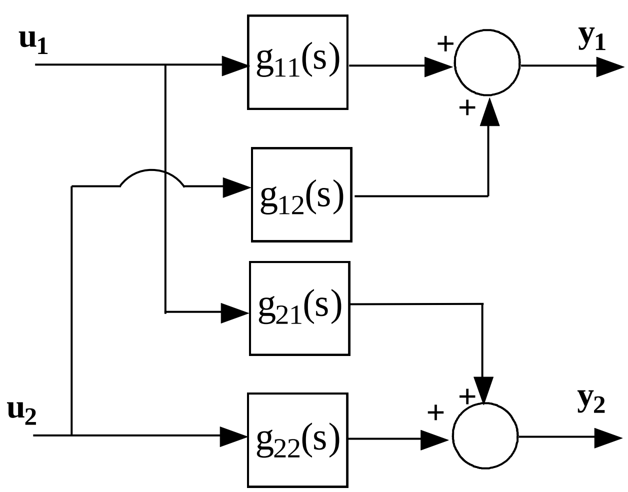

Fig. 2 Block diagram of an open loop 2 x 2 MIMO system

A CSTR is a well-qualified MIMO system as there are two controlled variables, reactor concentration and temperature which need to be maintained at their nominal operating values. The SISO control system designed in the previous chapters has ignored the interaction effect in its design.

The first step in the design of multiloop control system is to determine the mapping of the controlled variable to manipulated variable. The Relative Gain Array (RGA) analysis is performed on the CSTR and suggested the best pairing for the given CSTR model, Bristol (1966). From the loop pairing, it is found that for the best closed loop performance, the inlet coolant water flowrate $\mathbf{F_c}$ must be paired with concentration $\mathbf{C_A}$ and inlet flowrate **F** must be paired with reactor temperature **T**. The Fig. 3.2 shows the multiloop control scheme employed in this paper.

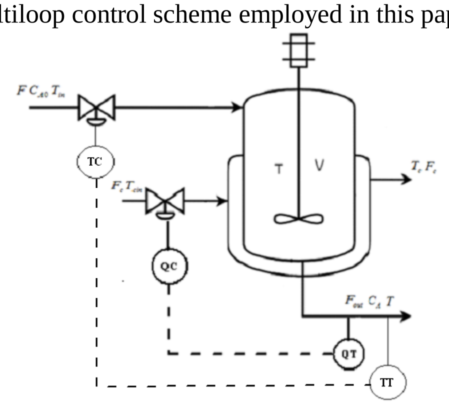

Fig. 3 Multiloop control scheme for CSTR

The RGA analysis is performed for the CSTR and it is computed as,

$$\lambda = \begin{matrix} Fc \\ F \end{matrix}\begin{bmatrix} 3.9880 & -2.9880 \\ -2.9880 & 3.9880 \end{bmatrix} \quad (10)$$

The RGA indicates that F_c must be paired with C_A, and F with T to have a better control. As λ_{ij} found to be small positive, the apparent closed loop gain is much higher than that of the open loop. This can cause performance degradation or even instability when the loop is closed. This pinpoints an input with little effect on a particular output in open loop will have a significant effect in closed loop due to coupling and feedback.

IV. DESIGN OF MULTILOOP CONTROL USING BIGGEST LOG MODULUS TUNING (BLT) METHOD FOR CSTR

A. The BLT algorithm

The Essential steps of the algorithm for this method are listed below (Senthilkumar and Lincon 2015).

Step 1: Determine the ultimate gain $\boldsymbol{K_u}$ and ultimate frequency $\boldsymbol{\omega_u}$ of each diagonal process transfer function by classical SISO method.

Step 2: Calculate the corresponding Ziegler-Nichols setting (K_{cZni} and T_{izNi}) for each loop.

Step 3: Assume the detuning factor f (typical value ranges are from 1 to 5).

Step 4: The gain and reset time for the feedback controllers are calculated from: $K_{ci} = \frac{K_{cZNi}}{f}$

$\boldsymbol{T_i} = \boldsymbol{T_{izNi}} \times \boldsymbol{f}$

Note: f remains the same for all loops.

Step 5: Compute the Closed Loop Log Modulus (CLM) using the above designed controller for a specified frequency range.

$$\mathrm{CLM} = 20 \log \left| \frac{\mathrm{W}}{1+\mathrm{W}} \right|$$

where $\mathrm{w} = -1 + \det(1 + \mathrm{G(s)B(s)})$, $\mathrm{G(s)}$ is the process transfer function and $\mathrm{B(s)}$ is the controller transfer function.

Step 6: Compute the CLM (Closed loop log modulus) from the data of CLM versus frequency.

Step 7: Check if $\mathrm{CLM} = 2\mathrm{N}$ where N is the number of loops;

If $\mathrm{CLM} = 2\mathrm{N}$ then stop, otherwise return to Step 3.

B. Implementation of BLT algorithm for CSTR control

The steady state profile has provided the idea of operating CSTR at three different operating regions. To study the multiloop control of the CSTR, the operating points are carefully chosen based on the steady state input/output response as lower ($\mathrm{F} = 70\,\mathrm{l/min}, \mathrm{F_c} = 60\,\mathrm{l/min}$), middle ($\mathrm{F} = 31\,\mathrm{l/min}, \mathrm{F_c} = 99\,\mathrm{l/min}$) and higher ($\mathrm{F} = 25\,\mathrm{l/min}, \mathrm{F_c} = 115\,\mathrm{l/min}$). The steady state value of the three regions is tabulated in Table III. The MIMO model for the three regions (lower, middle and higher) are obtained using process reaction curve method and specified in the equations (11) to (13) respectively.

TABLE III SELECTION OF OPERATING POINT FOR CSTR-MIMO PROCESS

Operating Region	$\mathbf{C_A}$ **(mole/l)**	**T (K)**	$\mathbf{T_c}$ **(K)**
Lower	0.05725	390.4	341.1
Middle	0.7963	318.3	306.1
Higher	0.8178	314.1	304.3

$$\mathrm{G(s)} = \begin{bmatrix} \dfrac{0.84e^{-0.1s}}{0.3s+1} & \dfrac{-0.46e^{-0.15s}}{0.75s+1} \\ \dfrac{-0.0017e^{-0.15s}}{0.45s+1} & \dfrac{0.0015e^{-0.25s}}{0.75s+1} \end{bmatrix} \quad (11)$$

$$\mathrm{G(s)} = \begin{bmatrix} \dfrac{0.5e^{-0.1s}}{1.2s+1} & \dfrac{-0.2e^{-0.05s}}{1.35s+1} \\ \dfrac{-0.0025e^{-2.05s}}{1.35s+1} & \dfrac{0.0039e^{-1.35s}}{1.65s+1} \end{bmatrix} \quad (12)$$

$$\mathrm{G(s)} = \begin{bmatrix} \dfrac{0.48e^{-0.1s}}{0.9s+1} & \dfrac{-0.04e^{-0.4s}}{0.6s+1} \\ \dfrac{-0.00068e^{-3.3s}}{1.2s+1} & \dfrac{0.00056e^{-0.9s}}{1.8s+1} \end{bmatrix} \quad (13)$$

The multiloop controllers are designed for the locally linearized models at the three operating points using BLT method. The manipulated variables for the control scheme are feed flow rate (F) and coolant flow rate ($\mathrm{F_c}$) and the controlled variables are the concentration of component A ($\mathrm{C_A}$) and reactor temperature (T). The multiloop controllers are designed using BLT procedure and the controller tuning constants are given in Table 6.2. In the design step of BLT, first the PI controller parameters are obtained using Ziegler-Nichols method for individual loop then the multiloop controller parameters are adjusted using the detuning factor f. The detuning factor of the CSTR process for all the three regions is found to be 1.195, 1.275 and 1.26 respectively.

TABLE IV MULTILOOP CONTROLLER PARAMETERS FOR CSTR PROCESS USING BLT METHOD

Operating Regions	**Kc**		**Ti**	
	Temperature Loop	**Concentration Loop**	**Temperature Loop**	**Concentration Loop**
Lower	2.4301	1361.4	0.3560	0.8897
Middle	13.8963	237.8381	0.4116	4.5860
Higher	11.1076	2452.4	0.4026	3.2329

C. Concentration control of CSTR using multiloop BLT method

To study the merit of closed loop system with the designed controller, combined servo and regulatory responses are generated through simulation as shown in the Fig. 4. The controller is designed for all the three regions of operation of CSTR. However, this paper presents the responses of servo tracking and regulatory feature of the designed controller only for the lower region. The disturbances are introduced purposefully at various sampling instants. The Feed concentration C_{A0}, the Inlet stream temperature T_{in} and Temperature of the inlet coolant water in the jacket T_{cin} are the potential disturbances to the CSTR. The disturbance pattern is shown in the Fig. 5 The Fig. 6 displays the interaction effect of concentration on the reactor temperature. The designed controller successfully tracks the setpoint change and at the same time reduces the interaction effect by bringing down the temperature at its reference.

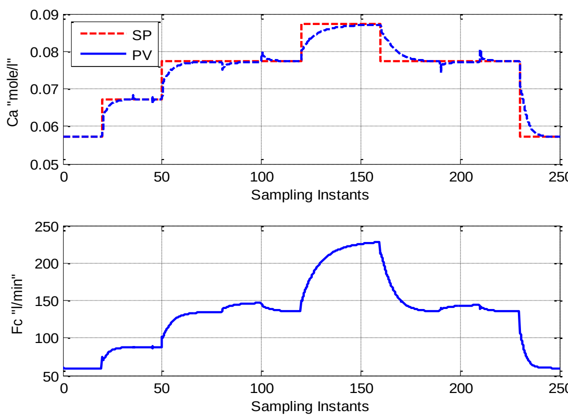

Fig. 4 Servo and regulatory response of multiloop control based on BLT method for concentration control at Lower region

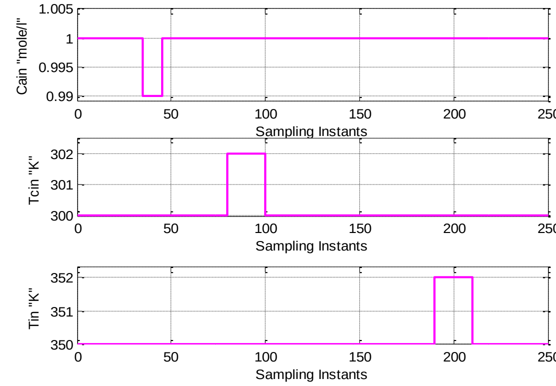

Fig. 5 Disturbance pattern used to study regulatory behaviour of the multiloop BLT method for concentration control at lower region

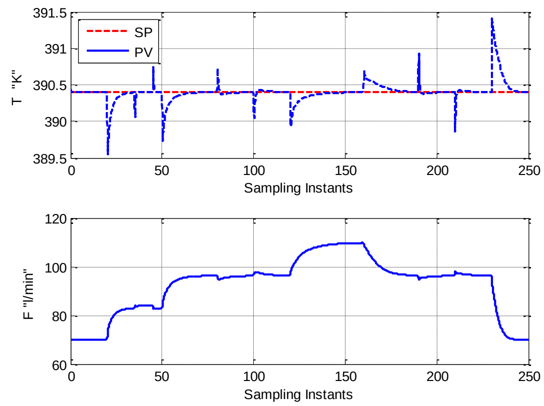

Fig. 6 Interaction behaviour of temperature under BLT control at Lower region

The servo and regulatory responses are analysed using the performance indices, ISE and IAE which are tabulated in the Tables V and VI.

TABLE V PERFORMANCE MEASURES OF MULTILOOP BLT METHOD FOR SETPOINT CHANGE DURING CONCENTRATION CONTROL

Operating Regions	**Disturbance Change**	**ISE**		**IAE**	
		$\boldsymbol{T}$	$\boldsymbol{C_A}$	$\boldsymbol{T}$	$\boldsymbol{C_A}$
LOWER	C_{A0}	0.263649	2.74E-06	1.478079	0.004325
	T_{cin}	0.458558	6.42E-05	4.0763	0.077035
	T_{in}	0.525928	4.03E-05	3.049855	0.054309
MIDDLE	C_{A0}	0.001268	0.005756	0.504374	1.806346
	T_{cin}	0.338011	0.213487	3.808853	18.00207
	T_{in}	0.035873	0.010168	1.02627	2.953164
HIGHER	C_{A0}	0.008184	0.000449	0.596277	0.240776
	T_{cin}	0.101956	0.004169	1.821058	0.894398
	T_{in}	0.02642	0.000605	0.792886	0.310614

TABLE VI PERFORMANCE MEASURES OF MULTILOOP BLT METHOD FOR DISTURBANCE CHANGE DURING CONCENTRATION CONTROL

Operating Regions	**Setpoint Change**	**ISE**		**IAE**	
		T	C_A	T	C_A
LOWER	0.0572-0.0673	7.505704	0.000653	19.00229	0.186877
	0.0673-0.0772	5.423591	0.001085	19.57204	0.311703
	0.0772-0.0872	3.313426	0.002213	19.68752	0.608792
	0.0872-0.0772	2.555689	0.002897	19.62726	0.607472
	0.0772-0.0572	2.54E-07	0.000401	0.000128	0.020015
MIDDLE	0.7963-0.8063	0.001984	0.010253	0.600567	2.333557
	0.8063-0.8163	0.003646	0.003085	0.208219	1.047291
	0.8163-0.8263	0.001191	0.020614	0.772968	4.707932
	0.8263-0.8163	0.002255	0.050046	1.139949	6.610832
	0.8163-0.7963	0.009026	0.078185	1.541579	6.320316
HIGHER	0.8178-0.8278	0.055098	0.000999	0.967585	0.249992
	0.8278-0.8378	0.040015	0.001351	0.858379	0.348968
	0.8378-0.8478	0.027117	0.00202	0.830327	0.526707
	0.8478-0.8378	0.02229	0.002282	0.817335	0.527004
	0.8378-0.8178	0.188169	0.005033	1.852324	0.5997

D. Temperature control of CSTR using multiloop BLT method

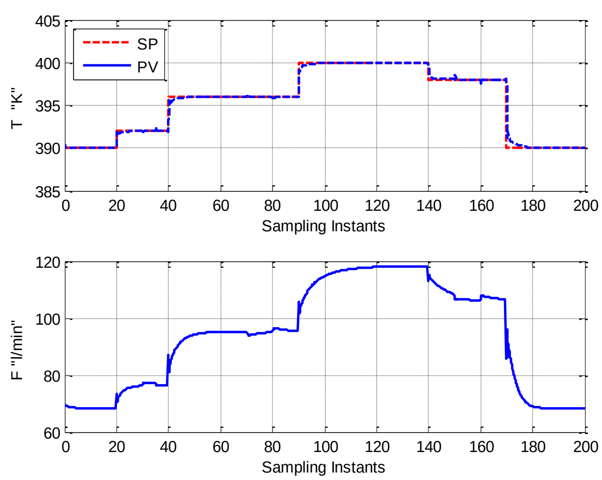

Fig. 7 Servo and regulatory response of multiloop control based on BLT method for temperature control at Lower region

To study the setpoint tracking feature of the designed controller while controlling the temperature of the reactor, the CSTR is operated at various regions by intentionally changing the setpoints from the nominal values over the entire range of operation. The disturbance attenuation capability of the designed controller is audited by perturbing the disturbance variables presented in the previous section from their nominal values sequentially at various sampling instants. The controller is designed for all the three regions of operation of CSTR. However, this paper presents the responses of servo tracking and regulatory feature of the designed controller only for the lower region. The Fig. 7, show the servo and regulatory response at various operating regions. The Fig. 8 show the interaction effect of the temperature over concentration. The servo and regulatory responses are analysed using the performance indices, ISE and IAE which are represented in the Tables VII and VIII.

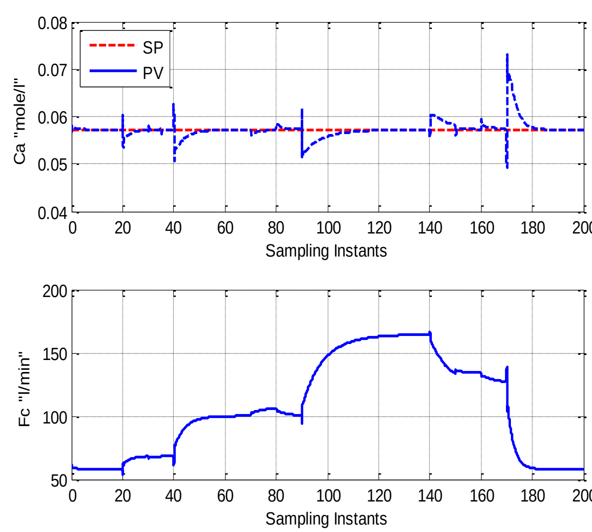

Fig. 8 Interaction behaviour of concentration under multiloop control based on BLT method at Lower region

TABLE VII PERFORMANCE MEASURES OF MULTILOOP BLT METHOD FOR SETPOINT CHANGE DURING TEMPERATURE CONTROL

Operating Regions	Setpoint Change	ISE		IAE	
		T	C_A	T	C_A
LOWER	390-392	7.736099173	0.000101497	12.59535832	0.071836429
	392-396	31.53375889	0.000556676	29.59296462	0.216807027
	396-400	31.89302263	0.001107204	35.2951566	0.422412308
	400-398	7.951037333	0.000427886	15.29961269	0.194316737
	398-390	64.14982945	2.71078E-08	8.00934728	0.000164552
MIDDLE	318.3-320.3	4.870758488	0.009123485	4.81229794	1.887522772
	320.3-324.3	20.17094975	0.081730303	11.17469595	7.573335385
	324.3-328.3	21.57248109	0.237101876	13.56499052	17.28714651
	328.3-326.3	5.327937833	0.077584226	6.268005917	9.944276369
	326.3-318.3	64.00017629	3.47035E-09	8.000010881	5.83153E-05
HIGHER	314.1-316.1	5.198077357	0.000518812	5.36915999	0.157561626
	316.1-320.1	21.67705389	0.002698223	11.82945808	0.454657653
	320.1-324.1	22.66509985	0.006129484	12.98521468	0.865334251
	324.1-322.1	5.542034276	0.001831273	5.96656307	0.480923024
	322.1-314.1	64.00162793	3.34327E-09	8.000101102	5.71498E-05

TABLE VIII PERFORMANCE MEASURES OF MULTILOOP BLT METHOD FOR DISTURBANCE CHANGE DURING TEMPERATURE CONTROL

Operating regions	Disturbance Change	ISE		IAE	
		T	C_A	T	C_A
LOWER	C_{A0}	0.219867704	1.42802E-06	1.418147663	0.003218989
	T_{cin}	0.310809173	2.32366E-05	3.175412116	0.038714598
	T_{in}	0.766860715	3.98115E-06	3.119078393	0.011081714
MIDDLE	C_{A0}	0.001897433	0.004879624	0.398053736	0.970581264
	T_{cin}	0.5067893	0.154377889	4.195812453	12.55975218
	T_{in}	0.169254731	0.024209092	1.832332298	4.546327263
HIGHER	C_{A0}	0.012859979	0.000281053	0.595719278	0.150377301
	T_{cin}	0.112566977	0.001708134	1.699764422	0.430851172
	T_{in}	0.111314901	0.000797824	1.439077994	0.321666264

V. CONCLUSION

The interaction effect of concentration on the temperature and vice versa in the CSTR during their control is completely ignored in the Single Input Single Output (SISO) control design that results in a performance degradation of the overall system. This challenge is very well addressed with the multiloop control techniques. In this paper, multiloop control system design based BLT is tested on the CSTR operated as a MIMO system. The multiloop PI controller using BLT method is presented and the performance evaluated using ISE and IAE. The CSTR is operated at three different regions and performance is evaluated for both concentration and temperature control. From the proposed multiloop control based on BLT method, it is observed that the interaction is very well negotiated and performance of the system is improved substantially.

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