System Identification and Design of Inverted Decoupling IMC PID Controller for Non-Minimum Phase Quadruple Tank Process

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ABSTRACT: *A systematic analytical and experimental method of identification of Two Input Two Output (TITO) Quadruple-Tank Process (QTP), operated at non-minimum phase condition has been presented. Parameters of the process transfer function matrix have been validated on an experimental laboratory-scale physical setup of the process. Appropriate input-output pairing and interaction among control loops have been studied based on the Relative Gain Array (RGA) analysis. Inverted Decoupling Internal Model Control (IMC) based Proportional Integral Derivative (PID) controller has been designed for the TITO process. The effect of changes in controller tuning parameters on the closed-loop response for servo problem has been reported in terms of quantitative performance indices such as Integral of Square of Error (ISE), Integral of Absolute Error (IAE), percentage overshoot and offset. The simulation results have been compared with the literature.*

KEYWORDS: *Inverted decoupling; IMC-PID controller; Quadruple Tank process; non-minimum phase; Transmission zeros; RGA analysis.*

INTRODUCTION

The control studies on complex Multiple Input Multiple Output (MIMO) systems such as distillation columns may well be studied with the help of representative Mathematical Models [1]. However, the laboratory-scale Quadruple-Tank Process (QTP) has come up as a cost effective, representative and safe alternative for experimental study of various MIMO control strategies [2- 4]. Modeling of QTP and modified system has been elaborately presented in literature [5-8] but system identification from experimental data has not been dealt with. The QTP can be operated to exhibit minimum and non-minimum phase behavior, by experimentally changing the location of transmission zeros of the system [9, 10]. The design of suitable controllers for MIMO non-minimum phase systems is a challenging task. The conventional PID controllers are ineffective because of the control loop interactions, inverse response and stability issues [11-13]. Various advanced control strategies have therefore been designed [14,15]. Model based controller design techniques have therefore come up as better alternative to deal with the drawbacks of conventional PID design methods. The design of Internal

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Model Control (IMC) based PID controllers are effective in case of SISO non-minimum phase systems since they provide a desired closed loop response by appropriately tuning the filter parameters [16,17]. However, in case of MIMO non-minimum phase systems, suitable decoupling techniques have to be used in combination with the IMC-PID controllers in order to negate the effect of interactions among the control loops [18-20].Controller tuning is however important in all design strategies.

In the present work, a systematic approach to system identification based on open loop experiments has been presented for a two input two output quadruple tank process operated at the non-minimum phase. IMC based PID controller has been designed for the process using the identified transfer function matrix. RGA analysis has been performed to identify the best CV-MV pairing. Closed loop computer simulations have been carried out for set point tracking. Inverted decoupling controller design method has been used to overcome the control loop interactions, and the quantitative performance indices (ISE, IAE, ITAE, % overshoot) have been compared for different controller tuning parameters, to evaluate the optimum design.

THEORITICAL SECTION

Identification of Quadruple Tank Process (QTP)

Process description

Schematic diagram of Quadruple Tank Process (QTP) (Make: Apex Innovations Pvt. Ltd. [39]) has been shown in Fig. 1. The experimental process consists of four cylindrical tanks. Two Variable Frequency Drive (VFD) regulated positive displacement pumps P1 and P2 are used to supply water from the reservoir to the four tanks, in fully circulating mode. Water from Pump 1 flows through a three-way valve where it is split into a (desired) fraction γ_1 and fed to tank 1 and tank 4. Similarly, water from Pump 2 flows through another three-way valve where it is split into another (desired) fraction γ_2 and fed to tank 2 and tank 3. The water outlet (through adjustable valves) from tank 3 and tank 4 serves as the second inlet source for tank 1 and tank 2 respectively,. Finally, the outlets of tank 1 and tank 2 drain water back to the reservoir, through respective adjustable valves. Level transmitters are used to measure the liquid levels of the two bottom tanks, tank 1 and tank 2. Signals from the level transmitters act as the two controlled variables (CV) that are sent to Serial based duel loop PID controller, which in turn is connected to the USB port of a computer. The physical process is operated in both open loop and closed loop modes, through the computer software. The controller output signals serve as the two Manipulated Variables (MV), which act as input to the two Variable Frequency Drives (VFD) for manipulating the water flowrate discharging through the two pumps. Mathematical model of the QTP has been shown in Appendix A. The experimental operating condition for the QTP to behave as a non-minimum phase system is: $0 < \gamma_1 + \gamma_2 < 1$

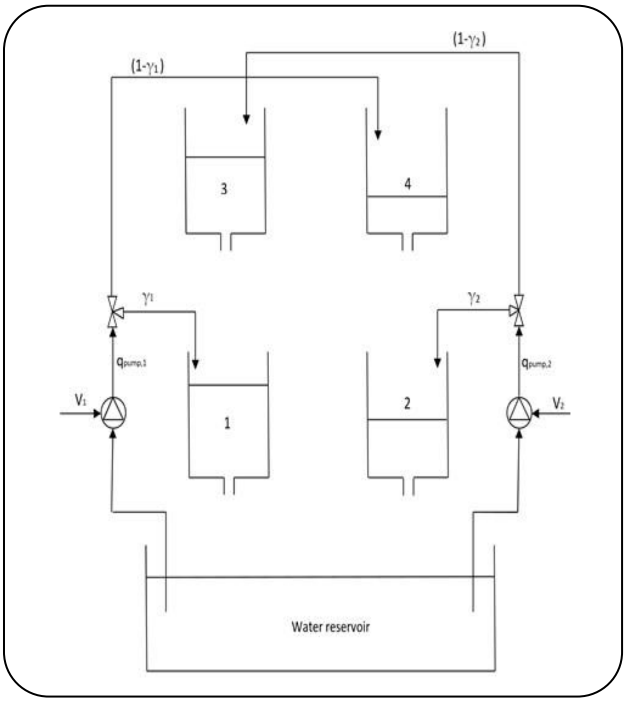

Fig. 1: Schematic Diagram of Quadruple Tank Process.

The QTP experimental setup parameters

The QTP experimental setup has the following (known) process parameters:

Inner Diameter (ID) of all the four tanks = 9.2 cm

Cross sectional area of all the four tanks A= 66.4761 cm^2

Maximum Height (H) of all the four tanks = 26.5 cm

Maximum flowrate of each Pump =55.5744 LPH

The unknown process parameters have been evaluated from open loop experiments, as shown in the following steps:

1- Firstly, both the pumps have been operated at maximum flowrate.

2- The two three-way valves have been adjusted for non-minimum phase condition. γ_1 and γ_2 have been fixed such that $\gamma_1 + \gamma_2 < 1$. This can be physically verified from the observation that the two upper tanks fill faster than the lower ones.

3- The output valve (resistance) is adjusted in such a way that the tank levels are maintained at 80-90% of maximum height.

4- Provide a sequence of step changes in F_1 (flowrate of Pump 1) alone, by keeping F_2 constant. Step 4 is repeated by keeping F_1 constant and providing a sequence of step changes in F_2 (flowrate of Pump 2) alone. The steady-state data has been recorded.

Parameter estimation

To begin with, the values of γ_1, γ_2 are estimated by closing the outlet valves of the tanks (running the tanks in pure capacity mode) and running the pumps to discharge the maximum flowrates. The (constant) slope of liquid level vs time curve is used to calculate the inlet flowrate to each tank based on the equation 1 (Appendix A). Values of γ_1, γ_2 are calculated as the ratio of the tank's inlet flowrate to the total flowrate discharging from the pump.

The parameter estimates (γ_1, γ_2, β_j, τ_i and K_i) from experimental steady-state open loop step response data have been shown in Tables1, 2, 3 and 4 respectively.

Process transfer function matrix

Based on the steady-state experimental data as shown in Tables 1, 2, 3 and 4, the elements of process transfer function matrix have been evaluated as:

For F_1 = 44.26 LPH and F_2 = 55.57 LPH;

$$G(s) = \begin{pmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{pmatrix} =$$

$$\begin{pmatrix} \dfrac{0.163}{(54.3s+1)} & \dfrac{0.612}{(54.3s+1)(73.0s+1)} \\ \dfrac{0.49}{(41.3s+1)(54.7s+1)} & \dfrac{0.155}{(41.3s+1)} \end{pmatrix}$$

Transmission zeros

The transmission zeros of the process have been calculated to be +0.0386, -0.0705, -0.0184 and -0.0242. Two Input Two Output (TITO) process has the one RHP transmission zero and hence exhibits non-minimum phase behavior.

Control loop interactions

Relative gain array

The control loop interactions for the quadruple tank process has been shown in Fig. 2. It can be observed that each of the two process outputs y1 and y2 (liquid levels in tank1 and tank 2) are affected by changes in either of the manipulated inputs u1 and u2 (pump flows)

Each elements of Relative Gain Array (RGA) is defined as the ratio of two steady state gains:

$$\lambda_{ij} = \frac{\left(\dfrac{\partial y_i}{\partial m_j}\right)_{Open-loop}}{\left(\dfrac{\partial y_i}{\partial m_j}\right)_{closed-loop, \not\in m_j loop}} \quad (1)$$

RGA for a MIMO process may be represented as:

$$\Lambda = \begin{pmatrix} \lambda_{11} & \cdots & \lambda_{1n} \\ \vdots & \ddots & \vdots \\ \lambda_{n1} & \cdots & \lambda_{nn} \end{pmatrix} \quad (2)$$

For the Two Input Two Output (TITO) quadruple tank process, the elements of RGA have been calculated as:

$$\left(\frac{\partial y_1}{\partial m_1}\right)_{open-loop} = K_{11} \quad (3)$$

$$\left(\frac{\partial y_1}{\partial m_1}\right)_{Closed-loop-2} = K_{11}\left(1 - \frac{K_{12}K_{21}}{K_{11}K_{22}}\right) \quad (4)$$

Define $\zeta = \dfrac{K_{12}K_{21}}{K_{11}K_{22}}$

$$\lambda_{11} = \frac{1}{1-\zeta} \quad (5)$$

$$\lambda_{12} = \lambda_{21} = \frac{-\zeta}{1-\zeta} \qquad \lambda_{11} = \lambda_{22} = \frac{1}{1-\zeta}$$

The RGA for the quadruple tank process obtained as:

$$\Lambda = \begin{pmatrix} -0.092 & 1.092 \\ 1.092 & -0.092 \end{pmatrix} \quad (6)$$

From the elements of RGA, it is observed that λ_{12} & $\lambda_{21} > 1$. It is recommended to avoid pairing mj with y_i if λ_{ij} takes a large high value.

Table 1: Steady-state open loop step response data of Quadruple tank process.

Flow rate of Pump1 (LPH)	Flow rate of Pump2 (LPH)	Steady State height of water in Tank 1(cm)	Steady State height of water in Tank 2(cm)	Steady State height of water in Tank 3(cm)	Steady State height of water in Tank 4(cm)	γ_1	γ_2
55.5744	55.5744	21.7216	19.97312	22.89152	21.05088	0.2	0.25
44.2584	55.5744	20.64384	15.33184	22.89152	14.58176	0.2	0.25
32.9424	55.5744	19.34592	10.9312	22.89152	8.73216	0.2	0.25
21.6264	55.5744	18.37824	7.16288	22.89152	4.40064	0.2	0.25
32.9424	55.5744	19.36384	10.9056	22.89152	8.6144	0.2	0.25
44.2584	55.5744	20.74368	15.21664	22.89152	14.31296	0.2	0.25
55.5744	55.5744	22.01344	20.39808	22.89152	21.4016	0.2	0.25
55.5744	38.6004	13.26848	18.49344	11.45088	21.4016	0.2	0.25
55.5744	21.6264	6.67392	16.63488	4.02944	21.4016	0.2	0.25
55.5744	32.9424	10.5216	17.98656	8.22016	21.4016	0.2	0.25
55.5744	44.2584	15.66464	19.12576	14.20032	21.4016	0.2	0.25
55.5744	55.5744	21.91616	20.81792	22.99648	21.4016	0.2	0.25

Table 2: Estimation of valve resistance β_j .

Flow rate of Pump1 (LPH)	Flow rate of Pump2 (LPH)	$\beta_1 \left(\frac{LPH}{\sqrt{cm}}\right)$	$\beta_2 \left(\frac{LPH}{\sqrt{cm}}\right)$	$\beta_3 \left(\frac{LPH}{\sqrt{cm}}\right)$	$\beta_4 \left(\frac{LPH}{\sqrt{cm}}\right)$
55.5744	55.5744	11.32798	13.05693	8.711616	9.690131
44.2584	55.5744	11.12181	12.59078	8.711616	9.272156
32.9424	55.5744	10.97428	12.17321	8.711616	8.918347
21.6264	55.5744	10.73157	11.65567	8.711616	8.247386
32.9424	55.5744	10.9692	12.18749	8.711616	8.979098
44.2584	55.5744	11.09501	12.63835	8.711616	9.358817
55.5744	55.5744	11.25264	12.92021	8.711616	9.610404
55.5744	38.6004	10.99908	12.58246	8.555268	9.610404
55.5744	21.6264	10.58092	12.22632	8.080219	9.610404
55.5744	32.9424	11.04346	12.425	8.617402	9.610404
55.5744	44.2584	11.19512	12.69616	8.808621	9.610404
55.5744	55.5744	11.27759	12.78926	8.691713	9.610404

Table 3: Estimation of time constants τ_i .

Flow rate of Pump1 (LPH)	Flow rate of Pump2 (LPH)	τ_1 (seconds)	τ_2 (seconds)	τ_3 (seconds)	τ_4 (seconds)
55.5744	55.5744	54.69519	45.50274	73.012	62.94499
44.2584	55.5744	54.30947	41.34283	73.012	54.74947
32.9424	55.5744	53.28123	36.10642	73.012	44.0486
21.6264	55.5744	53.10609	30.52546	73.012	33.81406
32.9424	55.5744	53.33058	36.02186	73.012	43.45457
44.2584	55.5744	54.57213	41.03219	73.012	53.74022
55.5744	55.5744	55.43004	46.47088	73.012	63.99369
55.5744	38.6004	44.02605	45.43587	52.58253	63.99369
55.5744	21.6264	32.45807	44.34756	33.02592	63.99369
55.5744	32.9424	39.04735	45.37675	44.23026	63.99369
55.5744	44.2584	46.99886	45.79232	56.87178	63.99369
55.5744	55.5744	55.18509	47.42736	73.34677	63.99369

Table 4: Estimation of steady-state gains K_i .

Flow rate of Pump1 (LPH)	Flow rate of Pump2 (LPH)	K11	K12	K21	K22
55.5744	55.5744	0.164571	0.617141	0.547648	0.17114
44.2584	55.5744	0.16341	0.612789	0.497582	0.155494
32.9424	55.5744	0.160317	0.601187	0.434559	0.1358
21.6264	55.5744	0.15979	0.599211	0.367389	0.114809
32.9424	55.5744	0.160465	0.601744	0.433541	0.135482
44.2584	55.5744	0.164201	0.615753	0.493843	0.154326
55.5744	55.5744	0.166782	0.625433	0.5593	0.174781
55.5744	38.6004	0.132469	0.496759	0.546844	0.170889
55.5744	21.6264	0.097662	0.366234	0.533745	0.166795
55.5744	32.9424	0.117489	0.440582	0.546132	0.170666
55.5744	44.2584	0.141414	0.530302	0.551134	0.172229
55.5744	55.5744	0.166045	0.622669	0.570812	0.178379

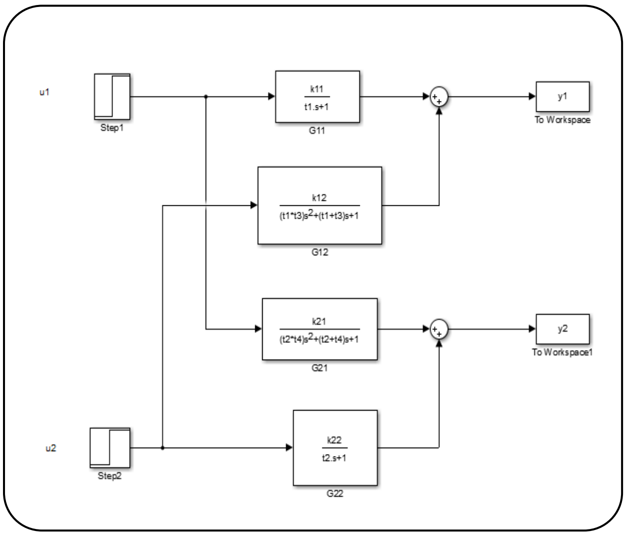

Fig. 2: Control loop interactions in quadruple tank process.

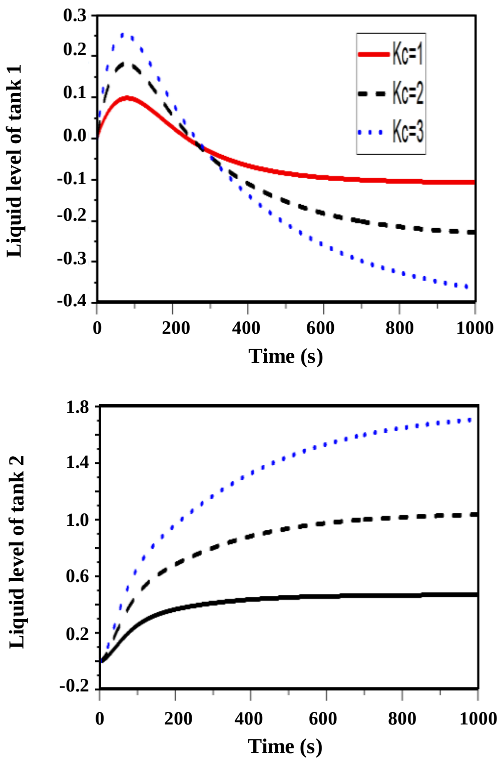

Fig. 3: Effect of process interaction on the closed loop response.

The closed loop response of the process with control loop interaction

The closed loop response of the quadruple tank process to step change in set point of liquid level in tank 1 has been studied at different values of the controller gain, as shown in Fig. 3. The liquid level in tank 1 exhibits an inverse response (due to the effect of RHP transmission zero). The effect of interaction can be clearly observed from the dynamics of tank 2. Moreover, good set-point tracking is not achieved even for different controller gains. This behavior emphasizes the need of decoupler design for the quadruple tank process.

Design of inverted decoupling controller

The decouplers for the process have been designed based on the following relations:

$$d_{21}(s) = -\frac{g_{21}(s)}{g_{22}(s)} \tag{9}$$

$$d_{12}(s) = -\frac{g_{12}(s)}{g_{11}(s)}$$

$$g^{*}_{11}(s) = g_{11}(s) + d_{21}(s)g_{12}(s)$$

$$g^{*}_{22}(s) = g_{22}(s) + d_{12}(s)g_{21}(s)$$

The decouplers effectively decouple the control loops (by nullifying the effect of interactions) and convert the two input two output process into two open loop equivalent transfer functions (OLETFs) for which, independent controllers can be designed. The closed loop block diagram of inverted decoupling controller for the quadruple tank process has been shown in Fig.4.

The closed loop response of the process with inverted decoupling controllers

Closed loop performance of the decoupled process has been studied, as shown in Fig. 5. Comparison of the two closed loop responses in Figs. 4 and 5 demonstrate the effectiveness of decoupler design. Further, the set-point tracking performance of the controller has been evaluated in terms of Quantitative Performance Indices (QPI), as indicated in Table 5. It has been observed that by increasing the controller gain, there is improvement in the closed loop response of tank 1, as indicated by the Integral of square of error (ISE), Integral of absolute error (IAE) and Offset values. However, the response of tank 2 becomes more oscillatory in nature. Improved controller performance may be obtained by introducing the Integral and Derivative control action modes as well. Closed loop stability is an important factor to be kept in mind while designing the conventional PID controller for the non-minimum phase multiple input multiple output process. This study therefore emphasizes the need of a more systematic model based controller design technique for the process.

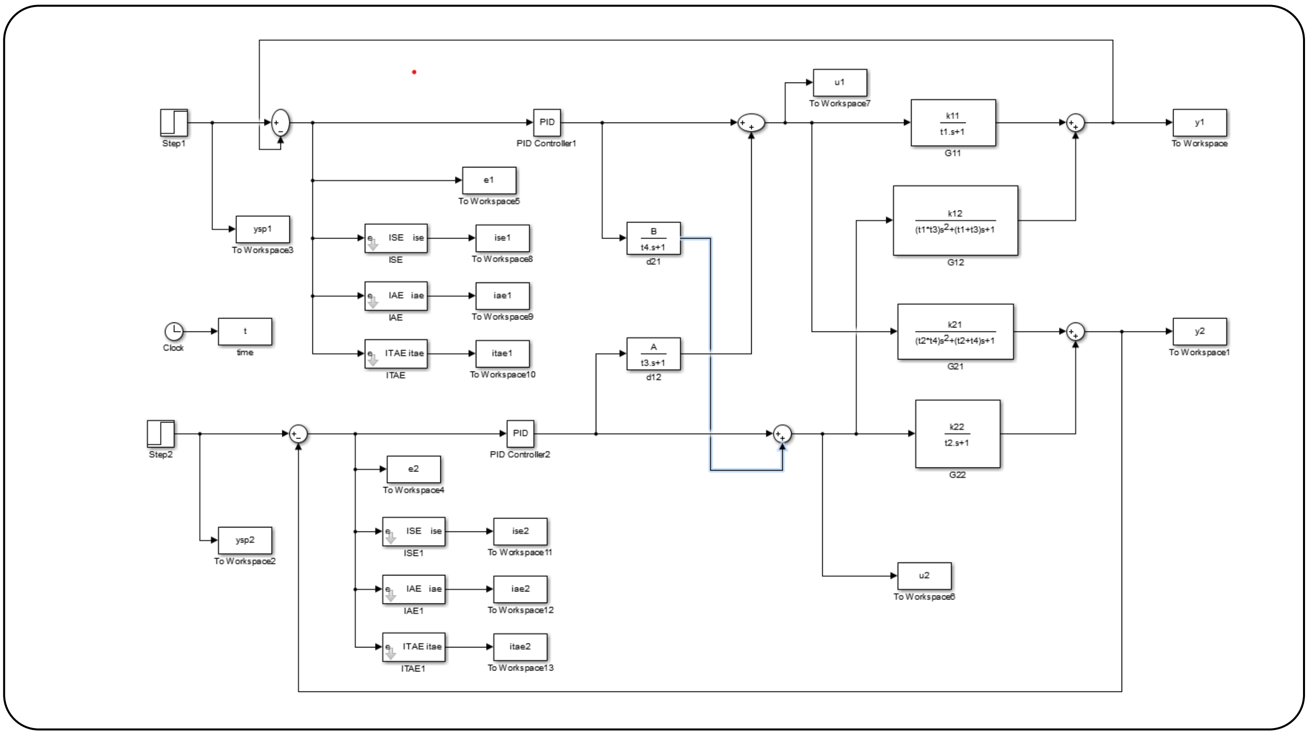

Fig. 4: Closed loop block diagram of Quadruple tank process with inverted decoupling controllers.

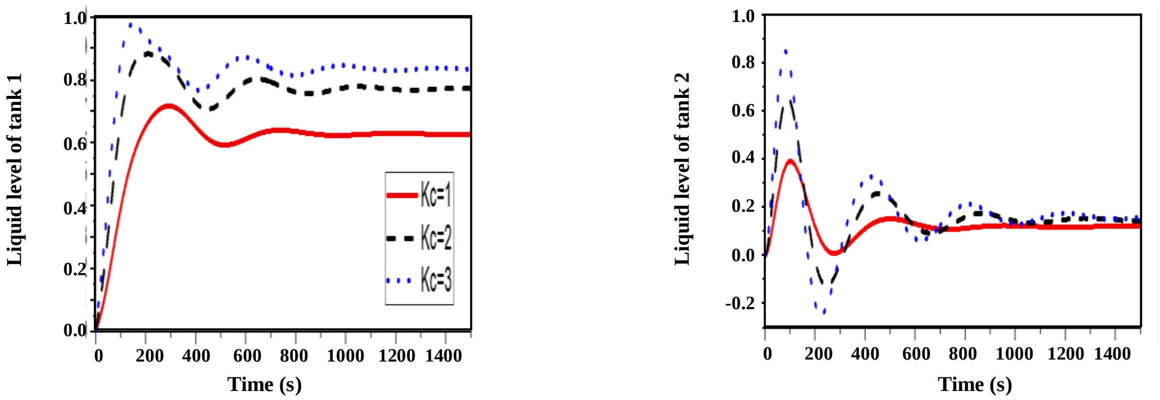

Fig. 5: Closed loop response of the decoupled quadruple tank process.

IMC based PID controller design

The Internal Model Control (IMC) technique has the advantage that it can be implemented within the Proportional Integral Derivative (PID) framework. Moreover, the IMC-PID controller design technique offers the advantage of reducing the controller tuning problem in terms of a single tuning parameter. In the present study, IMC based PID controller has been designed, based on the input-output pairing suggested in the RGA analysis of the process, as discussed in section 3. Since the decoupled Open Loop Equivalent Transfer Functions (OLETFs) as shown in Equation 9 exhibit higher order underdamped response, the IMC-PID controllers have been designed based on second order process transfer functions.

Control of liquid level in Tank 1

The IMC-PID controller for tank 1 is designed based on the second order process transfer function, g_{12} (s).

$$g_{12}(s) = \frac{k_{12}}{(\tau_1 s+1)(\tau_3 s+1)}$$

Table 5: Closed loop Quantitative performance indices (QPI) for the decoupled process.

KC	ISE	IAE	OFFSET
1	262.05	599.3	-0.37098
2	118.7955	373.8609	-0.22601
3	73.53796	271.5006	-0.16481

Desired close loop transfer function is:

$$g_{CL1}(s) = \frac{1}{\theta_1 s + 1}$$

IMC based PID controller parameters have been taken from literature [5]

Proportional gain $k_{c1} = \frac{\tau_1 + \tau_3}{k_{12}\theta_1}$ (10)

Integral time $\tau_{I1} = \tau_1 + \tau_3$

Derivative time $\tau_{D1} = \frac{\tau_1 \tau_3}{\tau_1 + \tau_3}$

Control of liquid level in Tank 2

The IMC-PID controller for tank 2 is designed based on the second order process transfer function, $g_{21}(s)$.

The process transfer function is:

$$g_{21}(s) = \frac{k_{21}}{(\tau_2 s+1)(\tau_4 s+1)}$$

Desired closed loop transfer function=

$$g_{CL2}(s) = \frac{1}{\theta_2 s + 1}$$

IMC based PID controller parameters have been taken from literature [5]

Proportional gain $k_{c2} = \frac{\tau_2 + \tau_4}{k_{21}\theta_2}$ (11)

Integral time $\tau_{I2} = \tau_2 + \tau_4$

Derivative time $\tau_{D2} = \frac{\tau_2 \tau_4}{\tau_2 + \tau_4}$

IMC-PID controller tuning

As shown in Equations 10 and 11, θ_1 & θ_2 act as the tuning parameters for the IMC-PID controller. Their nominal values are selected based on the various time constants in the process transfer function matrix. As an initial guess, we may assume $\theta_1 = \theta_2 = \theta$.

Closed loop response of IMC-PID decoupling controller

The closed loop response of liquid level in tank 1(control loop 1) and tank 2 (control loop 2) for different values of the IMC-PID controller tuning parameter θ, has been shown in Fig. 6 and the Quantitative Performance Indices (QPI) have been reported in Table 6. It has been observed that for lower values of θ, the response is more oscillatory and with larger overshoots. Hence, the controller performance has been tested at three different values of θ= 200, 300, 400. For all the values of θ under consideration, the error values are comparable and offset is completely eliminated. However, the overshoot decreases as θ is increased from 200 to 400. Hence the value of θ= 400 is recommended.

Comparative analysis

Internal Model Control-Proportional Integral (IMC-PI) and Fractional Order- Proportional Integral (FO-PI) control of two input two output (TITO) minimum phase quadruple tank process has been studied by [22]. The process transfer function matrix, its poles and transmission zeros of [22] have been reproduced below for comparison.

$$G_p(s) = \begin{pmatrix} g_{p11}(s) & g_{p12}(s) \\ g_{p21}(s) & g_{p22}(s) \end{pmatrix} =$$

$$\begin{pmatrix} \frac{11.89}{(121.4s+1)} & \frac{6.875}{(121.4s+1)(3.967s+1)} \\ \frac{6.738}{(84.73s+1)(3.109s+1)} & \frac{0.155}{(84.73s+1)} \end{pmatrix}$$

Poles of transfer function matrix:

p1= -0.0082, p2= -0.3216, p3= -0.0118, p4= -0.2521, p5= -0.0082, p6= -0.0118

Transmission zeros of the Transfer function matrix

z1= -0.4560, z2= -0.1177, z3= -0.0118, z4= -0.0082

The process exhibits minimum phase behavior since all its transmission zeros are negative. The IMC-PID decoupling controller proposed in the present work

Table 6: Closed loop Quantitative performance indices (QPI) for IMC-PID decoupling controller.

Theta	Closed loop response of tank 1 (y1)				Closed loop response of tank 1 (y2)			
	ISE	IAE	Offset	% Overshoot	ISE	IAE	Offset	% Overshoot
200	88.86	175.09	0.00	20.80	27.40	114.44	0.00	44.47
300	98.94	167.01	0.00	8.35	20.86	89.68	0.00	38.52
400	113.48	180.35	0.00	2.76	19.22	83.42	0.00	34.54

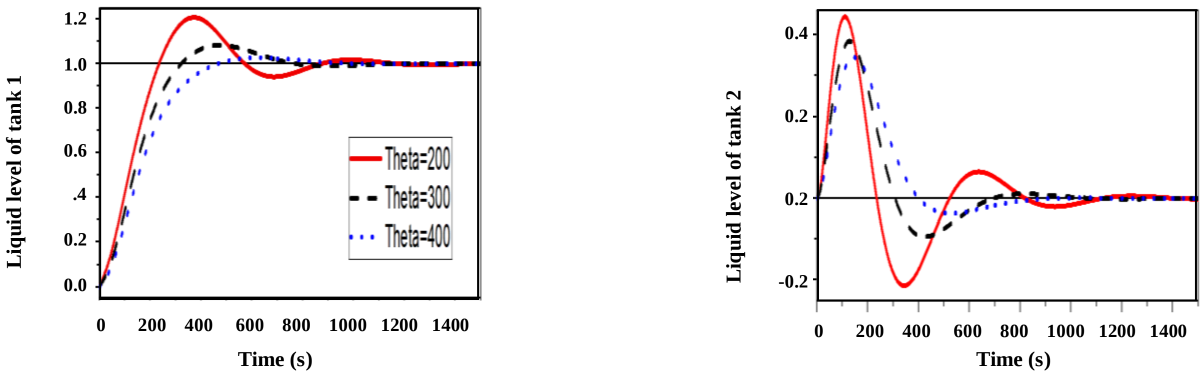

Fig. 6: Closed loop response of IMC-PID decoupling controller.

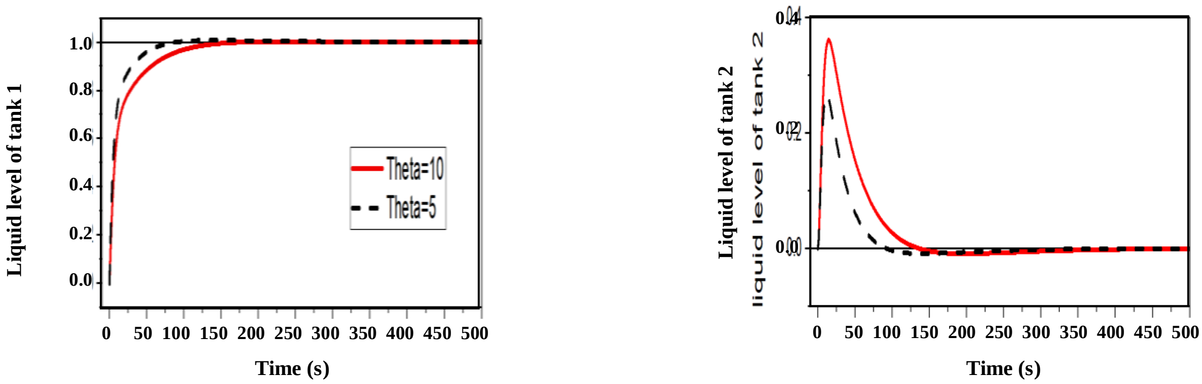

Fig. 7: Closed loop response of IMC-PID decoupling controller for transfer function of [22]r.

has been implemented on the process transfer function of [22] and the closed loop simulation results have been shown in Fig. 7 and Table 7. The proposed IMC-PID decoupling controller is shown to exhibit better performance than the IMC-PI controller of [22]

CONCLUSIONS

In the present work, an IMC-PID decoupling controller has been designed and tuned for two input two output experimental quadruple tank process, operated at non-minimum phase. System identification of the quadruple tank process (evaluation of the parameters of process transfer function matrix) has been carried out based on open loop experimental data. Transmission zeros of the process transfer function matrix have been evaluated to confirm the non-minimum phase behavior. Relative gain Array (RGA) has been evaluated to confirm the interaction among the two control loops and selection of input-output pairing of the controlled and manipulated variables has been decided based on the RGA analysis. IMC PID controller has been designed for two independent decoupled open loop equivalent transfer functions using the standard IMC rules. The IMC-PID decoupling controller parameter (theta) has been tuned to provide

Table 7: Closed-loop Quantitative performance indices (QPI) for IMC-PID decoupling controller for the transfer function of [22].

	Controller	Closed-loop response of tank 1 (y1)				Closed loop response of tank 1 (y2)			
		ISE	IAE	Offset	% Overshoot	ISE	IAE	Offset	% Overshoot
Present work	IMC-PID (Theta=10)	6.39	19.13	0.00	0.36	3.85	18.22	0.00	36.14
	IMC-PID (Theta=5)	3.98	12.14	0.00	0.89	1.55	10.17	0.00	26.75
Komathi et al. [2017]	IMC-PI	44.27	92.03	-	-	30.46	64.2	-	-
	FO-PI	0.0512	0.1571	-	-	0.0368	0.1159	-	-

good set-point tracking properties as evaluated from the quantitative performance indices such as Integral of Square of Error (ISE), Integral of Absolute Error (IAE), offset, and percentage overshoot. The developed control scheme has been tested on a similar two-input two output process and the results have been compared.

Symbols

λ	Elements of Relative Gain Array
F	Pump Flowrate
h_i	Liquid level in of ith tank
K_c	Proportional gain
G	Transfer function matrix of process
Υ	Split fraction of three-way valve
B_i	Outlet valve flow resistance of ith tank
Z	Transmission zeros
A_i	Area of the tank i
τ	Process Time constant
θ_1, θ_2	IMC PID controller tuning parameters

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