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Feedback Control of Fluid Catalytic Cracking Unit using Proportional Integral (PI) Controller

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***Abstract*— Performance of three proportional controllers using different design techniques were studied for the control of condenser inlet stream temperature, condenser liquid level and Heavy cat Naphtha (HCN) flow rate of Fluid catalytic cracking unit (FCCU) was investigated. The FCCU model used in this work was identified with the data collected from Romanian refinery. Three different sets of proportional integral (PI) controllers used for the simulation are Matlab PI modules, modulus optimum PI controller, and internal model control (IMC)-based PI controller. The behaviour of the three controllers was compared with published results. The closed-loop system was simulated using simulink in Matlab environment. The results of the simulation show that IMC-based PI controller outperformed both other two controllers in term of time domain performance metrics such as settling time and rise time.**

Keywords*— PI controller, condenser liquid level, condenser inlet stream temperature, heavy cat naphtha flow rate, fluid catalytic cracking unit (FCCU).

I. INTRODUCTION

Fluid catalytic cracking unit is a unit operation that convert heavy oils into gasoline, middle distills and gaseous product. It has been an integral part of oil refining process. Fluid catalytic unit accepts hydrocarbon chain and break them into smaller ones in chemical process called cracking. The fluid catalytic cracking unit (FCCU) uses an extremely hot catalyst to crack the hydrocarbon into shorter chain. Zeolite, bauxite, silica alumina and aluminum hydro silicate are some of the catalysts commonly used in an FCCU. It is one of the most complex reactors in the process industry which consists of a catalyst section and a fractionating section that operate together as an integrated processing unit. The catalyst section contains the reactor and regenerator, which, with the standpipe and riser, forms the catalyst circulation unit. The fluid catalyst is continuously circulated between the reactor and the regenerator using air, oil vapors, and steam as the conveying media. The fractionating section is a section in which the vapour products from the top of the reactor passing to the bottom of FCC column (fractionators) were distilled into the FCCU end products of cracked naphtha, fuel oil, and off-gas [1]. Controlling problem of FCCU is a challenging task due to its model complexity and cross coupling interaction between inputs and outputs variables [2]

In previous work, nonlinear constrained optimization strategy was applied to reactor-regenerator section of a fluid catalytic cracking (FCC) unit. The main contribution of the work is to combine nonlinear process model with the nonlinear constrained optimization algorithm and to apply it to a highly nonlinear fluid catalytic cracking process. The model results were tested in a real-time application and the constrained nonlinear optimization algorithm and strategies were tested in real-time also on the fluid catalytic cracking reactor-regenerator [3].

Morar and Agachi [4] implemented advanced control scheme on FCC unit of a Romania refinery. The study considered the modality of improving heat integration and steady state performance of the new heat exchanger network (HEN) design for a FCCU. Model Predictive Control (MPC) and the PID controller were used to analyze the behavior of the FCCU. Both controllers were able to stabilize heat transfer through the FCCU, however, MPC gave a better result in term of speed of response in controlling the temperature of the top output stream of the column.

The work of Morar and Agachi [4] was extended by Iancu and Agachi [5] Used FCC plant from a Romanian refinery for simulation and at the same time for the implementation of model predictive control (MPC) strategy, and developed an optimal advanced control scheme for the same heat integrated FCC industrial plant. The implemented MPC strategy focused on the response of the heat integrated process in terms of operation, product quality and cost reduction of the heat integrated plant and utilized Aspen

Hysys software to simulate the FCC heat integrated process. The implemented MPC strategy results revealed an improvement of process operation and the ability to assure higher products quality.

Pandimadeviet al [6] designed a multivariable feedback control configurations for FCC units and provided sufficient conditions to achieve regulation in terms of the steady-state gain matrix. Numerical simulations on a dynamic model based on a FCC unit operating in the partial combustion mode were used to show the effectiveness of several control configurations under disturbances. It was observed from their result that control performance with IMC design was satisfactory.

The aim of this work is to control the FCCU by taking into consideration the inlet stream temperature of the condenser, the liquid level of the condenser and the flow rate of the heavy cat naphtha in the condenser. For this aim to be achieved three sets of PI controller were employed and compared to know the best one for controlling each variable, and that which will give a stable control scheme. The FCCU model used was obtained from the work of [5], and the relative gain array (RGA) was employed as the controllability measure to test for the stablity and interactions between the variables of the plant. The PI controllers were designed based on three methods, which are, modulus optimum, Matlab modules and internal model control (IMC).The controllers were simulated with the plant separately by the aid of simulink in Matlab simulink environment, after the simulation results and observations were noted, and discussion and conclusions were drawn.

II. THE FCC PROCESS

The FCC process is considered as the primary conversion process in refining since it helps to produce about half of the total gasoline output in a refinery. There are two main stages in the FCC process, which are, the cracking stage and the regeneration stage. The former is a stage where the relevant reactions take place and the later is a stage where the catalyst is being regenerated by burning off the coke deposited on the bed, the worn-out catalyst is removed and recycled back to the riser to optimize the cracking process. Figure1 illustrates a typical FCC plant. The FCC process operation can be summarized as follow; at the bottom of the riser, feed oil is contacted with hot catalyst causing the feed to vaporize. When the oil vapor and catalyst flow up the riser, the cracking reactions occur. Coke is formed as a by-product of the cracking reactions and deposited on the catalyst, thereby reducing catalyst activity. The catalyst and products are separated in the reactor. The vapour products from the top of the reactor were passed to the bottom of FCC column (fractionators) where FCCU end products of cracked naphtha, fuel oil, and off-gas were being distilled, and the catalyst is regenerated in the regenerator for reuse. [7, 1].

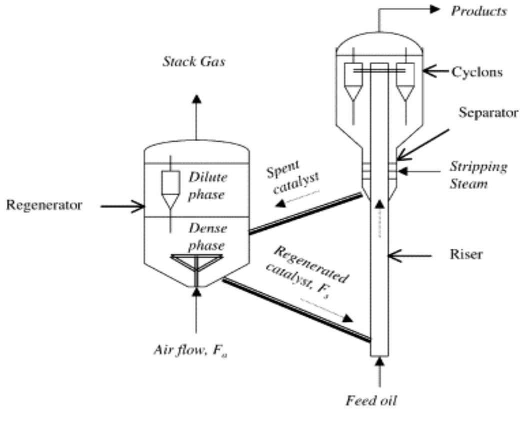

Fig.1. Schematic diagram of regenerator- reactor section of FCCU[7]

III. FCCU MODEL

The model used in this work consists of three inputs and three outputs. The input(manipulated) variables(MV) are reflux flow rate (MV$_1$), Gasoline flow rate (MV$_2$), heavy cat naphtha (HCN) feed flow rate (MV$_3$). The output (controlled) variables (CV) are condenser stream temperature(CV$_1$), Condenser liquid level(CV$_2$), bottom heavy cat naphtha (HCN) flow rate(CV$_3$). The transfer function matrix of the FCC plant is represented as follow;

$$\begin{pmatrix} CV1 \\ CV2 \\ CV3 \end{pmatrix} = \begin{pmatrix} \frac{-2.36}{2.56s+1} & \frac{0.567}{15.66s+1} & \frac{-1.5182\,e-^{6.66}}{45.83s+1} \\ \frac{-0.15685}{13.033s+1} & \frac{-0.312}{8.33s+1} & \frac{-0.068}{58.75s+1} \\ \frac{-0.2043}{29.03s+1} & \frac{0.1147}{32.16s+1} & \frac{1.41}{0.01s+1} \end{pmatrix} \begin{pmatrix} MV1 \\ MV2 \\ MV3 \end{pmatrix} \qquad (1)$$

The process gain matrix was found to be plant transfer function, K, and the RGA element, ^(K).

$$K = \begin{pmatrix} -2.36 & 0.567 & -1.5182 \\ -0.15685 & -0.312 & -0.068 \\ -0.2043 & 0.1147 & 1.41 \end{pmatrix} \qquad (2)$$

Relative gain array (RGA), $\Lambda(K)$, was computed using the relation

$$\Lambda(K) = K\mathrm{x}\ (K^{-1})^T \qquad (3)$$

where x implies element-by- element multiplication (the Schur product)

The RGA was computed as

$$\Lambda(K) = \begin{pmatrix} 0.7985 & 0.1044 & 0.0972 \\ 0.1196 & 0.887 & -0.0082 \\ 0.0819 & 0.0070 & 0.9111 \end{pmatrix} \qquad (4)$$

From the RGA-element it was discovered that the diagonal elements are very close to 1, this means that the pairing is preferable along the diagonal elements and that there is no serious interaction between the controls loops of the system, that is, the system is decentralized.

IV.DESIGN PROCEDURE FOR PI CONTROLLERS

There are three sets/categories of proportional integral controllers to be considered in this work, these are, modulus optimum PI controller, internal model control (IMC)–based PI controller andMatlab PI modules.

A) *Modulus Optimum (MO) PI Controller*

Modulus optimum is a method of selecting and tuning controller, this method is based on finding a controller that the frequency response from set-point to plant output is as close to one as possible especially for low frequency.MO design method optimizes the closed-loop transfer functionbetween the reference and the output signal. According to [8] the design procedure for MO design method of controllers is as follow; $K_cK_p=0.5$, $T_p=T_i$, and $\omega_0=\frac{0.7}{T}$

whereK$_p$= process gain, K$_c$=proportional gain of the controller, Tp=process time constant, Ti=integral time constant, and ω_0 =bandwidth.

Since the process gain (K$_p$) and process time constant (T$_p$) are known from the plant (G$_p$(s)) transfer function, the proportional gain of the controller(K$_c$) and the integral time(T$_i$) can be calculated and the PI transfer function for each of the diagonal elements of the plant(G$_p$(s)) can be computed using

$$Gc(s) = K_c\left[1 + \frac{1}{T_i s}\right] \qquad (5)$$

B) *Internal Model Control (IMC)-Based PI Controller*

IMCis a general design procedure for obtaining controllers that meet requirements for stability, performance, and robustness of the control system. One of its advantages is that it becomes very clear how process characteristics such as time delays and RHP zeros affect the inherent controllability of the process and that IMCs are much easier to tune than controllers in a standard feedback control structure.The concept of IMC is based on the simulation of the process model G_m(s)within the control structure [9].

The first step in IMC design is to factor the transfer function of the process model into invertible and non-invertible functions

$$G_m(s) = G_m^-(s)G_m^+(s) \tag{6}$$

whereG_m^-(s) is the invertible and G_m^+(s) is the non-invertible. The invertible function consists of time delays and RHP zeros [9].

After that, the controller $Q_{(s)}$is defined as:

$$Q(s) = (G_m^-(s))^{-1}G_f(s) \tag{7}$$

where$G_f(s)$ is a filter transfer function which guarantees that the controller $Q_{(s)}$is realizable.

The first order filter transfer function was employed. This has the form

$$G_f(s)=\frac{1}{(\lambda s+1)} \tag{8}$$

where λ is the filter tuning (adjustable) parameter which determines the speed of response. Increasing λincreases the closed-loop time constant and slows the speed of response; decreasing λ does the opposite. The higher the value of λ, the higher the robustness of the control system [10].

Assuming a perfect model (i.e$G_p(s)$=G_m(s) and since there is no time delays G_m^+(s) =1, therefore,the invertible (G_m^-(s)) for first order system can be represented as;

$$G_m^-(s)=\frac{K_p}{T_p s+1} \tag{9}$$

$$\text{and}(G_m^-(s))^{-1}=\frac{T_p s+1}{K_p} \tag{10}$$

Final form for controller $Q_{(s)}$ is derived from Equation 7 and this is represented as;

$$Q(s) = \frac{T_p s+1}{K_p(\lambda s+1)} \tag{11}$$

The IMC design procedure can be used to design conventional feedback controllers. Figure 1 shows the relation between a conventional feedback controller $G_c(s)$and IMC controller $Q_{(s)}$ which may be expressed with the formula below.

$$G_c(s)=\frac{Q(s)}{1-G_m(s)Q(s)}=\frac{T_p}{k_p\lambda}\left(1+\frac{1}{T_p s}\right) \tag{12}$$

Comparing$G_c(s)$ with PI controller transfer function, it was discovered that

$k_c = \frac{T_p}{k_p\lambda}$ and $T_i = T_p$

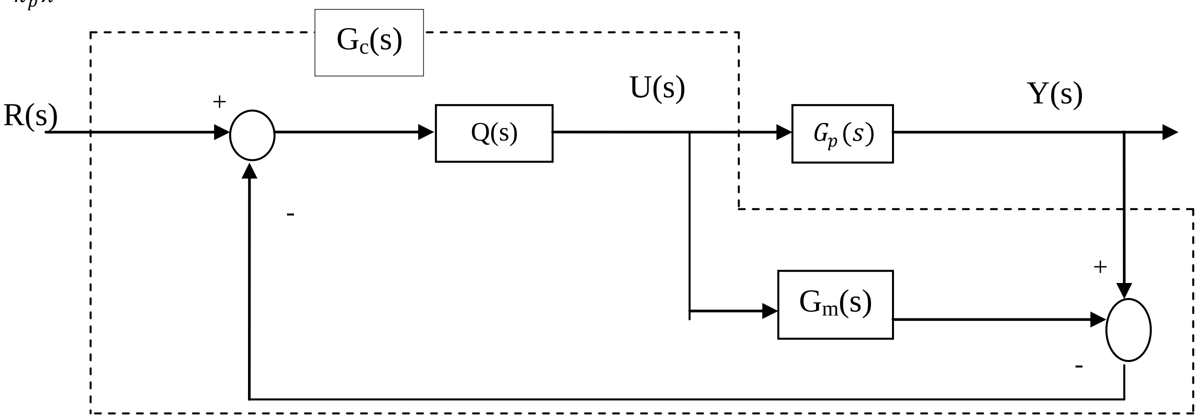

Fig. 2.Structure of internal model control.

Since the process gain (K_p) and process time constant (T_p) are known from the plant $G_p(s)$, transfer function, the proportional gain of the controller (K_c) and the integral time (T_i) can be calculated, and for the tuning parameter λ, since it can be manually adjusted by the operator [11]. Therefore for IMCPI-1, IMCPI-2 and IMCPI-3 shown in figure 2, the tuning parameter λ are 0.1, 0.6 and 0.01 respectively. The PI transfer function for each of the diagonal elements of the plant, $G_p(s)$, can be computed using

$$Gc(s) = K_c\left[1+\frac{1}{T_i s}\right] \qquad (13)$$

C) Matlab PI Modules controller

This is another set of PI controller, it generated from Matlab by computing the transfer function of a process first and after which the controller transfer function, $G_c(s)$, is generated by the Matlab command "pidtune ($G_p(s)$, 'pi')".Since K_p and T_p are known, the transfer functions were implemented and with the Matlab command, controller transfer functions are generated and alongside with it, Matlab gives value for K_c and K_i , Therefore, the controllers are computed using,

$$G_c(s) = \frac{k_c s + K_i}{s} \qquad (14)$$

V. SIMULATION OF THE CLOSED LOOP SYSTEM

The closed loop simulations were carried out using Simulink implemented Matlab environment as shown in Fig. 3 for closed loop involved IMC-based PI controllers.

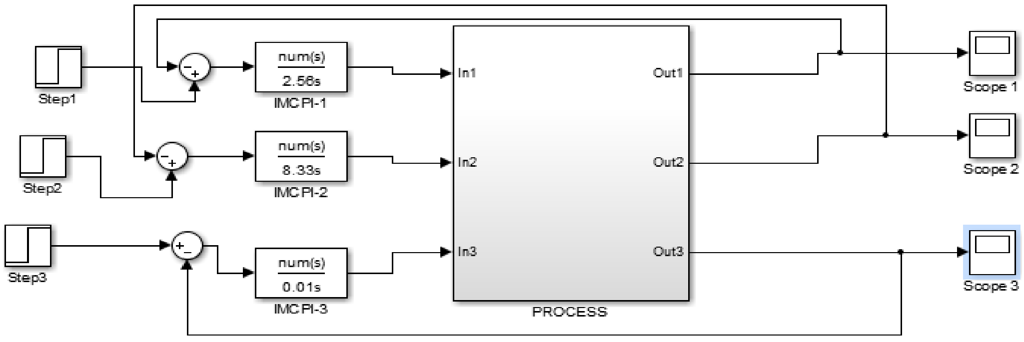

Fig. 3. Simulink representation of IMC-based PI controllers

VI. RESULTS AND DISCUSSION

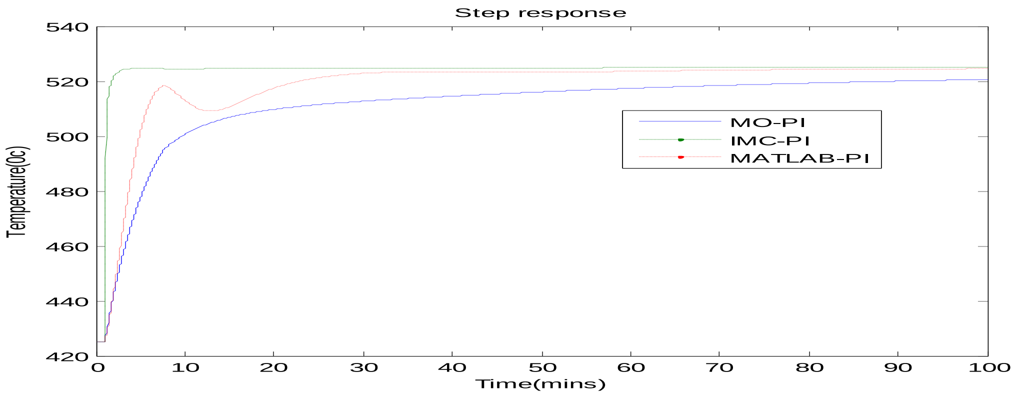

Fig.4. Condenser inlet stream temperature control

Fig. 4 shows theclosed loop response of PI Controllers on condenser Inlet stream temperature with set-point change 100°C. IMC-based PI controller is fastest in response in reaching the steady state followed by MATLAB PI controller, however MO PI cannot reach the steady state for the simulation period.

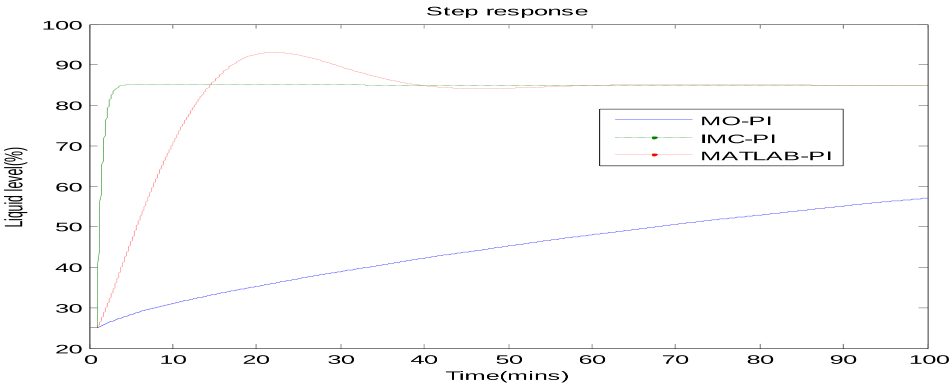

Fig. 5. Condenser liquid level control

. Fig. 5 shows the closed loop response for condenser liquid level control for set point change of 60%. Closed loop with IMC based-PI controller gives the fastest response in reaching the steady state. Closed loop with MATLAB PI comes next to IMC-based PI control system, however it is a bit oscillatory with overshoot. MO-PI is highly sluggish as its response is a little bit above 50% of the steady state value at the end of simulation period.

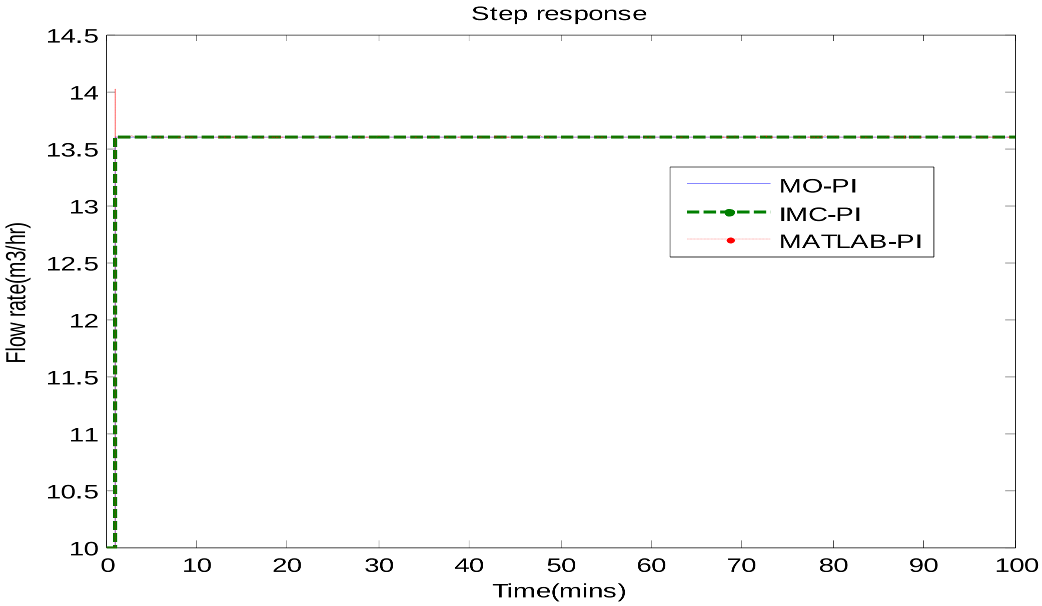

Fig.6. Heavy cat naphtha flow rate control

Fig. 6 shows closed loop response for heavy cat naphtha flow rate. The responses of the closed loop responses of the three controllers are almost the same in terms of speed of responses and overshoot.

Tables 1, 2 and 3 show response times for condenser inlet stream temperature,condenser liquid level and HCN flow rate, respectively. IMC-based PI controller gives the lowest rise time(4.14 mins) when compared with other PI controllers for condenser inlet stream temperature. Also, IMC-based PI controller gives the lowest rise time (11.98mins) when compared with other PI controllers for condenser liquid level. This implies that the time required for signal to change from low value to high value can easily be achieved with IMC-based PI controller. In the case of HCN flow rate control, all the three controllers give small values of rise time with no much significant difference. This implies that the time required for signal to change from low value to high value can easily be achieved with any of the three PI controllers.

Our results show that IMC-based PI controller gives best performance both in term of quality and speed of responses out of the three controllers considered. We compare the IMC-based PI controller performance with the performance of MPC controller presented in the works of [4] and [5]. IMC-based controller result compares well with their results. For the case of condenser inlet stream temperature IMC-based controller outperforms MPC controller from the work of [5]. MPC controller achieved set point tracking in 30mins however, IMC-based PI controller only needed about 15mins from the simulation start to bring the temperature to the set-point. The result from [4] disclosed that the condenser liquid level was stabilized in 30mins while [5] disclosed that it was stabilized in 25mins by using MPC controller. However, IMC-based PI controller stabilized the liquid level in about 22mins. The result of [5] showed that the MPC controller stabilized HCN flow rate in 10 minutes, however, IMC-based PI stabilized the flow in 2mins.

Table 1: RESPONSES TIME FOR INLET TEMPERATURE

Specifications	MO-PI	IMC-PI	MATLAB PI
Rise times (mins)	223.43	4.14	48.07
Settling time (mins)	725.36	14.59	280.66

Table 2: RESPONSE TIMES FOR CONDENSED LIQUID LEVEL

Specifications	MO-PI	IMC-PI	MATLAB PI
Rise time(mins)	802.21	11.98	100.63
Settling time(mins)	967.89	21.87	354.01

Table 3: RESPONSE TIMES FOR HCN FLOW RATE

Specifications	MO-PI	IMC-PI	MATLAB PI
Rise time(mins)	0.8	0.8	0.8
Settling time(mins)	1.99	1.98	1.98

VII. CONCLUSIONS

In this work, PI controllers obtained from three design techniques were considered for the control of condenser inlet stream temperature, condenser liquid level and heavy cat naphtha (HCN) flow rate of FCCU. MO-PI controller needed 725.36mins to bring the condenser inlet stream temperature to set-point, and Matlab PI needed 280.66mins to do the same. But IMC-based PI give fastest response since it just needed only 15mins to carry out the same task. MO-PI controller needed 967.89mins to bring the condenser liquid level to set-point, and Matlab-PI needed 354.02mins to do the same. But IMC-based PI gave fastest response since it just needed only 22mins to do the same task. MO-PI controller required 1.99mins to bring the flow rate to set-point, and Matlab-PI needed 1.98mins to do the same and IMC-based PI controller required just only about 2mins to carry out the same task. The three PI controllers gave almost the same response in term of speed of response. It can be concluded that IMC-based PI controller gave best performance out of the three controllers considered. IMC-based PI controller compared well with MPC controllers used for the same plant in the previous works of [4, 5].

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