ENHANCING INDUSTRIAL CHEMICAL PROCESS BASED ON DELAY CANCELLATION AND IMPROVED TRANSIENT RESPONSE PERFORMANCE

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Abstract: This paper presents enhancing industrial chemical process based on delay cancellation and improved transient response performance. It is desired to enhance the performance of an industrial chemical process. In order to achieve this, the dynamic characteristics of a chemical reactor that involves pH concentration in water treatment carried out using continuous stirred tank reactor (CSTR). A compensator was designed using the Control and Estimation Tools Manager (CETM). The results from the simulation conducted in MATLAB environment indicated that the compensator was able to cancel the time delay effect suffered by process and improved the transient response performance.

Keywords: CETM, Compensator, CSTR, Delay cancellation, Transient response

1. Introduction

As industrial chemical process and their control systems become more complex, achieving higher efficiency and improved control performance becomes more challenging. Also, the process become harder to control and maintain a steady state. For this reason, there is need to develop a system which will assist plant operators and enhance the general production process while ensuring effective control. Example of such industrial chemical process is the chemical reactor.

Chemical reactors are indispensable and influential factors in industrial chemical process. Chemical reactions in reactors can be in the form of continuous processing or batch processing. Continuous processing offers advantages over batch processing such as reduce labour, increased throughput, reduced production cost and so on. One area of industrial processes where chemical reactors have been largely deployed is the wastewater treatment.

Wastewater from industrial process comes out as pollutants. Treating some of these pollutants is costly and difficult. Also, the characteristics of wastewater may change significantly with respect to industrial activities. Nevertheless, the most essential possibility of wastewater treatment process is to regulate the effectiveness of such harmful wastewater. Since the pH is the most important characteristic of wastewater [11], pH-control to maintain desired level of wastewater concentration that is not harmful becomes worthwhile. This is known as neutralization.

Many different control algorithms and techniques have been developed and applied to wastewater treatment in chemical reactor. Also, application of computational control technique in chemical processes has been examined in [8]. This paper presents a Proportional-Integral-Derivative (PID) Tuned Compensator (PID-TC) for delay prone pH process in chemical reactor.

2. Literature Review

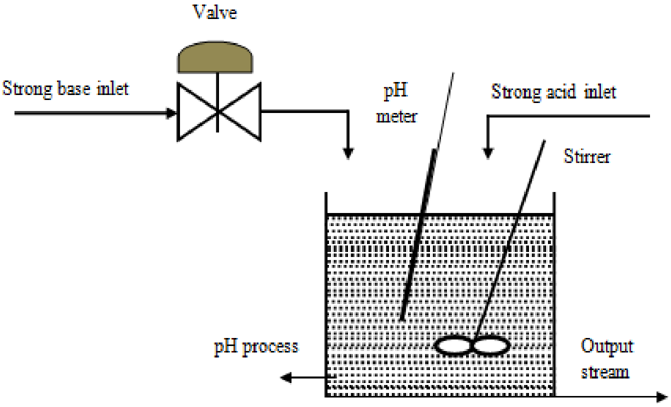
In this section the review of related works are presented based on the control technique or method used to achieved desired performance result. Conventional and particle Swam optimization based PID Control technique. According to [5] presented turning of proportional integral and derivative (PID) controllers for unstable continuous stirred tank reactors (CSTR). It proposed two PIDs controller design techniques for unstable Second Order plus Time Delay System with a Zero (SOPTDZ) based on internal model control (IMC) and Stability Analysis (SA) principle. The controllers were used to control unstable CSTRs whose reaction of order irreversible reaction performance comparison was carried out with the proposed method and the synthesis method. The simulation, results obtained showed that the controller designed by proposed showed more robust performance than the one designed using synthesis method on nonlinear unstable CSTRs. [9] presented Proportional Integral Derivative (PID) of a continuous stirred tank reactor (CSTR). It used non isothermal CSTR and different control modes. Simulation parameters were chosen at equilibrium state and dynamic point. It maintained that simulation results obtained indicated that stability of the non-isothermal CSTR at different turning point and disturbances. In [2] presented modelling and control of CSTR with PID Controller. A model of dynamics control for CSTR in methanol synthesis in a three-phase system was developed. Simulation of the reactor was performed for steady and transient states. Efficiency ratio for achieving maximum performance of the output for a unit reactor volume was calculated. Simulation in closed loop was conducted which allow the control process to receive data for optimum production capacity, with the elimination of local hot spot or temperature runaway. [6] studied design and analysis of PID controller for CSTR process. The objective of the study was to control temperature and load disturbance rejection of CSTR. Simulation result showed that the PID controller provided a less percent overshoot with efficient load disturbance rejection with a minimum setting time. [10] studied design of fractional order PID controller for a CSTR process. It proposed the application of fractional order PID (FOPID) controller in CSTR process controls. It employed soft computing techniques which comprises genetic algorithm (GA) and particle swarm optimization (PSO) to model the CSTR and for obtaining model parameters. It maintained that the developed model was able to compensate for the nonlinearity present in the CSTR. Simulation results were presented in terms PID and FOPID. The performance was analyzed with respect to Integral Square Error (ISE). It was observed that FOPID provided better performance than PID. [1] presented design and implementation of a PID controller for a CSTR system using particle swarm algorithms. It applied proportional integral (PI) and PID controller tuned with PSO, Adaptive Weighted PSO (AWPSO) algorithms to CSTR process to take care of the temperature and concentration control. Three error criteria were used to achieve the optimization process. These include integral of square error (ISE), the Integral of Absolute Error (IAE) and integral of Time Absolute Error (ITAE). In order to test the robustness of temperature and concentration performance of the process, some of the parameters of CSTR were altered. It maintained that better performance algorithm was observed. [4] carried out tuning of PID Control using optimization techniques for a multi-input-multi-output (MIMO) process. It considered two processes which consists of Quadruple Tank process and CSTR process. Dynamic model of the two processes was performed by linearization of the system due to MIMO process. In order to tune the controller parameters, two optimization techniques consisting of PSO, and GA were use. Performance comparison was for the two different optimization techniques used for tuning of PID controller gain parameters for the two process considered. It stated that the simulation results showed that PSO based turned provided better response than that of GA whereas, for the Quadruple Tank process, both optimization techniques provided almost the same response with slight difference in their peak overshot values.

3. System Design

This section presents the mathematical description of the chemical reactor process in a continuous stirring tank reactor (CSTR) and the subsequent design of a compensator that will be implemented as part of the networked system for ensuring that a predetermined pH concentration is maintained.

3.1 Mathematical Description of pH Process

A pH neutralization process for wastewater treatment is shown in Fig. 1. In this process, strong acid (HCl) and strong base (NaOH) of 1 molarity [11] are used.



Fig, 1 Model of a pH process [7]

Assuming no chemical reaction at given level, the equation for material balance can be expressed by:

[Rate of accumulation within vessel volume] = [Inflow rate to the pH process] -[Outflow rate from the pH process] (1)

$$V\frac{dX}{dt} = U - FX \qquad (2)$$

where V is the volume of the mixture in the pH process, X is the state variable of the nonlinear pH process, U is the pH process input flow rate, F is the pH output flow rate. The back titration curve for process flow is given by:

$$T_{(pH)} = X \qquad (3)$$

In a chemical reaction, the components of the system for the back titration curve (TC) produce the nonlinearity of the process flow and can be represented by:

$$C_{TC} = \frac{A[pH] + \sum_{i=1}^{n} a_i[pH]C_i}{\sum_{i=1}^{n} a_i[pH]X_i} \qquad (4)$$

where$a_i[pH]$ is the acid-base weighting factor (-1 for Strong acid and + 1 for strong base), n is the number of ions present in the reactor, C_i ion concentration of the i^th^ kind of process flow, X_i is the concentration of the i^th^ kind of neutralization liquid.

The value of pH is defined as the negative logarithmic value of the concentration of Hydrogen $[H^+]$ ions.

$$pH = -\log\left(H^+\right) \qquad (5)$$

For the neutralization process

$$A[pH] = 10[-pH_{sv}] - 10[pH_{sv} - 14] \qquad (6)$$

where pH_{sv} is the setpoint (or desired) value

In the neutralization process, the difference value between the actually measured pH and the set point value in line with the nonlinear conversion is given by:

$$Y = T(pH_{sv}) - T(pH) \qquad (7)$$

The First order differential equation is given by Eq.(2) and since X is equal to $T(pH)$, substituting into Equation (2) gives:

$$V\frac{d[pH]}{dt} = U - F[pH] \qquad (8)$$

Taking the Laplace transform of Eq. (8) and rearranging gives:

$$VspH(s) + FpH(s) = U(s) \qquad (9)$$

Further rearrangement of Eq. (8) gives:

$$\frac{pH(s)}{U(s)} = \frac{\frac{1}{F}}{\frac{V}{F}s + 1} \qquad (10)$$

where V/F is equal to the process time constant τ and 1/F is the process gain, K.

The pH process is a first order system with time delay due to pipe line and detection process for the measuring instrument (sensor). Hence it takes the general transfer function model of first order plus time delay (FOPTD) given by:

$$G(s) = \frac{Ke^{-T_D s}}{\tau s + 1} \qquad (11)$$

where $e^{-T_D s}$ is the time delay.

Substituting parameters obtained from real time experiments conducted in Dinesh and Deepika (2014) which was applied in Ram et al (2016), with K = 0.276, $\tau = 3.2$, and T_D = 5.005, Equation (11) becomes:

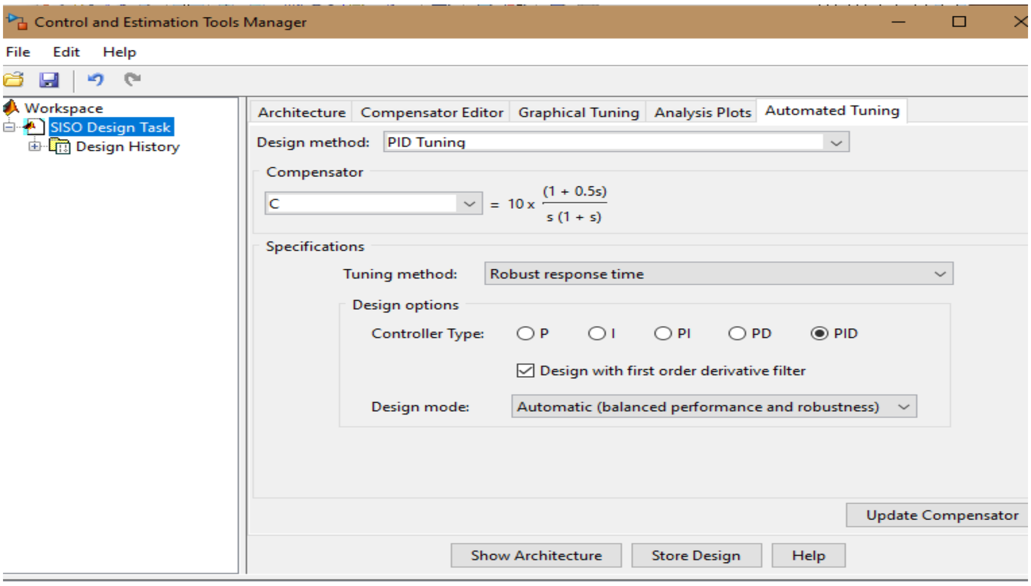
$$G(s) = \frac{0.276e^{-5.005s}}{3.2s + 1} \qquad (12)$$

Therefore, Eq. (12) is the established transfer function model for a pH neutralization process for wastewater treatment considered in this paper. It can be observed that the process is prone to delay.

3.2 Design of Compensator

Compensators are used as part of industrial process control loop or network whenever the response or output of the process is unstable and required to be stabilized to meet specific performance [4] or it is desired to eliminate certain limitation to proper or efficient process performance such as overcome the effect of time delay. A PID-TC was designed using the Control and Estimation Tools Manager (CETM) of the MATLAB to eliminate the effect process delay in a chemical reactor.

The MATLAB CETM tool can be used to design single input single out (SISO) closed loop network to regulate the transient characteristics and output (or response) of an industrial process. A PID-TC compensator has been implemented in [3] and [4], where it has shown to provide robust performance and ability to handle disturbance effect. Thus, similar approach is used in this paper to design a compensator for pH neutralization process in a CSTR. The tuning method employed is robust response time [3],[4]. However, the design mode employed was automatic (balanced and performance and robustness). Figure 2 shows the CETM too graphical user interface used to design the compensator. The designed compensator C



Design method: PID Tuning

Compensator

C = 10 x $\frac{(1 + 0.5s)}{s\,(1 + s)}$

Specifications

Tuning method: Robust response time

Design options

Controller Type: ○ P ○ I ○ PI ○ PD ● PID

☑ Design with first order derivative filter

Design mode: Automatic (balanced performance and robustness)

Fig. 2 Graphical user interface tuning of the MATLAB

The designed compensator C, with gain K = 10, real pole and real zero locations of -1 and -2 is given by:

$$C = 10 \times \frac{(1 + 0.5s)}{s(1 + s)} \qquad (13)$$

(13)

The designed system, which is proposed to compensate the closed loop network for regulating a chemical reactor process involving pH neutralization in water treatment, is shown in Fig. 3.

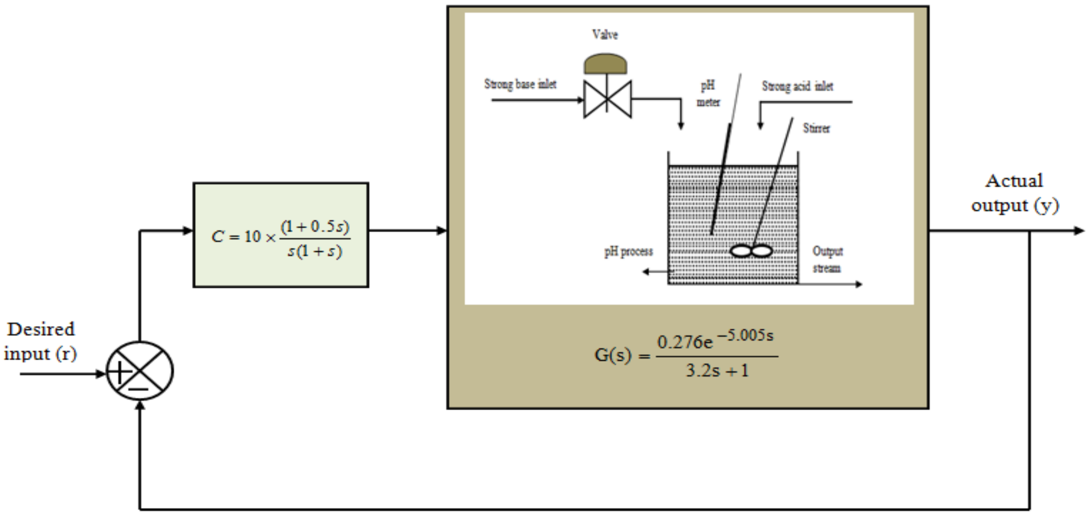


Fig. 3 System configuration

The closed loop network shown in Fig. 3 described the configuration of compensated chemical reactor process examined in this paper. As shown, the actual output, which is the response (or current pH concentration of the water treatment process) is fed back to the summing point where it is compared with the actual value or pH level expected (desired input). The difference or deviation between the desired level of pH concentration and the actual level of pH concentration is fed into compensator, which in turns manipulate the information via mathematical computation in order to send a correctional signal or command that ensures that chemical process is adjusted to meet the desired level at the input. This process continues until little or no deviation exists between the desired input and actual output such that the system settles.

4. Results

This section presents the computer simulation analysis carried to evaluate the response performance of the water treatment reactor using MATLAB. The simulations were conducted for three scenarios which include: the open loop network of the water treatment process, the closed loop network of the water treatment process without compensator, and the closed loop network of the water treatment process with compensator. In the open loop network, the system was evaluated assuming the actual output (or system response) and the desired input (that is the expected level of concentration) were not relatively compared. That is assuming no fraction of the actual output (the current pH concentrate level) is compared against the desired level. In the closed loop network without compensator, the system was analysed assuming a fraction of the actual output is compared relatively to the desired level but with no technique to ensure that the result of the comparison was used to ensure the chemical process is forced or made to meet a specified level of concentration. For the closed loop network with compensator, the system was evaluated to ensure that the result of the comparison is utilized by a technique that offers command to make sure the process response meets the desired level of concentration while eliminating the delay in the process. The simulation curves for the three scenarios are shown in Figures 4, 5, and 6. Table 1 is the numerical analysis of the system performance in terms of the transient characteristics of the response in time domain for each simulation curve obtained from the three scenarios.

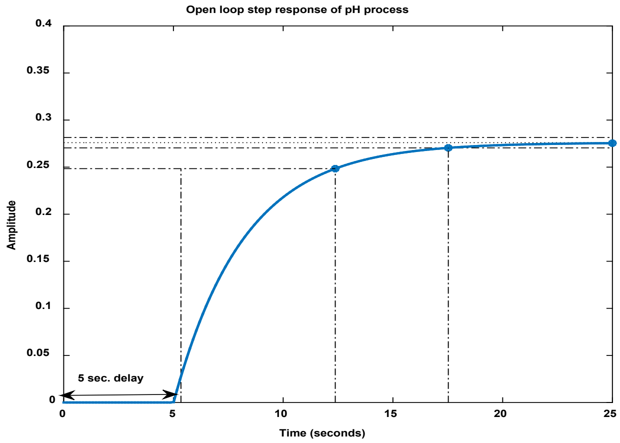


Figure 4 Step response of pH process in open loop

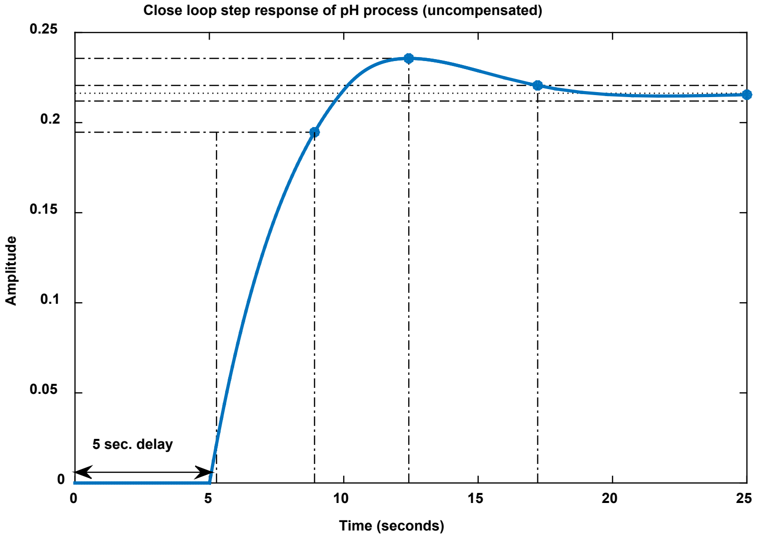


Figure 5 Step response of pH process in uncompensated closed loop

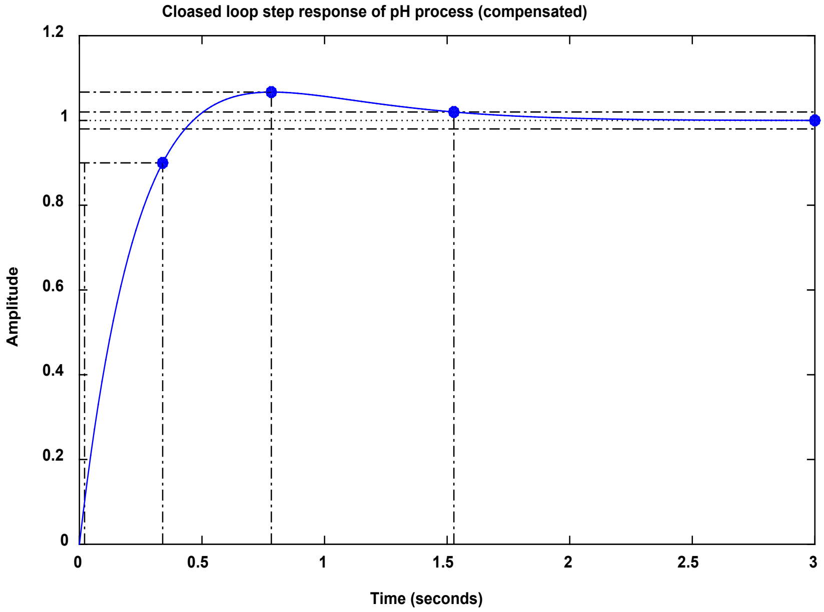


Figure 6 Step response of pH process in compensated closed loop

Table 1 Numerical analysis of transient response Characteristics

Case	Rise time (s)	Peak time (s)	Overshoot (%)	settling time (s)	Final value
Open loop network	7.03	25	0	17.5	0.275
Closed loop network without compensator	3.65	12.4	8.94	17.2	0.217
Closed loop network with compensator	0.319	0.783	6.7	1.53	1

Figure 4 is the simulation result of the evaluation of the step response performance of the system in open loop network arrangement. It can be seen that the still suffers a delay in response to input forcing signal for 5 seconds, and this largely affects the rise time and settling time as the values of these transient parameters can be seen to be very high 7.03 seconds and 17.5 seconds respectively. Thus, if the system is allowed to run in this mode, it will take 7.03 seconds before it will come up for chemical reaction process to start and even when it begins to run, it will take such a long time (17.5 seconds) for it to settle. Though, the system show promising performance in terms of overshoot (0%), this benefit is crushed due to the associated delay and the fact that the output (0.275 or 27.5%) fall short (by 72.5%) of the desire level of concentration, which is assumed as unit step input (that is 1 or 100%). In Figure 5, the uncompensated closed loop network is evaluated to observe the behaviour of transient parameters. As shown in Table 1, the system in this condition still suffers the effect of 5 seconds time delay, but outperformed the open loop system in terms of rise time, peak time, and settling time which are 3.65 seconds, 12.4 seconds and 17.2 seconds respectively. Nevertheless, the uncompensated closed loop system falls short in terms of overshoot and final value compared to the open loop system. The level of the actual output concentration (which is 0.217 or 21.7%) is 78.3% less than the desired level of concentration. This is unsatisfactory. With the compensator added to the closed loop network, simulation analysis revealed that the time delay suffered by the system in the previous modes was completely eliminated as shown in Figure 6. In addition, the system offers rise time of 0.319 second, peak time of 0.783 second, overshoot 6.7%, settling time of 1.53 seconds, and final value of 1. Thus, with the proposed compensator, the chemical process can achieve expected pH concentration at a very fast time (in terms of rise time) and with very much reduced overshoot including rapidly reaching and settling at the desired level of concentration. Thus 100% concentration level can be achieved using the developed compensator.

5. Conclusion

Simulations have been carried out in MATLAB environment to evaluate the performance of chemical reactor process involving maintaining a given pH concentration in water treatment facility. It was observed that the process suffered from delay which has duration of 5 seconds. The simulation analysis of the system using the proposed compensator revealed that the transient response of the system was improved and the delay was eliminated.

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