Adaptive PID control Parameters Optimization using Trust-Region-Reflective Algorithm for pH Neutralization Process

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Abstract: The pH control process has been used in industry in a wide number of applications. Its dynamics are highly nonlinear. The pH control process is subjected to uncertainties of mathematical model describing the kinetics changes of chemical process and the external disturbances. The pH control process using the PID control technique will be investigated in this paper. The setting and adjustment of PID controller parameters define the behavior of PID control. Due to external disturbances and changes of the pH of an environment with time, the adjustment of the PID control parameters should respond to these changes. The simulation of the pH control process and its control are studied using pH kinetics model adopted by [1] and PID control model. PID control parameters are estimated and tuned using a trust-region-reflective optimization technique. The estimated and tuned PID parameters are fed to a pH process control. Simulation results have demonstrated, that the use of trust-region-reflective tuned PID controller, are in a good dynamic behavior of the pH process, a perfect set point tracking with little overshot, gives better performance and high robustness.

Keywords: Control, PID, Tuning PID parameters, Optimization, titration, pH process.

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1. Introduction:

Proportional-Integral-Derivative (PID) controller is one of the earliest control technique that is still used widely in industrial because of its easy implementation, robust performance and being simple of physical principle of parameters. For achieving appropriate closed loop performance, three parameters of the PID controller must be tuned.

Tuning methods of PID parameters using optimization techniques are classified as traditional and intelligent methods. Conventional methods, such as Zigeler and simplex methods are not efficient to determine optimal PID parameters and usually does not achieve a good tuning; these techniques produce surge and high overshoot.

Recently, intelligent approaches such as genetic algorithm and particle swarm optimization have been proposed for PID parameters tuning. Genetic Algorithm (GA) has received much interest and has been applied successfully to solve the problem of optimal PID controller parameters. However, genetic algorithms may be not efficient for solving some complex optimization problems. This degradation in efficiency is apparent especially in applications where the parameters being tuned are highly correlated [1-5].

Iterative methods for optimization can be classified into two categories: line search method and trust region method. Trust region methods are robust, and can be applied to ill-conditioned problems. Trust region algorithm is employed for estimation of the PID parameters. The trust region approach is strongly associated with approximation. The technique uses a current guess of the solution of the optimization problem; an approximate model can be constructed near the current point. A solution of the approximate model can be taken as the next iterate point.

In fact, most line search algorithms also solve approximate models to obtain search directions. However, in a trust region algorithm, the approximate model is only trusted in a region near the current iterate. This seems reasonable, because for general nonlinear functions local approximate models (such as linear approximation and quadratic approximation) can only fit the original function locally. The region that the approximate model is trusted is called the trust region.

A trust region is normally a neighborhood centered at the current iterate. The trust region is adjusted from iteration to iteration. If the computations indicate the approximate model fit the original problem well, the trust region can be enlarged. Otherwise, when the approximate model does not converge, the trust region should be reduced.

The key contents of a trust region algorithm are how to compute the trust region trial step and how to decide whether a trial step should be accepted. A trust region is available at the beginning. Then an approximate model is constructed, and it is solved within the trust region, giving a solution which is called the trial step. A merit function is chosen, which is used for updating the next trust region and for choosing the new iterate point.

2. Design of PID Controller

One of the most common controlling methods in the market is the PID controller. Application of the PID controller involves choosing the K_P, K_I and K_D provides satisfactory closed-loop performance. These parameters must be selected so that the characteristics: response speed, settling time and proper overshot, all of which guarantee the system stability, would be satisfied.

As shown in **Figure 1,** PID controllers have three basic terms: proportional action, in which the actuation signal is proportional to the error signal, integral action, where the actuation signal is proportional to the time integral of the error signal and derivative action, where the actuation signal is proportional to time derivative of error signal.

To design a particular control loop, the values of the three parameters K_P, K_I and K_d have to be adjusted so that the control input provides acceptable performance from the plant. For example, classical control methods in the frequency domain or automatic methods like Ziegler-Nichols, known as PID tuning methodology

Although these methods provide a first approximation, the response produced usually needs further manual retuning by the designer before implementation. The main method for tuning the

PID parameters is based on trial and error, which is time consuming. There are different processes for different composition of proportional, integral and differential. The duty of control engineering is to adjust the coefficients of gain to attain the error reduction and dynamic responses simultaneously. The transfer function of PID controller is defined as follows :

$$G_{PID}(S) = K_P + \frac{K_I}{S} + K_D S \quad (1)$$

PID control is a linear control methodology with a very simple control structure. In this paper the controller operates directly on the error signal of pH value, which is the difference between the desired pH value and the actual pH value.

3. pH process model

Consider a pH neutralization process as shown in Fig. 2. The flow rates of acid, buffer, base and effluent streams are denoted by q_1, q_2, q_3, and q_4, respectively. Output of the process is the pH value of the effluent stream, and the flow rate of base stream, q_3 is the control input. A dynamic model is derived using the conservation laws and reactions equilibrium. The modeling assumptions include perfect mixing, constant volume of the neutralization tank (V), and complete solubility of the ions involved. The chemical reactions in the system are as follows [6-9]:

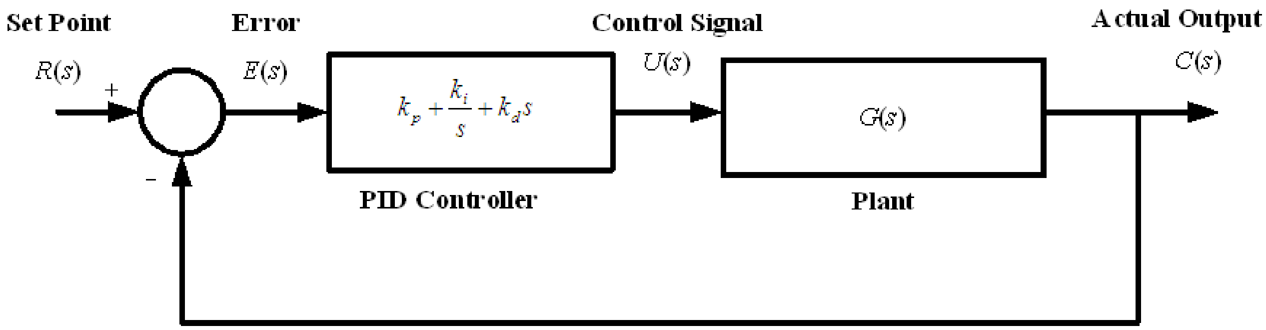


Fig. 1 Closed loop PID controlled system

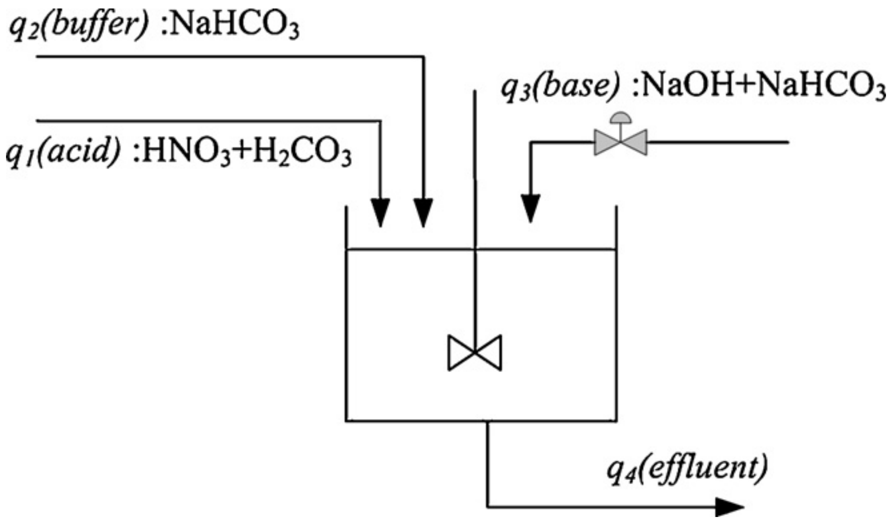


Fig. 2 pH neutralization process

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$
$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$
$$HNO_3 \rightarrow H^+ + NO_3^-$$
$$NaHCO_3 \rightarrow Na^+ + HCO_3^-$$
$$NaOH \rightarrow Na^+ + OH^-$$

The equilibrium constants for these reactions are:

$$Ka_1 = \frac{[HCO_3^-][H^+]}{[H_2CO_3]}$$
$$Ka_2 = \frac{[CO_3^{2-}][H^+]}{[HCO_3^-]}$$
$$Kw = [H^+] + [OH^-] + [CO_3^{2-}]$$

The chemical equilibrium equations are modeled using the reaction invariant concept [2]. For this system, concentrations of reaction invariants are defined as:

$$x_1 = [NO_3^-]$$
$$x_2 = [Na^+]$$
$$x_3 = [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}]$$

Denoting, $y = pH$ the ions neutrality balance in the tank results the following static equation:

$$h(x, y) = -x_1 + x_2 + x_3 c_{x3} + 10^{-y} - 10^{y-PK_w} = 0 \qquad (3)$$

$$c_{x3} = \frac{2 + 10^{PK_2 - y}}{1 + 10^{PK_2 - y} + 10^{PK_1 + PK_2 - 2y}}$$
$$PK_1 = -\log_{10} Ka_1$$
$$PK_2 = -\log_{10} Ka_2$$

The dynamic equations are given by:

$$\frac{d\dot{x}_1}{dt} = \frac{q_1}{V}(w_{11} - x_1) + \frac{q_2}{V}(w_{21} - x_1) + \frac{q_3}{V}(\propto_1 - x_1) \qquad (3)$$

$$\frac{d\dot{x}_2}{dt} = \frac{q_1}{V}(w_{12} - x_2) + \frac{q_2}{V}(w_{22} - x_2) + \frac{q_3}{V}(\propto_2 - x_2) \qquad (4)$$

$$\frac{d\dot{x}_3}{dt} = \frac{q_1}{V}(w_{13} - x_3) + \frac{q_2}{V}(w_{23} - x_3) + \frac{q_3}{V}(\propto_3 - x_3) \qquad (5)$$

Where:

V: Volume of the mixing tank, ml

Kw: Dissociation constant of water, 10^{-14}

Ka_i: ith dissociation constant of acid

w_i: Concentration of the ith species in the process stream, mol/l (mole/liter)

w_{1i}: Concentration of the ith species in the acid stream, mol/l

w_{2i}: Concentration of the ith species in the buffer stream, mol/l

q_i: Flow rate of acid, buffer and base stream in simulation, ml/s (mil-liter/second)

$\propto_i$: Concentration of the ith species in the titrating stream, mol/l

x_i: Reaction invariant of ith species, mol/l

y: Process variable, pH

u: Flow rate of the titrating stream, or ml/s

4. Simulation of the pH neutralization process with PID controller

The pH Neutralization process is achieved through three liquid streams: an acid flow (q_1), a bluffer flow (q_2), and a base flow (q_3). It is desired to control the pH of the effluent stream at a specified set point in the presence of disturbances in buffer flow rate and composition. The parameters of the model and operating conditions are summarized in Table 1.

To tune the PID parameters the following minimization problem has been set. Estimate K vector parameters [Kp, Ki, Kd] such that error, fitness function $|pH_c - pH_t|$, is minimum. Where pHc are the value calculated through the described model which relates the PH to flow rates q_1, q_2 and q_3 and concentration of the different species. Where pH_t is the target pH.

When the optimum values of the K vector of the controller is reached, adjust the q_3 to achieve the desired pH. The trust region reflective algorithm is employed to solve the optimization problem. The simulation method combines SIMULINK module and M-FILE where the main program is realized in SIMULINK and the optimized PID controller vector is predicted using M-File.

5. Results and Discussion

To check the performances of the controller for set-point tracking and load rejection, three subsequent changes are applied to the set-point along with disturbances in feed concentration and buffer flow rate. Figure 3a and 3b show the response of the pH neutralization process obtained by using the trust region reflective optimization.

Table 1: Nominal process parameters in simulation

Parameter	Values	Parameter	Values
V	2900 ml	Ka1	4.47×10^-7
q1	16.6 ml/s	Ka1	5.62×10^-11

q2	0.55 ml/s	Ka1	1.00×10^-14
q3	15.8 ml/s	α1, α2, α3	[0 0.00305 5×10^-5]
w11, w12, w13	(0.003, 5, 0.00305)10^-5	W21, w22, w23	[0, 0.003, 0.03]

algorithm. The results of pH system are shown in Figures 3, 4, 5, and 6 respectively.

The results show that the process output is tracked well in spite of variation in feed composition and buffer flow rate. Figures 3a and 3b show the response of the controller to a sudden step up and step down of the required pH setting. In step down case, figure 3b, the controller response shows no steady state error after 100 sec form the step down initiation. The response of the controller shows no overshoot and the rise times is 40sec and the steady state error is 2% in step up case as shown in figure 3a.

Figure 4a and 4b the response of the controller to a different buffer flow rates q2=1.1 ml/s and 0.55 ml/s respectively. The Controller shows no steady error in both cases. For q2=1.1ml/s the rise time is 150sec and 200sec for q2=0.55ml/s. The controller shows 0.5 overshoot in the two cases. In case of changing the feed composition, w_{11}, The controller shows rising time decrease form 200 sec to 150 sec when the w_{11} changes from 0.0021 to 0.00391. There is no change in the overshoot or the steady state error in both cases. Figure 6a and 6b illustrate the performance of the controller with the change of the w_{12} when w_{11}=0.0039 and w_{11}=0.0021. For both cases the steady state error is zero. The rise time increases with the decrease of w_{12} from 200 sec to 500 sec for cases a and b respectively. Figure 6a shows an overshoot of 0.3 pH value. For case b there is no overshoot.

6. Conclusion

In this paper, the PID controller has been designed and optimized by trust region reflective optimization algorithm. The proposed method is tested on pH neutralization process in order to demonstrate its effectiveness and robustness for solution of the desired optimization problem.

From the results, it is demonstrated that the optimized PID improve the performances of PH neutralization process in order to achieve minimum settling time with no overshoot and nearly zero steady state error.

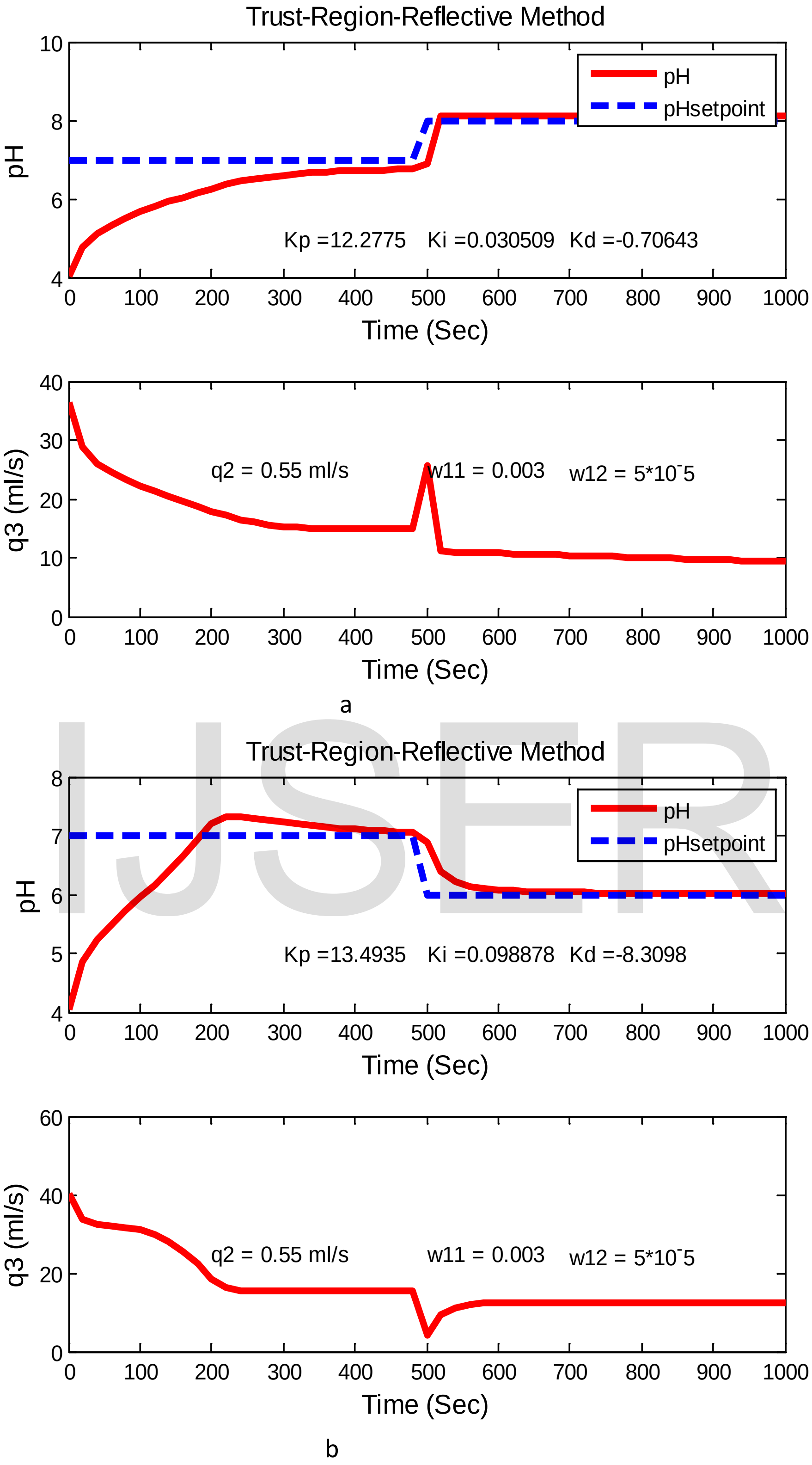
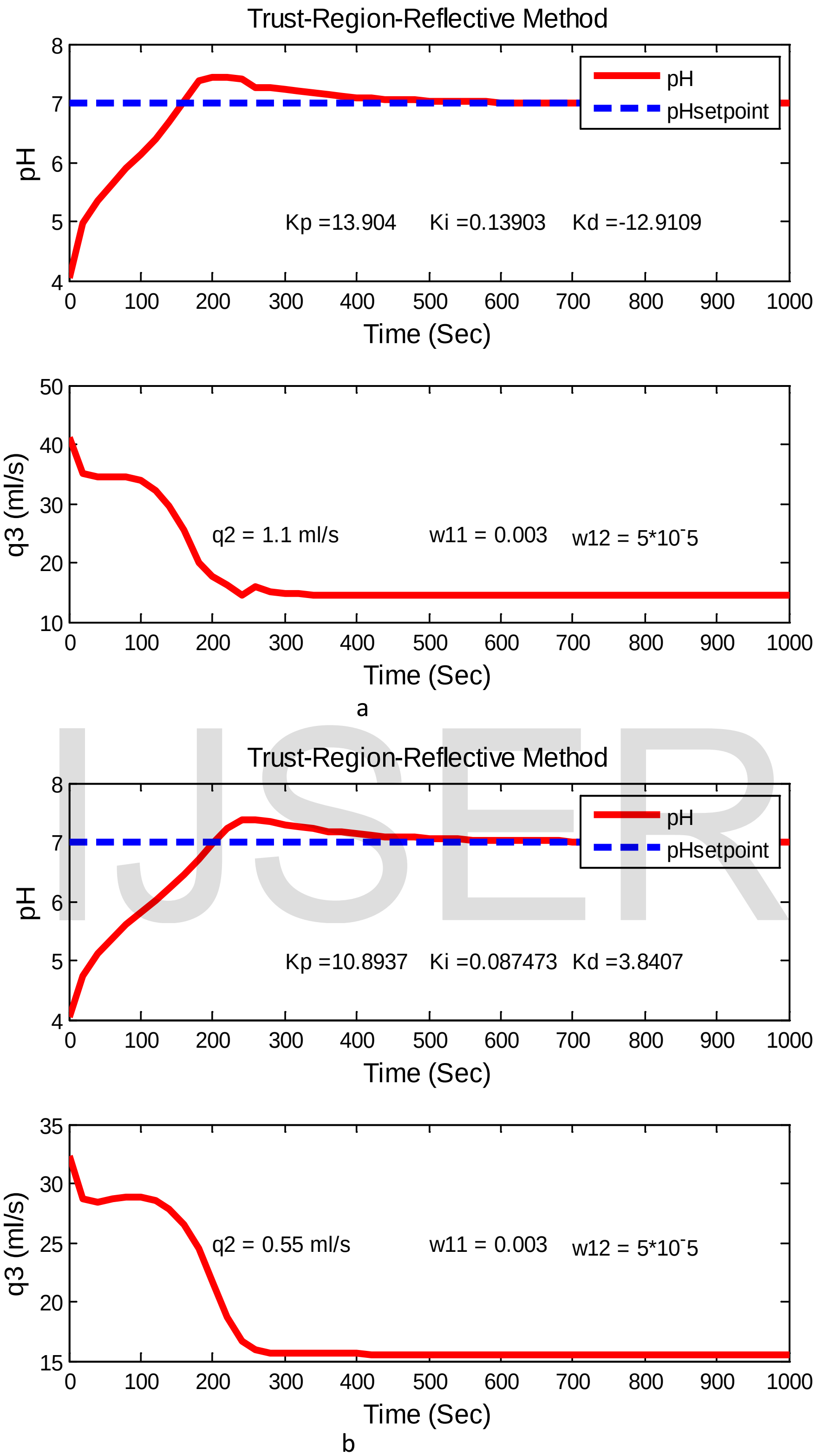


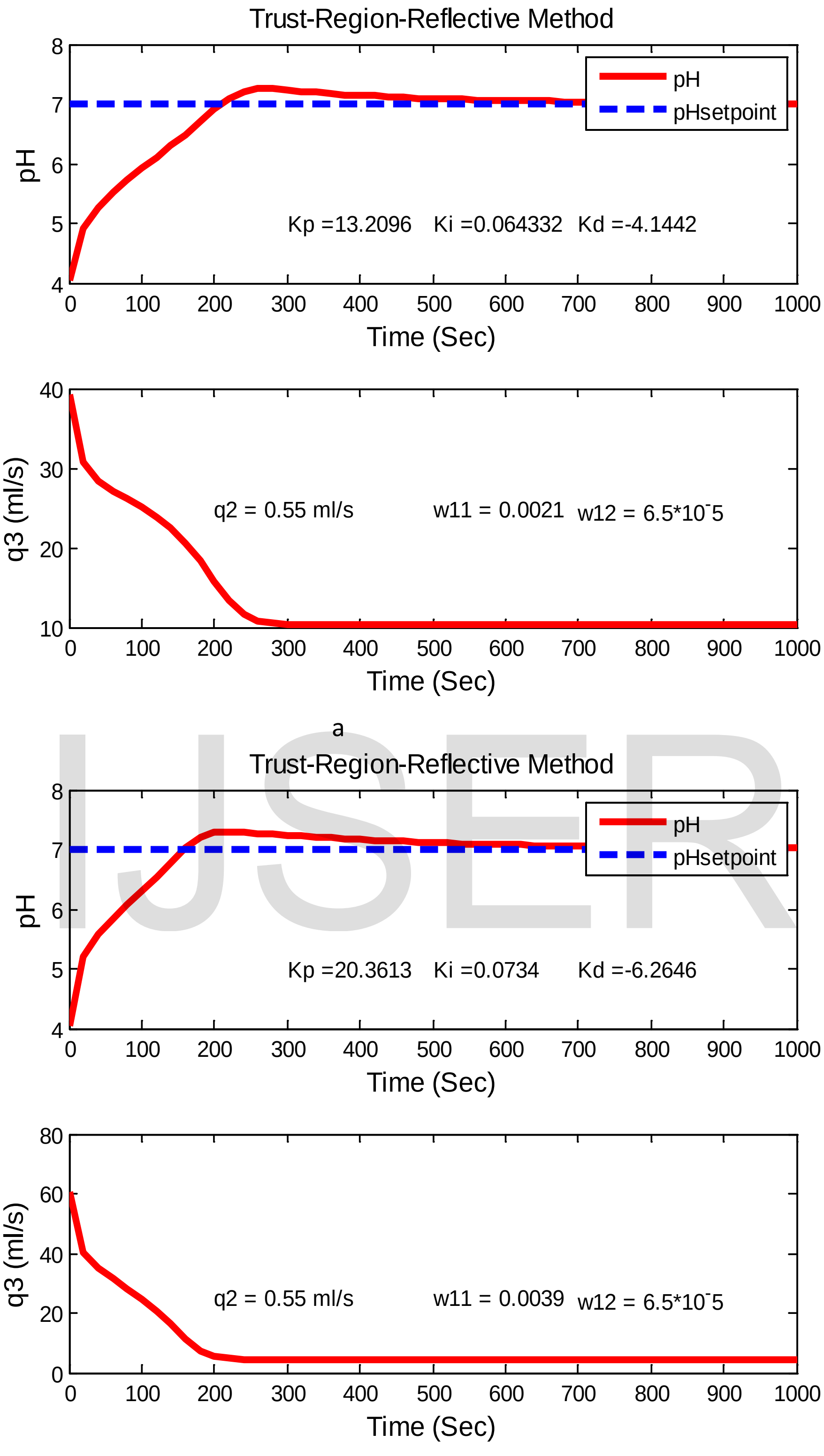
Fig. 3 The response of the pH neutralization process with change in set point



a

b

Fig. 4 The response of the pH neutralization process with change in buffer flow rate (q_2)



a

b

Fig. 5 The response of the pH neutralization process with change in feed composition

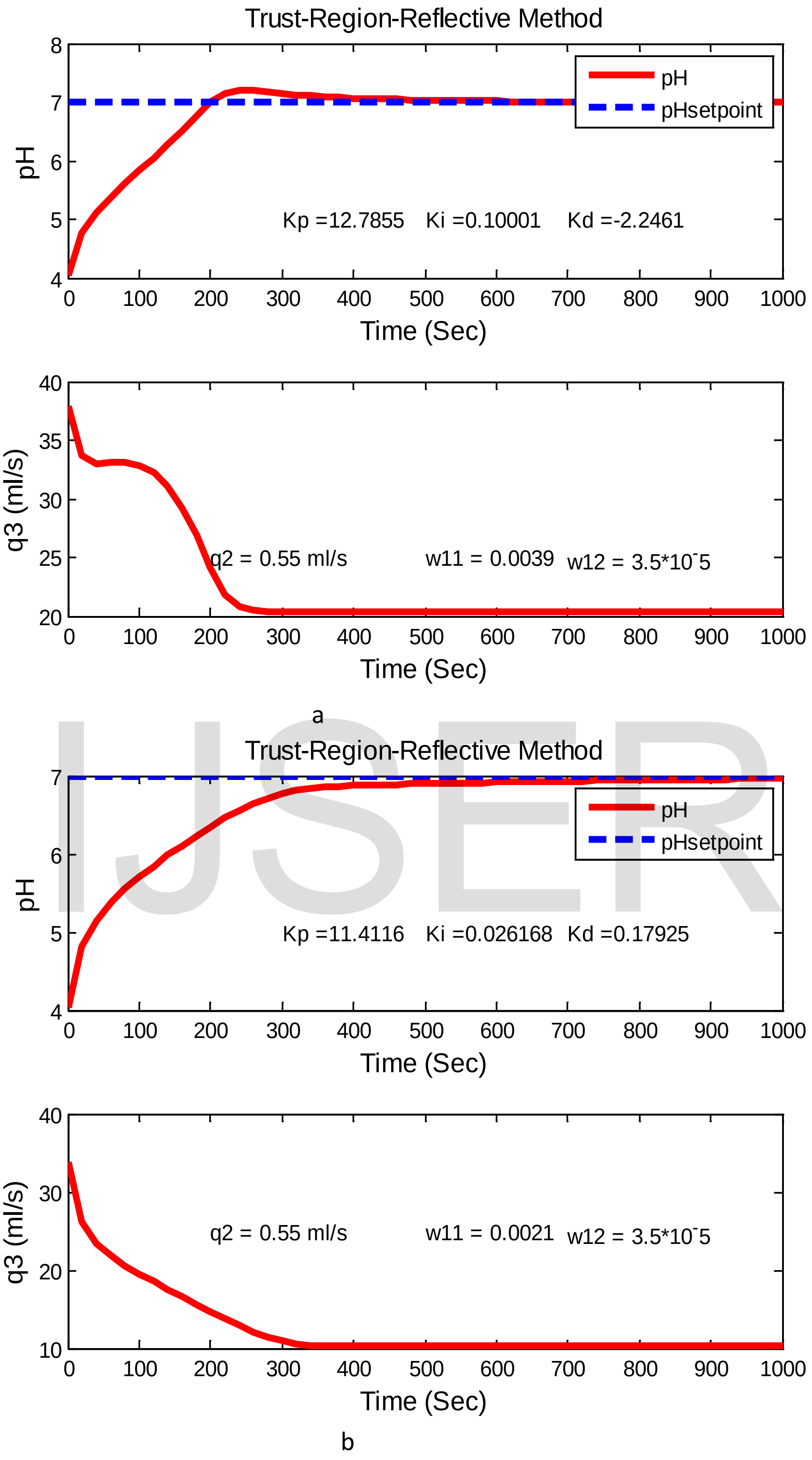


Fig. 6 The response of the pH neutralization process with change in feed composition

7. References

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