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Parameter estimation and scheduling approach to the pH control problem

IMAD M. ALATIQI AND A. MAKBOOL

Department of Chemical Engineering, Kuwait University, PO Box 5969, Safat 13060, Kuwait

ABSTRACT

Feed back control of the pH processes is quite difficult and highly nonlinear. In this paper parameter scheduling control-strategy has been proposed, which takes care of the non-linearity, by identifying the pH process as a variable structure problem. Since the system parameters like dead time, process gain and time constants vary with acid/alkali ratio, one could parameterize the control parameters to vary accordingly.

INTRODUCTION

pH processes are commonly encountered in the chemical and allied industries. It poses an important problem in many processes, particularly in effluent waste water treatment. Therefore, the development and solution of pH control systems forms a vital part of chemical engineering dynamic modeling.

The pH control problem is highly nonlinear and thus a difficult one. Feedback control of such systems is quite difficult, because the ionic concentration, which determines acidity/alkalinity, cannot be directly measured. Usually it is practicable to measure pH (Kneen & Rogers 1972), which takes the form of a potential difference in an electrolytic cell, and is related to the concentration $[H^+]$ of hydrogen ions (in kg mol m^{-3}) by

$$pH = -\log_{10}[H^+] \quad (1)$$

Severe logarithmic non linearity of Eqn. 1 makes the feedback control of pH systems difficult (Shinskey 1990). Astrom & Wittenmark (1989) illustrated that a controller tuned from pH 8 would result in an unstable response at pH 7.

Recently there have been numerous published papers indicating various ways of overcoming this control problem. Some of these techniques include Global Linearization (Kravaris & Kantor 1990), Internal Mode Control (Henson & Seborg 1991), Robust Nonlinear Control Law technique (Wong *et al.* 1994), etc. However, the most commonly used procedure is to linearize the process around an operating state, and use commercially available PID routines. For a mildly nonlinear process this technique of linearizing gives satisfactory performance. In the case of pH process, since the nonlinearity is severe, the performance is very unsatisfactory.

In this paper, parameter scheduling control strategy has been proposed. For the pH control in a waste water treatment, this technique takes care of non linearity, by identifying the pH process as a variable structure problem. The system parameters like dead time, process gain and time constants, vary with acid/alkali ratio. Hence, the control parameters may vary accordingly. This technique has been successfully applied (Alatiqi & Meziou 1992) for two industrial processes with variable structure.

The pH process will be modeled via experimental identification using laboratory setup. The severer non linearity of pH control problem provides a stringent test case for the proposed parameter scheduling technique.

PROCESS

The process considered, is the control of pH in standard acid/alkali mixing system that is required in water treatment. The setup and schematic presentations of the process are shown in Figs. 1 & 2, respectively.

Stock alkali solution is placed in a 100 liter capacity feed tank, acid reagent is contained in a 50 liter tank, placed adjacent to the alkali tank. Alkali and acid reagents are pumped into a stirred mixing vessel via variable area flow meters, valves and pneumatically controlled valves. An overflow from the mixing vessel is fed under gravity to a sump tank, where the treated alkali solution is held, prior to discharge to the drain. The pH of the solution in the mixing vessel is monitored by a dip electrode. The current in the range 4–20 mA is supplied to the pH transmitter/indicator and an electronic controller. A current/pressure (I/P) transducer converts the signal to the range 3–15 psig, which is fed to the control valve. The equipment was designed and commissioned by Armfield, Inc. of U.K.

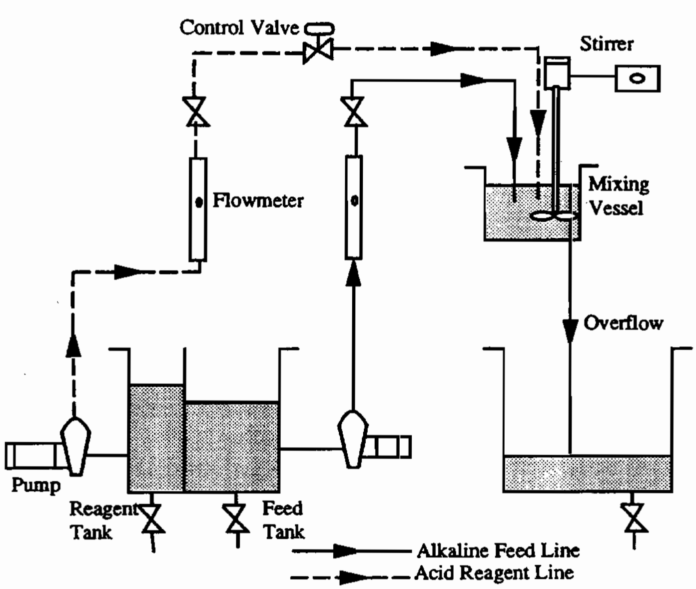

Fig. 1. Schematic diagram.

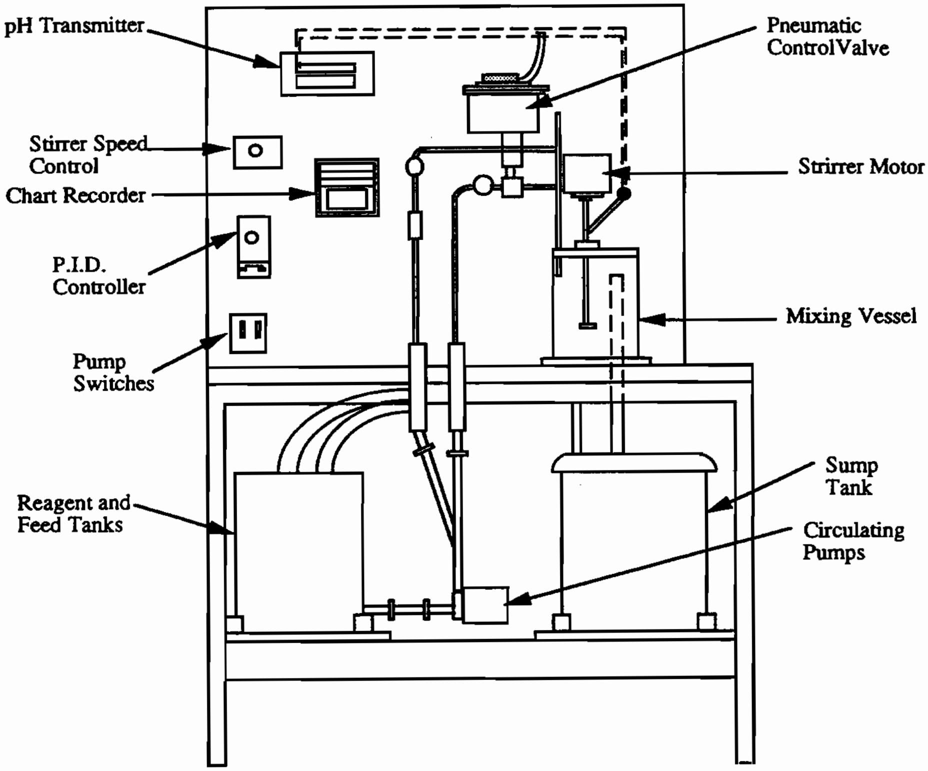

Fig. 2. Experimental setup.

PROCESS IDENTIFICATION

The open loop experimental-response curves, obtained as a result of the step-change in acid flow rate, are typical of the second order transfer function.

$$G_p(S) = \frac{K_p e^{-\theta s}}{(\tau 1s + 1)(\tau 2s + 1)} \quad (2)$$

$$K_p = \left(\frac{\Delta \text{pH}}{\Delta \text{Fa}}\right)_{t \to \infty} \quad (3)$$

The effect of enforcing a step-change in the acid flow rate (Fa) corresponding to valve opening percentage (VOP) on the steady state values of pH is shown in Table 1. Alkali

Table 1. Step change in the acid flow rate.

Fa L/min	Acid/Alkali ratio	VOP	pH	X (cm)
0.10	0.20	40	11.76	0.66
0.20	0.40	51	10.85	0.84
0.29	0.58	60	9.80	0.99
0.475	0.950	70	6.72	1.15
0.72	1.44	80	3.36	1.32
0.94	1.88	90	2.8	1.48

flow rate (Fb) was maintained at a steady state of 0.5 L/min. X is the distance position in cm (VOP * 1.65/100). After each incremental change in Fa, we observe the pH response until a new steady state is reached, then a new step change is enforced.

Transmitter transfer function:

$$G_t = K_t = \frac{100\%}{14} \tag{4}$$

Transmitter receives a signal from the probe, which measures pH on the scale of 14. Transmitter converts it to the scale of 100%.

Valve transfer function:

$$G_v = K_v = \frac{\Delta \text{Fa}}{\Delta \text{VCP}} \tag{5}$$

VCP is the valve closing percentage. The maximum acid flow rate, when the valve is 100% open, is 1.04 L/min.

$$K_v = \frac{1.04}{100\%}\ (\text{L/min})$$

Valve linearity was assumed. Inspection of Table 1 reveals that the flow rate varies approximately linearly with X.

Process transfer function:
Response curves obtained as a result of the open loop test described above were subjected to curve smoothing, in order to determine the process parameters. Figure 3 shows a typical response curve after application of curve smoothing. (Oldenbourg & Saritorius 1954) method for the estimation of the process parameters was utilized.

$$\tau_a = \tau 1 \left(\frac{\tau 2}{\tau 1}\right)^{\tau 2/(\tau 2 - \tau 1)} \tag{6}$$

$$\tau_c = \tau 1 - \tau 2 \tag{7}$$

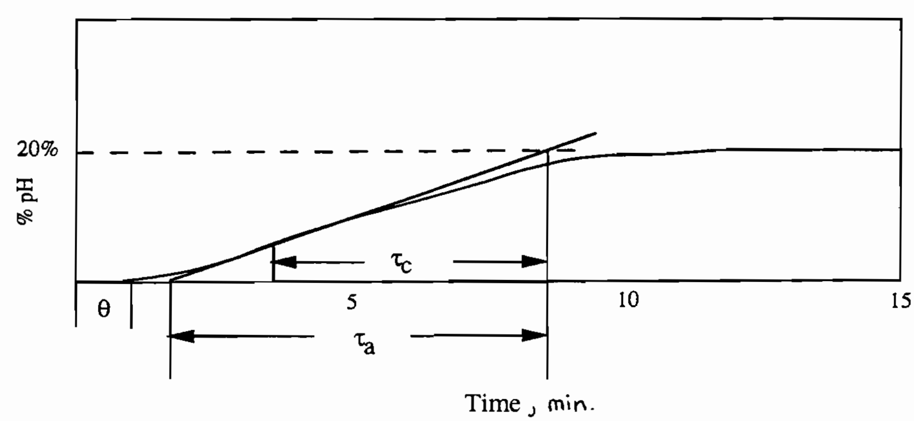

Fig. 3. Estimation of process parameters from the response curve.

Table 2. Process parameters.

pH	$\tau 1$ (min)	$\tau 2$ (min)	θ (min)	K_p (min/l)
2.8	0.72	1.29	0.161	−3.0
3.08	2.14	2.71	0.11	−9.0
3.36	3.15	3.73	0.08	−14.0
5.04	3.68	4.40	0.078	−23.0
6.72	1.28	2.42	0.164	−17.0
8.26	0.77	2.35	0.162	−13.0
9.8	1.86	3.44	0.121	−12.0
10.32	2.02	3.37	0.127	−11.0
10.85	1.72	2.66	0.161	−9.0

Since values of τ_a and τ_c are known, Eqns. 5 & 6 can be solved simultaneously to obtain $\tau 1$ and $\tau 2$. Chebyshev's polynomial Theorem was applied for interpolation, to obtain additional values. Table 2 shows the values of the process parameters for different readings of Fa and hence pH.

From Fig. 4, which shows the polynomial curve fits of the fifth order

$$\tau 1(x) = -52.596 + 37.423x - 8.651x^2 + 0.823x^3 - 0.0279x^4 + 0.0000161x^5 \quad (8a)$$

$$\tau 2(x) = -52.762 + 38.201x - 8.95x^2 + 0.871x^3 - 0.0304x^4 + 0.0002637x^5 \quad (8b)$$

$$\theta(x) = 2.1727 - 1.448x + 0.3478x^2 - 0.03446x^3 + 0.0012x^4 - 0.00000096x^5 \quad (8c)$$

$$K_p(x) = 180.991 - 120.489x + 25.07x^2 - 2.133x^3 + 0.0585x^4 - 0.000524x^5 \quad (8d)$$

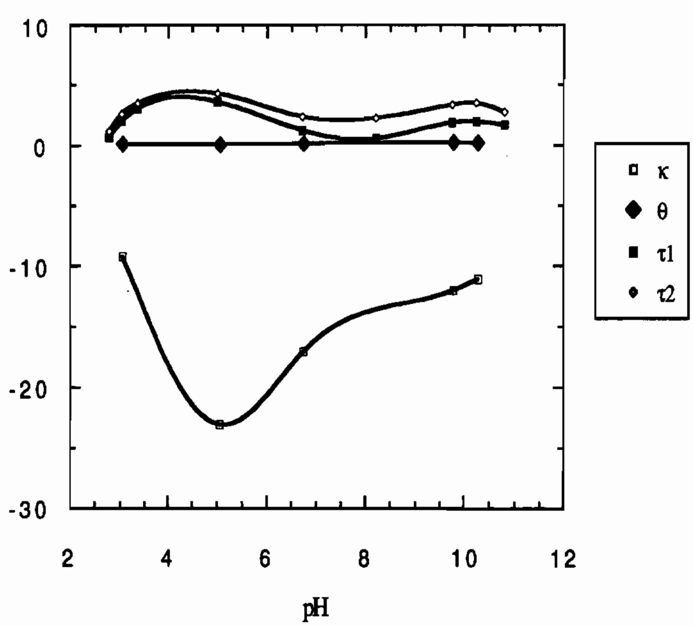

Fig. 4. Polynomial curve fitting of the process parameters.

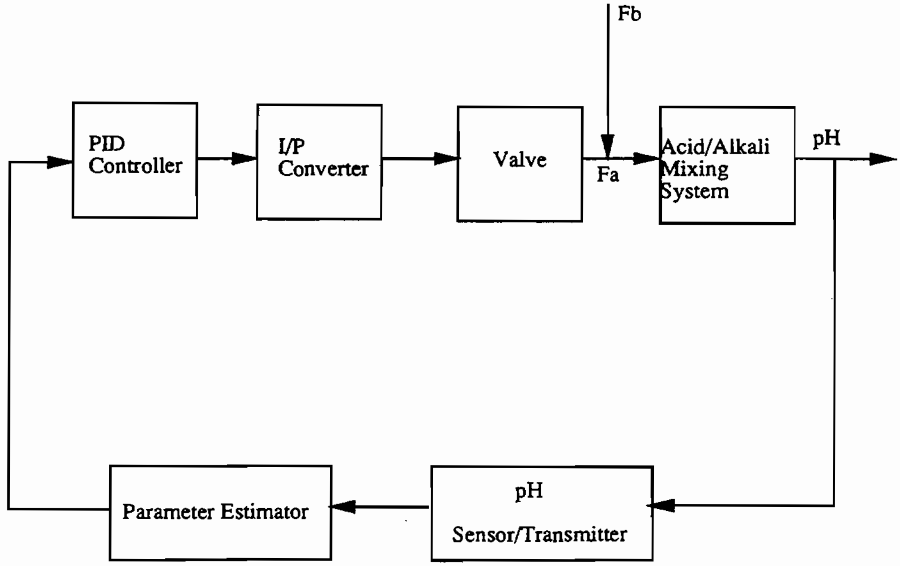

Fig. 5. Block diagram for the pH feedback control system.

CLOSED-LOOP RESPONSE

Block diagram for the pH feedback control system is shown in Fig. 5. Parameter scheduling approach is implemented by feeding the pH measurement to a parameter estimator.

Loop gain:

$$K_p' = K_p * K_v * K_t \tag{9}$$

Table 3, shows K_p' values and the controller settings for a PID controller using Ziegler-Nichols method (Ziegler & Nichols 1942), at different pH readings. It is clear that the process gain approaches a maximum value near the neutral range and decreases as we move away from neutrality in either direction. This observation is in line with the suggestions of Shinskey (1988) and Astrom & Wittenmark (1989). The maximum detected K_p is slightly shifted to the acidic region. This could be related to the unidirectional steps in acid rate. Ideally one would repeat the experiment from the opposite direction (high flow to low flow) and average the results.

Table 3. Loop gain and controller settings.

pH	K_p'	K_c	τI (min)	τ_D (min)
2.8	0.223	34.41	0.86	0.22
3.08	0.669	37.7	1.15	0.29
3.36	1.04	48.1	1.15	0.29
5.04	1.709	32.44	1.19	0.3
6.72	1.263	10.69	1.17	0.29
8.26	0.966	12.46	0.98	0.25
9.8	0.891	29.04	1.2	0.3
10.32	0.817	31.18	1.26	0.32
10.85	0.669	24.8	1.29	0.32

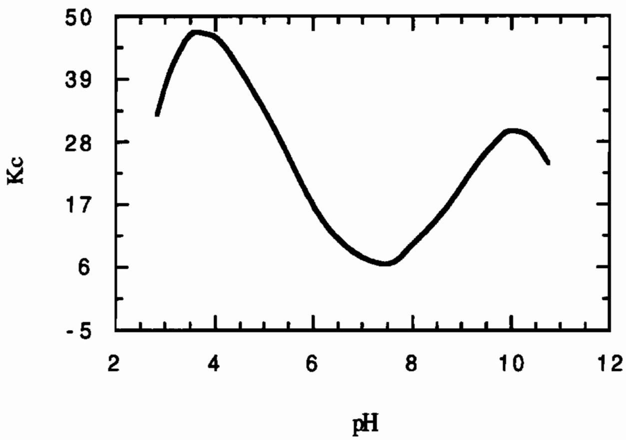

Fig. 6. Relation between the control gain (K_c) and pH.

Figure 6 shows the relation between control gain (K_c) and pH. Similar relations were obtained for τI and τ_D, where severe nonlinearities were observed. The controller parameters were fitted as a function of pH using polynomial curve fit of the 4th and 5th order. The results are shown in the following equations

$$\tau_J(x) = -3.343 + 2.904x - 0.64x^2 + 0.057x^3 - 0.00183x^4 \quad \text{(10a)}$$

$$\tau_D(x) = -0.86 + 0.7512x - 0.1677x^2 + 0.0153x^3 - 0.000495x^4 \quad \text{(10b)}$$

$$K_c(x) = -359.598 + 292.004x - 71.927x^2 + 6.938x^3 - 0.206x^4 - 0.002095x^5 \quad \text{(10c)}$$

Closed-loop response at three different values of pH (4, 7, 10, since these values

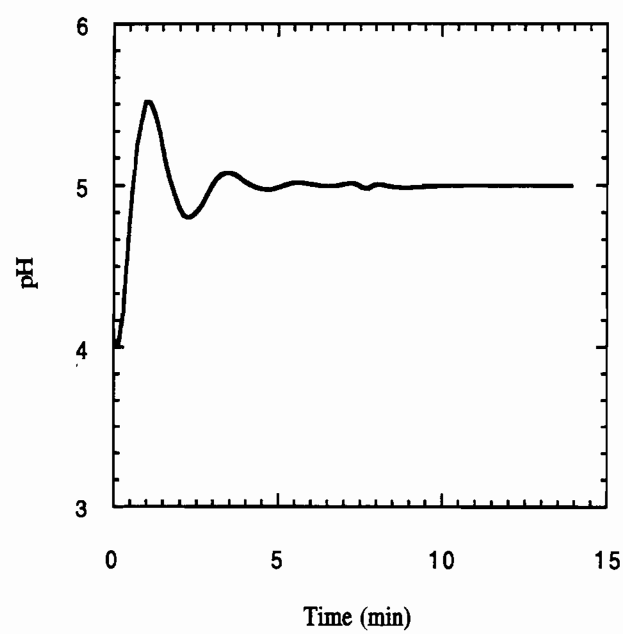

Fig. 7. Closed-loop dynamic response due to unit step change in the set point (base value pH = 4).

represent the peaks for process and controller parameters) was obtained, and a sample response is shown in Fig. 7 for pH value of 4. Similar responses were attained for the cases of pH of 7 and 10, with decay ratios of 0.238 and 0.304 respectively.

It is clear from Fig. 7 that two factors affect the value of K_c. Near the neutral region the effect of high process gain and low lags values result in low controllers gain requirements. At the extreme pH values the effect of time lags predominate at K_c correlates very well with a maxima as near each end.

CONCLUSIONS

The pH control problem was considered using experimental identification. The pH-acid flow transfer function was modeled by a second order plus dead time function with variable parameters. The non-linearity of the parameters in the transfer function were mapped to the control parameters via Chebyshev's polynomial theorem for interpolation. The parameter scheduling technique shown can be implemented via digital control, where the estimator can use measured pH values on line, and update the control parameters accordingly. The simulation results indicate that the control performance can be maintained via parameter scheduling, even with the large process gain variations.

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NOMENCLATURE

Roman Letters

Fa	acid flow rate (L/min)
Fb	alkali flow rate (L/min)
$G_p(s)$	process transfer function
$G_t(s)$	transmitter transfer function
$G_v(s)$	valve transfer function
K_p	process gain (min/L)
K_t	transmitter gain
K_v	valve gain (L/min)
K'_p	loop gain
K_c	control gain
s	Laplace variable
VOP	valve opening percentage
VCP	valve closing percentage
X	distance position (cm)

Greek letters

τ	time constant (min)
τ_a	variable defined in Eqn. 6 and Fig. 3
τ_c	variable defined in Eq. 7 and Fig. 3

θ dead time (min)
τ_I integral time (min)
τ_D derivative time (min)

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جدولة المتغيرات في نظام السيطرة
وفي مسألة الأس الهيدروجيني

عماد العتيقي و أحمد مقبول
قسم الهندسة الكيميائية بجامعة الكويت،
ص. ب 5969 الصفاة ـ الكويت 13060

خلاصة

السيطرة العكسية لخاصية الاس الهيدروجيني من العمليات الصعبة بإعتبار خواصها اللاخطية. في هذه الورقة نقترح جدولة المتغيرات في نظام السيطرة الذي يتعامل مع اللاخطية بواسطة عملية تحديد الاس الهيدروجيني كعملية متعددة الهيكل، وحيث أن متغيرات النظام، مثل الزمن الميت والمحصل وثوابت الزمن، تتغير مع نسبة تغير الحامض إلى القلوي، فأنه يمكن جدولة متغيرات السيطرة تبعا لذلك.