Indian Journal of Chemical Technology
Vol. 22, May-July 2015, pp. 141-147

*p*H Control of industrial effluent using CDM based PI controllers

B Meenakshipriya[1,*], K Saravanan[2], K Krishnamurthy[3] & P Kanthabhabha[4]

[1]Department of Mechatronics Engineering, School of Building and Mechanical Sciences, Kongu Engineering College, Perundurai, Tamilnadu, India

[2]Department of Chemical Engineering, School of Chemical and Food Sciences, Kongu Engineering College, Perundurai, Tamilnadu, India

[3]School of Building and Mechanical Sciences, Kongu Engineering College, Perundurai, Tamilnadu, India

[4]Department of Chemical Engineering, Annamalai University, Annamalai Nagar, Tamilnadu, India

E-mail: b.meenakshipriya@gmail.com

Received 1 April 2013; accepted 4 June 2014

Coefficient Diagram Method (CDM) based PI controllers (CDM-PI and CDM-PI-P) has been implemented in a *p*H neutralization system to control the *p*H value of industrial effluent. The proposed techniques are tested with collected effluent in lab-scale *p*H neutralization system. Experimental runs are carried out at the operating point of *p*H 8 as per the requirement of PCETP and the regulatory performance in terms of Error Indices (ISE and IAE) and Total variations (TV) are reported. The results of the proposed control techniques are compared with conventional control techniques such as Ziegler Nichols PI controller (ZN-PI) and Internal Model Control based PI controller (IMC-PI). The experimental results show that the proposed CDM based PI controllers had impeccable performance with industrial effluent in *p*H neutralization system.

Keywords: CDM-PI, CDM-PI-P, Industrial effluents, *p*H control

Textile industry is one of the main pillars of Indian economy constituting approximately 14% of industrial production, 4% of Gross Domestic Product (GDP) and 11% to the country's export earnings according to the Annual Report 2012-13 of the Ministry of Textiles. It is the second largest employment generator after agriculture. Even though textile industry plays an important role in the Indian economy in multiple ways, it also causes major environmental impact. This industry continuously threatens the livelihood by discharging the effluent into the rivers and nearby canals. Hence, the proper treatment is essential for a healthy and eco-friendly atmosphere. In accordance with the environmental conservation act and environmental rules, it is mandatory to install Effluent Treatment Plants (ETPs) to treat the wastewater before it is discharged. An important and common technique used in wastewater treatment system is neutralization. The purpose of neutralization is to adjust or control the *p*H value of the wastewater so that it does not have impact over the environment. However, it is very difficult to control *p*H process with adequate performance due to its severe nonlinearity, time varying properties and sensibility to small disturbance when working near the equivalence point. Therefore, more reliable, accurate, robust, efficient and flexible control systems are required for *p*H neutralization process.

Several control strategies are reported in the literature to control *p*H problem such as adaptive control[1], self-tuning adaptive controller[2], model reference adaptive control[3], internal model control[4], model predictive control[5], neural network[6], fuzzy logic[7], non-linear gain scheduling based on neuro-fuzzy controller[8] and genetic algorithm[9]. The above methods are quite complex and difficult to implement in the existing distributed control systems. Though there have been significant developments in control systems for the past two decades, the chronic PI controllers are still popular for *p*H neutralization process due to its structural simplicity and reliability. Many research studies on controller tuning have reported that the control loops are not properly tuned when they are implemented, while other loops are not updated sufficiently[10].

Classical control and Modern control approaches have well performed for simple control applications, but not for complex systems. Coefficient Diagram Method (CDM) is an algebraic approach which has paved way for such systems. CDM, established by

Prof. S. Manabe in the year 1991, is a polynomial based approach and so no crises arise as a result of pole zero cancellation. Though CDM is a recent and unfamiliar design approach, it's essential idea has been used in control community for more than 30 years with successful implementation in several applications such as steel mill control[11], gas turbine control[12], control of robotic manipulators[13], space craft control[14], control of DC motor[15], and control of chemical processes such as temperature control[16], heat exchanger system[17] and level control[18].

From the literature, it is clear that the CDM is an efficient and fertile control tool which makes the designer to design a controller under the conditions of stability, robustness and time domain performance. Hence, a simple and efficient control strategy, CDM based PI controllers, namely CDM-PI and CDM-PI-P are proposed for the *p*H neutralization system. These control strategies are already implemented and validated in lab-scale *p*H neutralization system with synthetic effluents consist of strong base (NaOH, 0.1N) and strong acid (HCl, 0.1N)[19,20]. As the continuation of previous work, this work is carried out to investigate the performance of the proposed CDM-PI and CDM-PI-P controllers with real industrial effluents in lab-scale *p*H neutralization system.

Experimental Section

The first stage of this work describes the sample collection of industrial effluents at Perundurai Common Effluent Treatment Plant (PCETP) in detail. In the second stage, the development of *p*H system model and tuning parameters of CDM-PI, CDM-PI-P, ZN-PI and IMC-PI controllers are presented. In the third stage, the proposed control strategies are tested with collected industrial effluents in lab-scale *p*H neutralization system and the performance are compared with conventional PI control techniques.

Overview of Perundurai Common Effluent Treatment (PECTP)

PCETP has been established in the industrial area (SIPCOT), Perundurai, Erode District, Tamilnadu, India. The maximum operating volume of PCETP is 3600 m^3/day to treat the wash water with TDS range of < 2100 mg/L. The present work has been formulated based on the field study conducted at the primary treatment plant of PCETP. The sequence of operation adopted in the primary treatment plant of PCETP is shown in Fig. 1 and plant specifications are given in Table 1.

The effluent first passes through the bar screen (1) which is placed in the influent of the receiving sump. It is used to take care of rags and large objects in the effluent, so that these objects do not destroy the forthcoming units. To maintain the uniform flow in the treatment plant, the receiving sump (2) is used. From the receiving sump, the effluent is pumped to the equalization tank (3), where three floating aerators are used to obtain the homogeneity in the effluent.

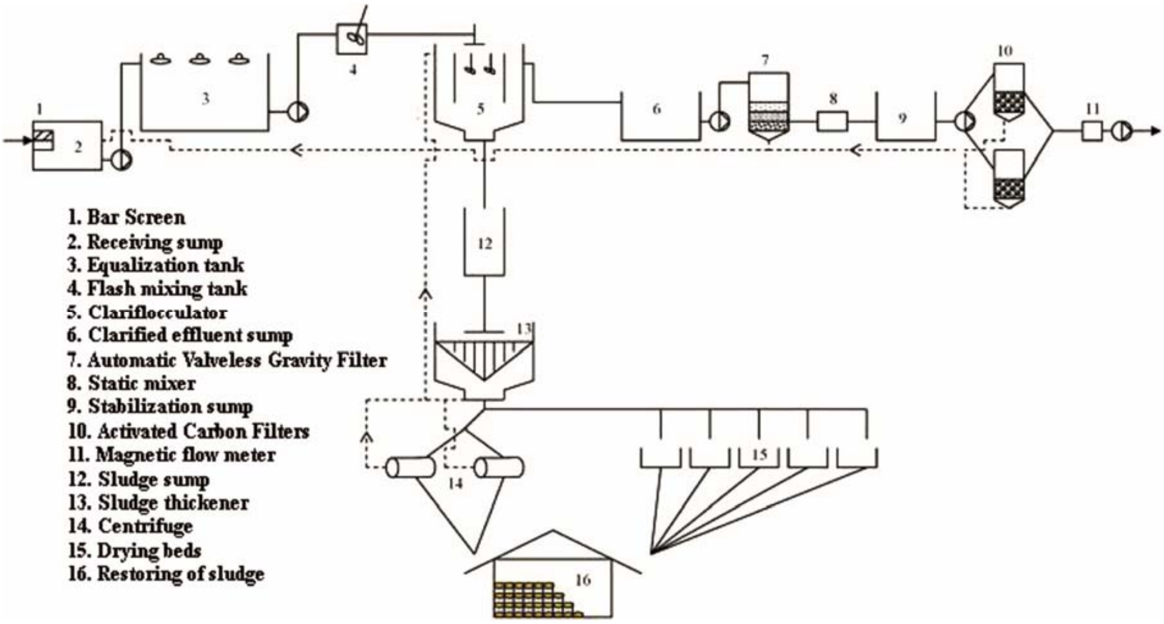

Fig. 1 — Layout of the primary treatment plant-PCETP

The outlet from the equalization tank is pumped to the flash mixing tank (4) with the help of a centrifugal pump. To enhance the settling process, the effluent is mixed with lime, iron sulphate and polyelectrolyte in the flash mixing tank.

The effluent from flash mixing tank is fed into the clariflocculator (5) where both flocculation and sedimentation take place. During sedimentation, the *p*H value should be maintained approximately at 11 to ensure that none of the metal hydroxides re-dissolve and become soluble in the effluent. The outlet from the clariflocculator led to the clarified effluent sump (6) which is used to maintain a constant flow for the next unit. Then, the effluent is pumped to the Automatic Valveless Gravity Filter (AVGF) (7).

Hydrochloric acid (HCl) is added and mixed with the effluent in a static mixer (8) from AVGF to reduce the *p*H around 8. The effluent then is led to the stabilization sump (9) to stabilize the *p*H of the effluent. The effluent from stabilization sump is distributed into two parallel Activated Carbon Filters (ACFs) (10). The clean effluent from ACF flows through magnetic flow meter (11) which records TDS and *p*H. Finally, the effluent is pumped by a booster pump to the biological treatment plant.

The sludge from the bottom of the clariflocculator is collected in the sludge sump (12) which is essential to maintain the constant flow for the next unit. Further, the sludge is fed to the sludge thickener (13) where the solid content of the sludge is increased by removing a portion of the liquid fraction. From the sludge thickener, the sludge can flow in two different ways. Most of the sludge is fed to the centrifuge (14) which separates liquids from solids by increasing the gravity power. The remaining sludge is fed to the drying beds (15) which are used to dewater digested sludge. In the final stage of operation, the sludge is packed in sacks and stored under a roof (16) until further notice from the concerned authority.

Table 1 — PCETP specifications

Description	Capacity m^3/hr	Retention time min
Receiving sump	132-150	45
Equalization tank	150	1440
Flash mixing tank	3-4	2
Clariflocculator	450-350	240
Clarified effluent sump	145-150	30
Automatic valveless gravity filter	50	15
Stabilization sump	130-135	30
Activated carbon filter	10	8

Collection of Industrial effluent

Collection of samples always presents serious difficulties because of large variations in flow and composition. It is very important that a sample collected should be truly representative of the whole of the effluent that passed in the given time. Thus the raw effluent samples are collected at the outlet of equalization tank and a sample of effluent before HCl dosing is collected at the outlet of the Automatic Valveless Gravity Filter (AVGF) at a regular interval of 1 hour to analyze the effluent characteristics. The primary characteristics of the raw effluent and effluent before HCl dosing are analyzed as per standard methods[21] at PCETP laboratory. The measured values are tabulated in Table 2.

For this experimentation, effluent samples of 500 liters are collected at one week interval at the outlet of AVGF. The collected effluents are used to conduct the experiments in *p*H system within 2 hour. The

Table 2 — Characterization of industrial effluent and effluent samples

S No	Parameter	Range of value		Value (Effluent before HCl dosing)	
		Raw effluent	Effluent before HCl dosing	Sample 1	Sample 2
1	*p*H	8.0-9.0	10.0-11.0	10.5	10.8
2	Total Dissolved Solids (TDS, mg/L)	1800-2000	1800-2000	1850	2000
3	Turbidity (Nephelometric Turbidity Units, NTU)	20-40	10-15	10	12
4	Chemical Oxygen Demand (COD, mg/L)	750-1000	350-450	400	400
5	Biological Oxygen Demand (BOD, mg/L)	250-350	150-250	150	150
6	Total Hardness (mg/L)	120-200	150-225	210	185
7	Total Alkalinity (mg/L)	750-1000	800-1200	900	880
8	Chlorides (mg/L)	600-850	600-850	700	820
9	Sulphates (mg/L)	250-300	250-300	250	280

primary characteristics of collected samples 1 and 2 are shown in Table 2 and it interprets that the *p*H value of these samples are within the specified range as given in the same table.

Computation of PI controller parameters

The *p*H system is approximated as first order plus time delay (FOPTD) model to compute the PI controller parameters. For model identification, the experiments are carried out in lab-scale *p*H neutralization system by considering 0.1N of HCl and 0.1N of NaOH as reactants and it is discussed in[19,20]. The reactants are selected based on the field study conducted at PCETP. From the field study, it is observed that the effluent is mostly alkali waste (10-12 *p*H) and it is being neutralized by HCl to maintain the *p*H around 8 for the survival of bacteria in the biological treatment. However, as per the environmental legislation, it is necessary to maintain the *p*H value of the effluent between 5.5 and 9 before it is being discharged into the environment. Therefore, for the present study, 0.1N of NaOH is used since its maximum alkalinity is also around 12 *p*H. For the strong-acid and strong-base neutralization process, the normality of both reactants is to be considered as same to reduce the complexity in model identification. Hence, 0.1 N of HCl is taken as a neutralizing agent. The identified FOPTD model for computing the PI controller parameters are as follows:

$$G(s)=\frac{K_p}{\tau_p s+1}e^{-\theta s}=\frac{7.0921}{8.54s+1}e^{-1.71s} \qquad \ldots(1)$$

where K_p = Process gain (%/%); τ_p = Process time constant (Min); θ = Process delay (min).

Conventional PI controllers

The PI controller parameters are computed based on the FOPTD model given in Eq (1). To analyze the performance of the proposed CDM based PI controllers, the existing conventional PI control techniques such as such as Ziegler Nichols[22] and Internal Model Control (IMC)[23] based PI tuning rules are considered for comparative studies. For convenience, these techniques are abbreviated as ZN-PI and IMC-PI respectively. The conventional PI controller tuning rules and the value of computed parameters are given in Table 3.

CDM based PI controllers

The CDM-PI and CDM-PI-P controller settings are worked out based on the design procedure given in[19,20]. The design calculations are as follows:

Step 1: FOPTD Model of pH system represented in Eq (1) is:

$$G(s)=\frac{K_p}{\tau_p s+1}e^{-\theta s}=\frac{7.0921}{8.54s+1}e^{-1.71s}$$

Step 2: Equivalent transfer function of the above said FOPTD model using first order Pade's approximation technique is:

$$G(s)=\frac{-12.1275s+14.1842}{14.6034s^2+18.79s+2}$$

Step 3: First degree CDM controller polynomials (A(s) and B(s)) are chosen as $A(s)=s$ and $B(s)=k_1 s+k_0$

Step 4: For CDM-PI controller:-Selected stability indices values are $\gamma_1 = 2.5$ and $\gamma_2 = 2$

For CDM-PI-P controller:-Selected stability indices values (γ_1, γ_2) and tuning factor (λ) are $\gamma_1 = 3$, $\gamma_2 = 2.5$ and $\lambda = 0.7$

Step 5: Calculated $P(s)$ = s $(14.6s^2+18.79s+2)$ + $(k_1 s+k_0)$ $(-12.13s+14.18)$

Table 3 — Conventional PI controllers

Conventional PI controllers	PI controllers tuning rule	PI controller parameters
ZN-PI	$K_c=\frac{0.9\tau_p}{\theta K_p}$	$K_c = 0.6338$
	$T_i = 3.33\theta$	$T_i = 5.69$ min
IMC-PI	$K_c \frac{\tau_p+0.5\theta}{K_p(\lambda)}$	$K_c = 0.4557$
	$T_i = \tau_p + 0.5\theta$	$T_i = 9.395$ min

where, K_c — Controller gain; K_p — Process gain; τ_p — Process time constant; T_i — Integral time constant; λ — Tuning factor (Recommended value 1.7θ); θ— Process delay

Table 4 — CDM based PI controllers

CDM based PI controllers	CDM based PI controllers tuning rule	CDM based PI controller parameters
CDM-PI	$K_c = k_1$	$K_c = 0.6176$
	$T_i = \frac{k_1}{k_0}$	$T_i = 4.3544$ min
	$C_f(S) = \frac{1}{T_i S + 1}$	$C_f(S) = \frac{1}{4.3544S + 1}$
CDM-PI-P	$K_c = \frac{\lambda k_1}{(1+\lambda)}$	$K_c = 0.3111$
	$T_i = \frac{k_1}{(1+\lambda)k_0}$	$T_i = 2.19$ min
	$K_f = \frac{k_1}{(1+\lambda)}$	$K_f = 0.4445$
	$G_f(s) = \frac{K_c(1+T_i s)}{(K_c + K_f)T_i s + K_c}$	$G_f(s) = \frac{0.3111(1+2.19s)}{1.655s + 0.311}$

where, K_c — Controller gain; T_i-Integral time constant; k_1 and k_0 — Coefficients of CDM controller polynomials; λ — Tuning factor; K_f — Feedback proportional gain; $C_f(s)$ — Feedforward controller transfer function and $G_f(s)$ — Pre-filter element transfer function

Step 6: Computed coefficients of CDM controller polynomials

For CDM-PI controller:–k_1= 0.6176 and k_0= 0.1418

For CDM-PI-P controller:–k_1= 0.7556 and k_0= 0.1418

Step 7: Selected PI controller transfer function is:

$$C(s) = K_c\left(1 + \frac{1}{T_i\, s}\right)$$

Step 8: Comparing the CDM controller polynomials with PI controller transfer function, the CDM based PI controller parameters are computed and shown in Table 4.

Results and Discussions

Investigation of ZN-PI, IMC-PI, CDM-PI and CDM-PI-P controllers with industrial effluent in laboratory scale *p*H neutralization system is described in this section. For this investigation, the collected industrial effluent is fed to the mixing tank at a constant flow rate of 0.5 lpm and HCl of 0.1 N is added to the mixing tank through the control valve which is controlled by the PI controller as shown in Fig. 2.

Fig. 2 — *p*H system with industrial effluent

As per the requirement of PCETP, the *p*H value of effluent is to be maintained around 8. Hence the experimental runs are carried out at the operating point of *p*H 8 to analyze the performance of above said controllers. The behavior of the feed flow rate of acid and *p*H response of the process with load disturbance using above said controllers was studied. It is seen that the *p*H response is measured without load disturbance for the first 3000 sec and it is measured with load disturbance for the next 3330 sec.

Table 5 — Performance measures of controllers at the operating point of *p*H 8 for effluent samples

Controllers	Performance Measures					
	Sample 1			Sample 2		
	ISE	IAE	TV	ISE	IAE	TV
ZN-PI	1116.15	948.29	466.10	1186.27	954.33	333.49
IMC-PI	836.63	863.62	154.87	1092.37	1000.28	294.77
CDM-PI	198.42	421.53	62.94	131.80	341.70	75.99
CDM-PI-P	49.37	202.96	75.58	65.99	233.00	93.35

Here the load disturbance is introduced by increasing the water flow rate from 0 to 1 lpm. The performance measures such as error indices and total variations are calculated for the period of t = 0 to 6330 sec with a step size of 5 sec and it is given in Table 5. The performance of ZN-PI, IMC-PI, CDM-PI and CDM-PI-P controllers at the operating point of *p*H 8 was studied with industrial effluents (sample 1).

The ZN-PI controller maintains the *p*H value in the range of 5 to 9.5 without load disturbance since the % of acid flow rate varies from 10 to 27 %. After introducing the load disturbance at t = 3000 sec, the *p*H value varies from 5.5 to 10 till t = 4650 sec while the % of acid flow rate increases upto 30%. Then the *p*H value brought to its previous range. It is observed that the ZN-PI controllers provide rapid changes in the control action. Thus, it could not able to maintain the *p*H value in the required range since the process gain of the operating point (*p*H 8) is high. The performance IMC-PI controller is quite better than the ZN-PI controller. This controller provides the output in the range of 6.0 to 9.0 *p*H without load disturbance with the variation of 17 to 27% of acid flow rate respectively. Similarly with load disturbance, the *p*H value varies from 6.0 to 9.6 till t = 4900 sec while increase the % of acid flow rate upto 29%. It is clear that the controller provides slight deviation in the controller actions before and after load disturbance. Though they offer smooth and consistent action, it could not able to maintain the *p*H value in the required range.

The performance of the CDM-PI and CDM-PI-P controllers with industrial effluent reveal that the controller maintains the *p*H value in the range of 7.5 to 8.7 and 7.6 to 8.4 without load disturbance since the % of acid flow rate varies from 13 to 18% and 15 to 17% respectively. Similarly, with load disturbance, they maintain the *p*H value from 7.1 to 9.1 till t = 4900 sec and 7.0 to 8.5 till t = 3300 sec while the % of acid flow rate decreases upto 7 and 13% respectively. It is observed that the CDM based controllers provide better result with the industrial effluent at the required operating point of *p*H 8 than the other control techniques.

Similar to the previous experimental analysis, the performance of ZN-PI, IMC-PI, CDM-PI and CDM-PI-P controllers at the operating point of *p*H 8 with the industrial effluent (sample 2) are also investigated. The performance of sample 2 is similar to that of sample 1. Without load disturbances, the *p*H value varies from 5.0 to 9.5 with the acid flow rate of 10 to 30%, 6.0 to 9.5 with the acid flow rate of 17 to 28%, 7.4 to 8.6 with the acid flow rate of 15 to 18% and 7.5 to 8.5 with the acid flow rate of 13 to 18% for the controllers ZN-PI, IMC-PI, CDM-PI and CDM-PI-P respectively. Similarly, after introducing the load disturbance, the pH value varies from 5.0 to 10.0 till t = 5675 sec, 6.3 to 9.9 till t = 4345 sec, 7.0 to 8.8 till t = 3685 sec and 6.7 to 8.5 till t = 3245 sec for the controllers ZN-PI, IMC-PI, CDM-PI and CDM-PI-P respectively because of variation in the acid flow rate. The comparative performance of the above said controllers in terms of ISE, IAE and $TV = \sum_{k=1}^{\infty} \left| y(k+1) - y(k) \right|$ at the operating point of *p*H 8 with the industrial effluent (sample 1 and sample 2) is shown in Table 5.

The numerical values interpret that the CDM based controllers exhibit minimum error indices and provide smooth and consistent (lowest TV value) response when compared to other conventional PI controllers. From the results, it is proved that the other conventional PI controllers could not able to offer the satisfied results at the required operating point instead the CDM based PI controllers provide the sustained oscillation about the operating point of *p*H 8 with ± 5% tolerance error and met the necessary range of *p*H (around 8) as per the requirement of PCETP.

Conclusion

The performance of CDM-PI and CDM-PI-P controllers are tested with industrial effluent in lab-scale *p*H neutralization system which is collected at PCETP. The performance measure substantiates that the CDM-PI and CDM-PI-P controllers exhibit minimum error indices and provide smooth and consistent response. CDM furnishes a convenient and flexible design under the conditions of stability and robustness which provides excellent performance in terms of disturbance rejection. The proposed control strategy works well against the uncertainties of the nonlinear *p*H system and also, it is found that the CDM based PI controllers have impeccable performance with the industrial effluent in laboratory scale *p*H neutralization system. Thus it is hoped that the favourable outcome of this research work may contribute in the process control field to reduce the gap between theoretical and practical approach.

Acknowledgement

The authors show their sincere gratitude to Perundurai Common Effluent Treatment Plant (PCETP), Perundurai, Tamilnadu, India for collecting industrial effluent samples to validate the research work. The authors show their special gratitude is due in good measure to University Grant Commission (UGC), New Delhi, India for providing financial support to carry out this research work (File No. 35-116/ 2008 (SR) dated 25.03.2009).

References

1 Henson M A & Seborg D E, *Int J Adaptive Control Signal Process*, 11 (1997) 171.
2 Lin F, Brandt R D & Saikalis G, *Proceed, Am Cont Conference,* (Chicago) 2000, 3676.
3 Palancer M C, Aragon J M, Miguens J A & Torrecilla J S, *Indust Eng Chem Res*, 35 (1996) 4100.
4 Hu Q, Saha P & Rangaiah G P, *Control Eng Pract*, 8 (2000) 1167.
5 Sanaz Mahmoodi, Javad Poshtan, Mohammad Reza Jahed-Motlagh & Allahyar Montazeri, *Chem Eng J*, 146 (2009) 328.
6 Bernt M Akesson, Hannu T Toivonen, Jonas B Waller & Rasmus H Nystrom, *J Comput Chem Eng*, 29 (2005) 323.
7 Ahmed D F, Al-Dawery S K H & Al-Anbari H A O, *Emirates J Eng Res*, 12 (2007) 89.
8 Zhang J, *Indust Eng Chem Res*, 40 (2001) 3164.
9 Valarmathi K, Devaraj D & Radhakrishnan T K, *Brazilian J Chem Eng*, 26 (2009), 99.
10 Astrom K J & Hugglund T, *PID controllers: Theory, design and tuning* (ISA Publication Research, Triangle Park, NC) 1995.
11 Kessler C, *Regelungstechnik*, 8 (1960), 261.
12 Thanaka Y, *SICE Transactions*, 28 (1992b), 1501.
13 Ucar A & Hamamci S E, *Proc, IEEE Int Conf Electro Circuits Systems* (Jounieh, Lebanon), 2 (2000), 777.
14 Manabe S, *Proc, IFAC Symp Automatic Control Aerospace* (Bologna, Italy), 2001, 499.
15 Hamamci S E & Koksal M, *Proc, Mediterranean Conf Control Automation* (Dubrovnik, Crotia), 2001.
16 Koksal M and Hamamci S E, *Proc, IEEE Conf Control Appl*, 2 (2003), 1437.
17 Bhaba P K, Somasundaram S & Karunanithi T, *Chem Eng World*, 40 (2005), 75.
18 Bhaba P K & Somasundaram S, *Modern Appl Sci*, 3 (2009), 38-45.
19 Meenakshipriya B, Saravanan K, Somasundaram S & Kanthabhabha P, *Instrument Sci Technol*, 39 (2011) 273.
20 Meenakshipriya B, Saravanan K, Krishnamurthy K & Bhaba P K, *Asian J Sci Res*, 5 (2012) 78.
21 Clesceri L S, Greenberg A E & Eaton A D, *Standard methods for the examination of water and wastewater* (American Public Health Association, Washington) 1998.
22 Ziegler J G & Nichols N B, *ASME Transactions*, 64 (1942) 759.
23 Rivera D E, Morari M & Skogested S, *Indust Eng Chem Res*, 25 (1986) 252.