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Study the Stability of a Wastewater Treatment Unit using LABVIEW

Dr. Ghainm M. Alwan — **Assist. Prof.**
Farooq A. Mehdi — **Assist. Lecture**
Chemical Engineering Dept.- University of Technology

Abstract

This study was devoted to limit the stability conditions of the wastewater treatment unit.

LABVIEW was a powerful and versatile graphical programming language in automation control and date acquisition of the system. The on-line show that accurate and stable control responses were obtained in the present work. The actual phase plane proved to a better technique to limit the regions of the non-linear system stability compared to other theoretical techniques. Limit cycle did not appear in the present system.

Keywords: **Stability, LABVIEW, pH Control, Phase Plane**.

دراسة استقرارية وحدة معالجة المياه الصناعية باستخدام برنامج LABVIEW

الخلاصة

هذه الدراسة تشير الى اسلوب تحديد ظروف الاستقرارية لوحدة معالجة المياه الصناعية. LABVIEW هي لغة برمجة الرسم التي استخدمت في تشغيل و السيطرة الاتوماتيكية و اكتساب النتائج العملية للمنظومة الحالية. السيطرة عن بعد اثبتت استقراريتها. ان اسلوب مخطط الطور احقيقي اثبت انه الافضل في تحديد ظروف الاستقرارية للمنظومة اللاخطية مقارنة بباقي الطرق الاخرى. لم تظهر الدورة الحدية في هذا النظام.

الكلمات الدالة: استقرارية، LABVIEW ، سيطرة على دالة الحموضة، مخطط الطور

Nomenclatures

E	Error in pH (pH set value – pmeasured)	[pH]	$G_m(s)$	Transfer function of measuring element	[–]
F	Flow rate of chemicals additives	[cc/sec]	$G_{p1}(s)$	Transfer function of $Ca(OH)_2$ system	[pH/cc/sec]
$G_c(s)$	Transfer function of controller	[mv/pH]	$G_{p2}(s)$	Transfer function of Na_2S system	[pH/cc/sec]
$G_L(s)$	Transfer function of load	[–]	$G_v(s)$		

	Transfer function of valve	[liter/sec/mv]
K_c	Proportional gain	[mv/pH]
s	Laplacian variable	[sec^{-1}]
t	Time	[sec]
t_d	Time delay	[sec]

Greek Symbols

τ_p	Time constant	[sec]
τ_D	Derivative time	[sec]
τ_I	Integral time	[sec]

List of Abbreviations

IMC	Internal model control
ITAE	Integral Time of Absolute of Error
P	Proportional
PI	Proportional-Integral
PID	Proportional-Integral-derivative

Introduction

Wastewater from metal finishing industries contains contaminants such as heavy metals, organic substances, cyanides and suspended solids at levels, which are hazardous to the environment and pose potential health risks to the public. Heavy metals, in particular, are of great concern because of their toxicity to human and other biological life. Heavy metal typically present in metal finishing wastewater are; cadmium, chromium, copper, iron, zinc …etc (Sultan, 1998) [1].

Conventionally, metal finishing waste streams are treated by chemical means and the quality of treated effluents much meets discharge standards. The techniques used in the convention treatment of wastewater involve precipitation of heavy metals flocculation, settling and discharge. The treatment requires adjustment of pH as well as the addition of chemicals (acid and caustic … etc).

pH is monitored and controlled by manipulating a base stream, which is usually a solution of a lime or sodium sulfide. Modern treatment plants involve physical and chemical precipitation where maintenance of pH is the key factor for efficient treatment. Most of the process uses a pH sensor (glass electrode) as the on-line measuring for control (Chaudhuri, 2006) [2].

LABVIEW is a graphical programming language that has its roots in automation control and data acquisition (Canete et al, 2008) [3].

In the present work, the LABVIEW technique is used to operate and control the system automatically by on-line digital computer.

The analysis of the stability for the nonlinear pH process of the wastewater plant is usually the most important to design and select the suitable automatic control system.

The system was unsteady state and nonlinear process, so that the use of analytical methods to limit the stability conditions was less accurate because the time solution of the system different equations could not be easily obtained (Ogata, 1982) [4].

Phase plane analysis of a nonlinear dynamic system is based on conceptual simplification of changing to a co-ordinate system (the phase plane) in which time no longer appears explicitly but is replaced by a differential function. When dx/dt is plotted against x, a curve is produced (known as a phase portrait) on which time is a parameter. In general, for a particular nonlinear response function, there will be a number of different curves (or trajectories) specified by differing initial conditions, and the stability of the response for particular initial conditions may be shown by the direction and behaviour of the corresponding trajectory (Pollard, 1981) [5].

In the present work, the critical variable was the pH of wastewater for industrial application; it is widely used PID control (Emerson, 2004) [6]. The tuning of control parameters were found by two methods; Internal Model Control (IMC) and the Integral Time of Absolute Error (ITAE) criteria.

The motion or path of the pH was more effective and sufficient to get clear picture for limiting the stability of the system.

Experimental Set-up and Procedure

A Lab-scale experimental wastewater plant coupled to laptop computer was used to evaluate the performance of the control software developed in LABVIEW. The experimental rig (Figure 1) was designed and constructed into the best way to simulate the real process and collect the desirable data. The process consists of mainly equipments:

1. Two mixing tanks.
2. Two chemical reagent storages for $Ca(OH)_2$ and Na_2S.
3. Dosing pump.
4. Motorized control valve.
5. Inputs/output interface system.
6. Digital computer (*hp* Laptop).

Experimental Procedure

Before starting, the system was always cleaned from any contaminated material. The pH sensor was calibrated by standard solutions. All power supplies were ready. The experimental runs were achieved automatically by on-line digital computer.

The desired (value) was the pH which was the key factor for efficient treatment, so that it was monitored and controlled by manipulating the base streams of $Ca(OH)_2$ and Na_2S (Input variables). The pH of the wastewater was controlled within the natural to slightly alkaline range (pH 7.8) as explained in the scientific report of (EPA, 2005)[7].

<u>Open Loop</u>

1. The LABVIEW program (Version 8.2) was designed to operate and control the system.
2. Filling the precipitator (1) with one liter of the wastewater at the initial conditions of pH 7 and 25 ^oC.
3. Creating 100% step change in inlet flow rate (0.45 cc/sec) of $Ca(OH)_2$ or Na_2S by the manual valve V3.
4. When reaching to the desired value (pH 7.8), the system was automatically shutdown.
5. Recording & plotting the pH of water into tank as function of time.

Closed Loop

1. Selecting the values of controller's parameters (Kc, τ_I & τ_D) by directly tuning the desired knobs in the front panel appeared on the monitor (Figure 2).
2. Filling the precipitator (1) with the wastewater at initial conditions of pH 7 and 25 ^oC (as explained above).
3. Starting the operation of the closed loop system using the servo technique with (10 % step change in set value).
4. Recording & plotting the pH, error and controller action responses directly by the computer.

Phase – Plane Analysis

P Control

Figure (3) illustrates the phase plane for various values of proportional gain (Kc) against +ve 10% step change in set values (servomechanism). For Kc of 0.2, the process path (trajectory) has stable condition (node type) around new steady state (pH 7.55). When Kc was increased to 0.44 & 1.0 the speed of the trajectories paths increased and seem to be as a stable node new steady state points (pH 7.64 & pH 7.73) respectively.

The steady state error (offset) regarding equilibrium point (pH 7.8) could be decreased by increasing the value of Kc. The limit cycle did not appear in the present work because of hunting oscillation at maximum value of Kc, due to the nature of the process which always increased the pH (batch dynamic titration) of the system.

PI Control

The trajectories of PI mode had the node motion (stable node) around the steady state point (pH 7.8). When the integral time constant decreased from 5.0 seconds to 0.5 second the speed of the process path also has increased to reach the equilibrium point (Figure 4).

PD Control

PD control appears the instability and noisy trajectories (unstable focus) as shown in Figure (5) for different values of derivative time constant (τ_D) greater than 0.5 second. Because the noisy mixing and the highly sensitivity of derivative mode. However, PD control was undesirable for pH control of the Present wastewater treatment unit. (at τ_D greater than 0.5 second).

PID Control

The phase plane of the PID shows the stable node type as shown in Figures (6 & 7). The offset was eliminated. The speed of trajectory was less than that of PI control to reach the equilibrium point (pH 7.8) as shown in Figure (6). In addition, the process path of optimum PID by IMC method was faster than that of ITAE criteria to reach the equilibrium point as shown in Figure (7).

Theoretical Analysis

The Routh – Hurwitz technique was used to study the stability of the present system depended on characteristic equation of closed loop system (Chau, 2001) [8].

Hurwitz test for the polynomial coefficients

For a given *n*-th order polynomial;

$$P(s) = a_n s^n + a_{n-1} s^{n-1} + ... + a_2 s^2 + a_1 s + a_o \quad .... (١)$$

All the roots are in the left hand plane if and only if all the coefficients a_o, …, a_n are positive definite. If any one of the coefficients is negative, at least one root has a positive real part (i.e., in the right hand plane). If any of the coefficients is zero, not all of the roots are in the left hand plane: it is likely that some of them are on the imaginary axis.

Routh array construction

If the characteristic polynomial passes the coefficient test, we then construct the Routh array to find the necessary and sufficient conditions for stability. The Routh criterion states that in order to have a stable system, all the coefficients in the first column of the array must be positive definite. If any of the coefficients in the first column is negative, there is at least one root with a positive real part. The number of sign changes is the number of positive poles.

To handle the time delay, Padé approximation was used to put the function as a ratio of two polynomials. The approximation is more accurate than a first order Taylor series expansion. The simplest is the first order (1/1) Padé approximation: (Chau, 2001) [8].

$$e^{-t_d s} \approx \frac{1-\frac{td}{2}s}{1+\frac{td}{2}s} \quad \text{.........................(٢)}$$

In the present work, the dynamics characteristic of the pH process was studied using the process reaction curve method (Stephanopouls, 1984) [9]. The transfer functions for $Ca(OH)_2$ and Na_2S solutions were approximately similar. Then the transfer function of the open loop system was represented by first order lag system with dead time (Figure 8), which is:

$$G_p(s) = \frac{pH(s)}{F(s)} = \frac{1.6}{5s+1}e^{-4s} \quad \text{...(٣)}$$

While the transfer function of pH electrode and control valve (From technical sheets of instruments) are:

$$G_m(s) = \frac{1}{s+1} \quad \text{.................................(٤)}$$

$$G_v(s) = \frac{1}{6s+1} \quad \text{................................(٥)}$$

P Control

For the optimum setting when Kc= 0.44, the characteristic equation, with the aid of MATLAB computer program as shown in (Appendix) is:

$$30s^4 + 56s^3 + 32.5s^2 + 6.293s + 0.8533 = 0 \quad \text{....................................... (٦)}$$

All coefficients of Equation (6) are positive. Then the Routh array is:

1: 30.0	32.5	0.8533
2: 56.0	6.293	0
3: 29.1288	0.8533	
4: 4.6525	0	
5: 0.8533		

Since the coefficients of the first column are positive, so the system is stable.

PI control

With K_c=0.46, τ_I = 5 seconds, the characteristic equation is:

$$150\ s^5 + 280\ s^4 + 162.5\ s^3 + 31.31 s^2 + 3.608\ s + 0.3694 = 0 \quad \text{……………….(٧)}$$

The Routh array is:

1:	150.0	162.5	3.608
2:	280.0	31.31	0.3694
3:	145.7268	3.4101	0
4:	24.7578	0.3694	
5:	1.235	0	
6:	0.3694		

From the above results, the control system with PI mode is stable.

PD control

Stochastic effect due to noisy mixing was difficult to represent by mathematical model for PD control.

PID control

For the PID control with controller setting of Kc=0.94, τ_I = 7 second and τ_D= 1.42 second, then the characteristic equation is:

$$210\ s^5 + 392\ s^4 + 212.6\ s^3 + 45.95\ s^2 + 7.25\ s + 0.75 = 0 \quad \text{………………… (٨)}$$

All coefficients of above equation are positive, and then the Routh array is:

1:	210.0	212.6	7.25
2:	392.0	45.95	0.75
3:	187.9839	6.8482	0
4:	31.6695	0.75	
5:	2.396	0	
6:	0.75		

Since all coefficients of the first column are positive, these indicate that the system is stable with PID control.

These results are confirmed and proved the same results which were obtained by phase plane technique (Figure 6). However, the experimental phase plane technique is still the best and accurate method for limit the stability conditions compared with others methods which are needed to solve a set of theoretical complex non-linear differential equations.

Conclusions

1. LABVIEW was the powerful and versatile programming language for operate and control the wastewater treatment system.
2. On-line experimental phase plane technique gave a clear picture of the process paths.
3. Phase portrait was accurate to study and limit the stability conditions of the non-linear wastewater treatment system.
4. For the batch titration condition, the system would be stable for P, PI & PID controllers. PI mode was better than others controllers for pH adjustment.
5. Limits cycle did not appear in the present process.
6. PD control was not suitable for the present system due to the significant process time delay and mixing noise.
7. pH response of the system with IMC method was faster than ITAE criteria to reach the equilibrium point.

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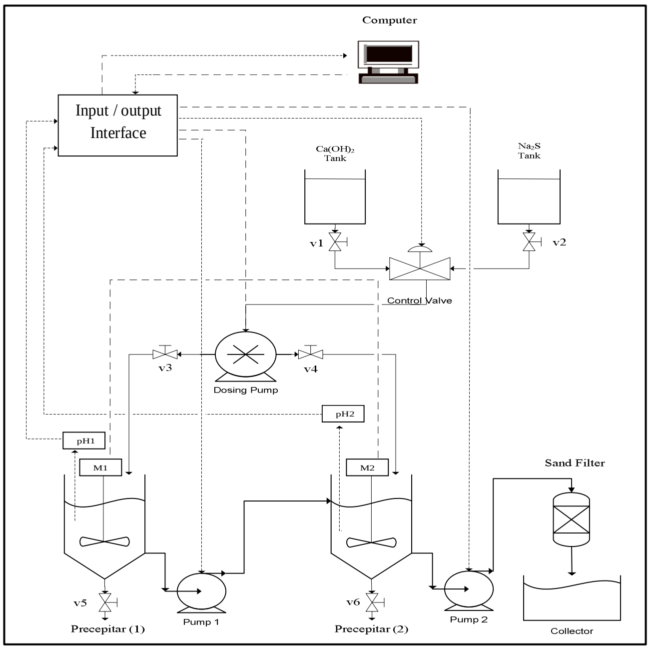
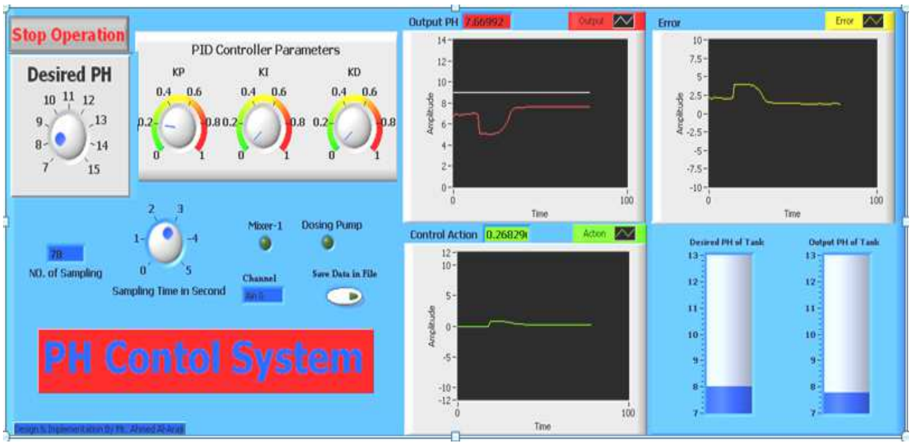
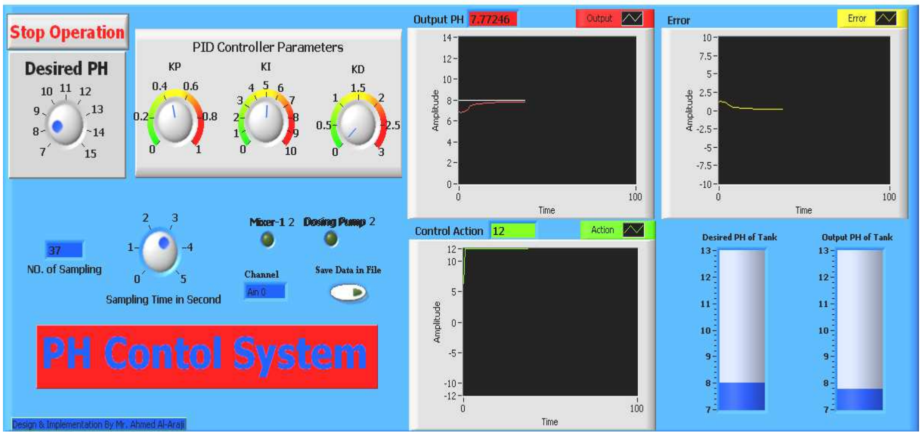


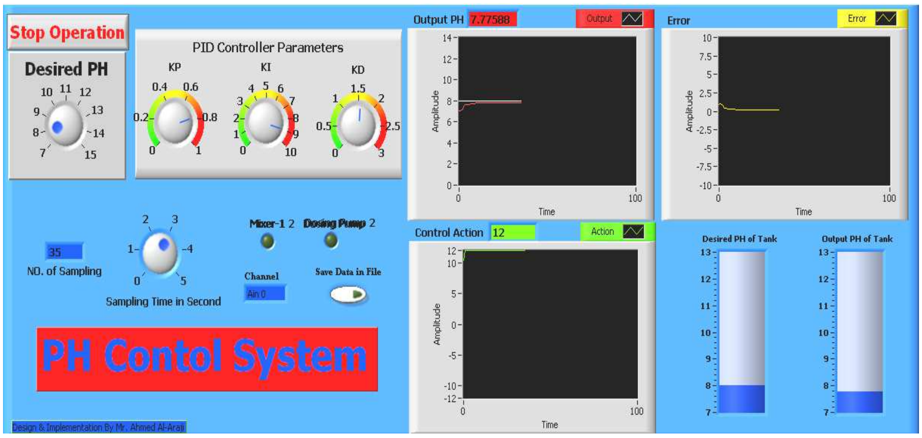
Figure (1): Block Diagram of On-Line Experimental Set-up.



(a) With P- Control



(b) With PI-Control



(c) With PID-Control

Figure (2): Front Panel of Input/output Interfacing with the Virtual Instruments.

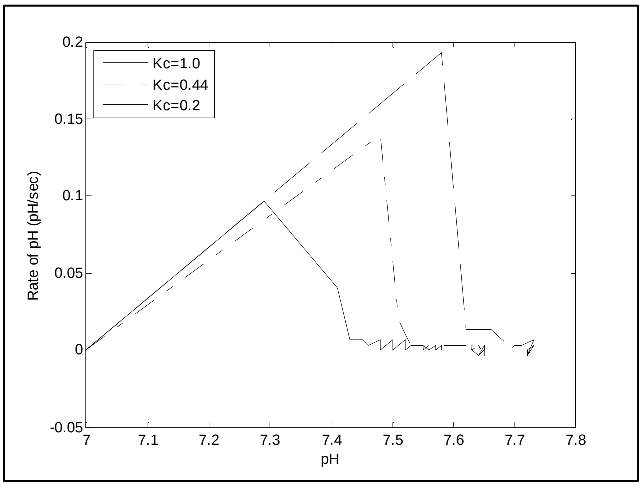


Figure (3): Phase Plane for P-Control.

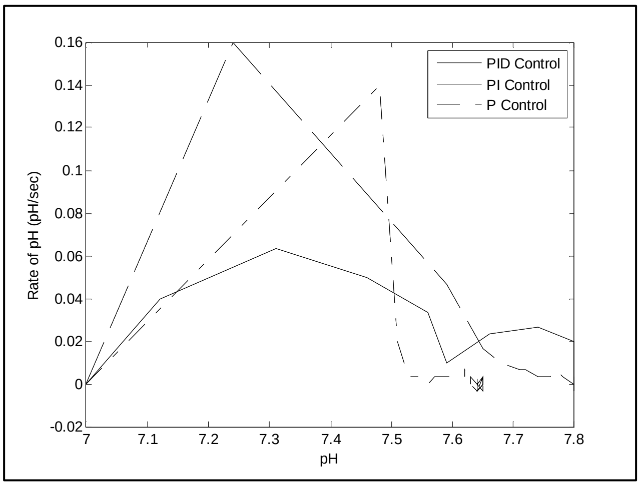


Figure (6): Process Paths of t he System for Different Control Modes.

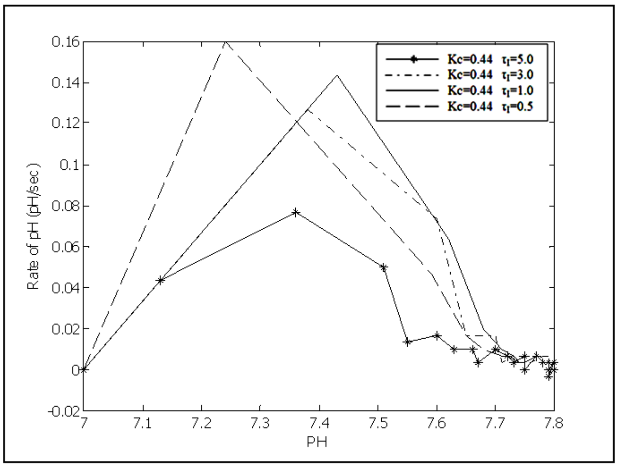


Figure (4): Phase Plane for PI-Control.

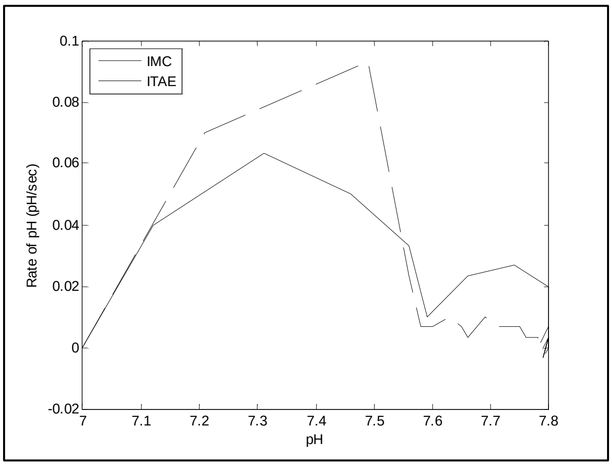


Figure (7): Comparison between the Optimum PID Control using IMC & ITAE Methods.

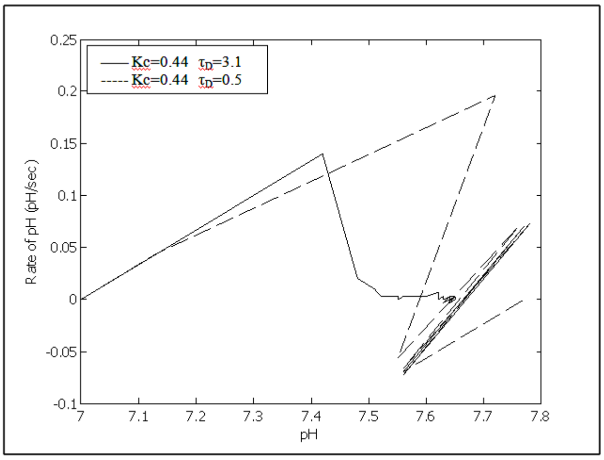
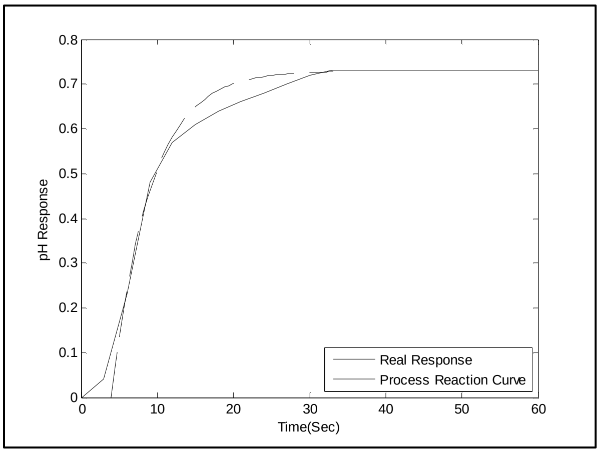


Figure (5): Phase Plane for PD-Control.



Figure(8): Open Loop Response Against +ve 100% Step Change in $Ca(OH)_2$ and Na_2S Flow Rate Solutions.

Table (1): Optimum Control Parameters of PI Action.

Control Tuning Methods	Control Parameters			IAE
	K_c	τ_I	τ_D	
Internal Model Control	0.46	5	-	5.32
Minimum ITAE criteria	0.44	5.5	-	6.20

Table (2): Optimum Control Parameters of PID Action.

Control Tuning Methods	Control Parameters			IAE
	K_c	τ_I	τ_D	
Internal Model Control	0.934	7	1.42	7.68
Minimum ITAE criteria	0.727	7.37	1.25	8.7

Appendix

Computer Program for determining the characteristic equation and Routh array

```
%MATLAB Program
%Study the Stability
%define the Transfer function of process with delay time
clear all, clc
%define the Transfer function of process with delay time
num=[1.606];den=[5 1];
[numdt,dendt]=pade(4,1);
%define the Transfer function of valve
numv=[1];denv=[6 1];
%define the Transfer function of measuring element
numm=[1];denm=[1 1];
[numpdt,denpdt]=series(num,den,numdt,dendt);
[numpv,denpv]=series(numpdt,denpdt,numv,denv);
%Define the adjusted parameter of controller
kc=  ,ti=  , td=  ,
%For PID control
numc=[kc*ti*td kc*ti kc];
denc=[0 ti 0];
%For PI control
numc=[kc*ti kc];
denc=[ti 0];
%For P control
numc=[kc];
denc=[1];
[numol,denol]=series(numpv,denpv,numc,denc);
[numcl,dencl]=feedback(numol,denol,numm,denm);
TFCL=tf(numcl,dencl)
%where the TFCL is Transfer function of close loop
```

```
%For determining the Routh array
a=[((dencl(2)*dencl(3))-(dencl(1)*dencl(4)))/dencl(2)  ((dencl(2)*dencl(5))-
(dencl(1)*dencl(6)))/dencl(2)]
b=[((a(1)*dencl(4))-(a(2)*dencl(2)))/a(1)]
```