Inferential Control of a Wastewater Treatment Unit

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Abstract

Inferential control of a wastewater treatment was studied using Cu element by adding $Ca(OH)_2$ and calculating the pH and concentration of Cu in solution. The semi-batch pH process system dynamically behaved as a first order system with dead time lag using Sundaresan and Krishnaswamy's method. Values of the K, τ and t_d were equal to the 1.62 pH/cm^3 sec^{-1}, 3 sec, 1sec respectively for measured variable while -13.76 mg L^{-1}/cm^3 sec^{-1}, 2 sec and 1 sec for unmeasured variable. The tuning of control parameters was carried by Internal Model Control (IMC). The Integral of Absolute of Error (IAE) criteria was used to determine initial values of proportional gain (K_c) and Integral time constant (τ_I) for PI controller where the value of Kc and τ_I were equaled to 1 mv /pH and 3 sec respectively. LabVIEW technique was used in control and data acquisition while MATLAB program was used in simulation work.

Keywords: Inferential Control, pH Control, LABVIEW, MATLAB.

السيطرة الاستدلالية لوحدة المعالجة المياة الثقيلة

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الخلاصة

تم دراسة نظام السيطرة بالاستدلال على الحامضية لوحدة معالجة المياه الصناعية و ذاك من خلال استخدام عنصر Cu و بواسطة اضافة $Ca(OH)_2$ و حساب الحامضية و التراكيز لمادة Cu حيث ان العملية شبه مستمرة ديناميكياً و من الدرجة الاولى مع وجود اعاقة زمنية باستخدام طريقة Sundaresan and Krishnaswamy's method . وجدت قيم K, τ and t_d مساوية الى $1.62\ pH/cm^3\ sec^{-1}$, 3 sec, 1sec حسب الترتيب بالنسبة الى المتغير المقاس بينما $-13.76\ mg\ L^{-1}/cm^3\ sec^{-1}$, 2 sec and 1 sec على الترتيب بالنسبة اللى المتغير الغير مقاس . تم توصيف مؤشرات السيطرة بطريقة Internal Model Control لايجاد قيم الابتدائية للمعاملات نظام السيطرة من نوع PI controller حيث وجت قيم Kc و τ_Iمساويا الى 1 mv /pH، 3 sec على الترتيب. تم استخدام معيار الخطا المطلق (IAE). تم استخدام برنامج LABVIEW 8.2 في جمع المعلومات و السيطرة على المنظومة عمليا في حين تم استخدام برنامج MATLAB 7.10 للمحاكاة نظريا.

الكلمات المفتاحية: السيطرة الاستدلالية، السيطرة على الحامضية، LABVIEW , MATLAB .

Nomenclature

A	Magnitude of step change	[cm^3/sec]
E	Error in pH (pH set value – pH measured)	[pH]
F	Flow rate of chemicals additives (cu^{+2})	[cm^3/sec]
$G_c(s)$	Transfer function of controller	[mv/pH]
$G_L(s)$	Transfer function of load	[–]
$G_m(s)$	Transfer function of measuring element	[mv/pH]
$G_{p1}(s)$	Transfer function of unmeasured controlled output	[mg L^{-1}/ cm^3 sec^{-1}]
$G_{p2}(s)$	Transfer function of measured controlled output	[pH/ cm^3 sec^{-1}]
$G_v(s)$	Transfer function of valve	[cm^3 sec^{-1}/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_I	Integral time	[sec]

List of Abbreviations

IMC	Internal model control
IAE	Integral of Absolute of Error
PI	Proportional-Integral
LabVIEW	Laboratory Virtual Instrument Engineering Workbench

Introduction

It is important to emphasize that the success on an inferential control scheme depends heavily on the availability of a good estimator. This is turn depends on how well the process was known. This if the process transfer functions G_{p1}, G_{p2}, G_{d1} and G_{d2} are perfect known. In chemical process control the variable that is most commonly inferred is composition. This is due to the lack of reliable, rapid, and economical measuring devices for a wide spectrum of chemical systems. Thus inferential control may be used for control of chemical reactors, distillation columns, and other mass transfer operations such as driers and absorbers. (1)

In many processes, pH neutralization is a very fast and simple reaction. In terms of practical control, it is recognized as a difficult control problem (Shinskey 1973; Pishvaie et al. 2000; Wright et al. 1991). The difficulties arise from high process nonlinearity (the process gain can change tens or hundreds of times over a small pH range) and from changes in the pH characteristics due to changes in influent concentration. Various techniques have been developed to control process pH. Young and Rao (1986) presented a variable structure controller ("sliding mode control for a neutralization process") involving strong acids and bases. Parrish and Brosilow (1988) used non-linear inferential control in a simple simulated neutralization process, using static estimation of the concentration of a single monoprotic weak acid. Kulkarni et al. (1991) presented non-linear internal model control for a simulated system of sodium hydroxide (NaOH) and hydrochloric acid (HCl). Li et al. (1990a) and Li and Biegler (1990b) presented non-linear feedback methods for a simulated neutralization process. (2)

The need for pH control in chemical and biological processes has arisen significantly in industries such as wastewater treatment, electro-hydrolysis, pharmaceuticals and many other industrial plants. Due to highly nonlinear characteristics, time-varying nature, variations in titration curve and inaccessible state measurements, pH control is a challenging problem. Consequently, pH control is considered as a benchmark for modeling and control of highly nonlinear processes. To apply a model-based control scheme, availability of an accurate process dynamic model is inevitable. McAvoy, Hsu, and Lowenthal (1972) derived a mathematical model from material balance and chemical equilibria. Gustafsson, Skrifvars, Sandström, and Waller (1995) proposed a pH model for control purposes that takes into account several phenomena such as precipitation and formation of chemical complexes. Wright and Kravaris (1991) introduced the strong acid equivalent concept and used it for pH control. Since pH process has a nonlinear dynamic, standard linear control techniques are not suitable for controlling this type of process. [3]

The control of pH is a very important problem in many processes, particularly in effluent wastewater treatment. The development and solution of mathematical models of these systems is, therefore, a vital part of chemical engineering dynamic modelling. [4]

The most common composition loop is pH: it is controlled in wastewater-treatment plants, chemical processes of various types, metal-finishing operations. All of these measurements use electrodes which report ion concentration on a logarithmic scale, giving these loops a special character not found in others.

The control of pH is common in chemical process and biotechnological industries. For instants, the pH of effluent streams from wastewater treatment plants must be maintained within stringent environment limits, high performance and robust pH control is often difficult to achieve due to nonlinear and time-varying process characteristics. [5]

The process includes calculation of pH, reaction Cu metal ions with hydroxide ($Ca(OH)_2$). The goal of the water treatment plants is to remove organic matter and to reduce the water's nitrogen content to less than 20 mg/l in all forms. Precipitation is the process used to remove soluble metal ions from solutions as hydroxydes. The process is pH controlled. By raising the pH with lime or sodium hydroxide, the corresponding metallic oxide precipitates out. Figure (1) shows the solubility curves of some heavy-metal hydroxides as a function of the pH of the solution.

As can be seen in Figure (1), copper at a pH of 6 will start precipitating from the solution at a concentration of about 20 mg/l, while if the pH is raised to 8, its solubility drops to 0.05 mg/l. Several metals such as chromium and zinc are amphoteric, being soluble at both alkaline and acidic conditions. [6,7]

Inferential Control

The block diagram of the semi-batch pH process is shown in Figure (2.a). in this diagram the unmeasured controlled output (y), one secondary measured output (z) affected by the manipulated variable m and disturbance d. The disturbance is considered to be unmeasured. The transfer functions in the block diagram indicate the relationships between the various inputs and outputs, and they are assumed to be perfectly known.

From Figure (1.a) the input-output relationships were easily driven as the following:

$$\overline{y} = G_{p1}\overline{m} + G_{d1}\overline{d} \quad (1)$$

$$\overline{z} = G_{p2}\overline{m} + G_{d2}\overline{d} \quad (2)$$

Equation (2) can be solved with respect to $\overline{d}$ to find the following estimate on unmeasured disturbance.

$$\overline{d} = \frac{1}{G_{d2}}\overline{z} - \frac{G_{p2}}{G_{d2}}\overline{m} \quad (3)$$

By substituting the estimate above into Equation (1) and find the following relationship:

$$\overline{y} = \left[G_{p1} - \frac{G_{d1}}{G_{d2}}\right]\overline{m} + \frac{G_{d1}}{G_{d2}}\overline{z} \quad (4)$$

The Equation (4) provides the needed estimator which relates the unmeasured controlled output to measured quantities like m and z. Figure (2.b) shows the structure of the resulting inferential control system. Notice that the estimated value of the unmeasured output plays the same role as a regular measured output; that is, it is compared to the desired set point and the difference is the actuating signal for the controller. (1)

In many plants, the variable of interest cannot be measured continuously, accurately, or quickly enough for adequate closed-loop control. Often a secondary variable is used as an inferential measure of the first, simply because it is the best available. In a case like this, however, product quality may suffer both from poor control of the inferential variable and from its indifferent relationship to the primary variable. (1)

One could also try to estimate the quality ("inferential control") by using a suitable algorithm that uses conventional measured values of temperature, pressure, etc. A simple example is the pressure compensation of temperature measurements on the tray of a distillation column. For binary mixtures this yields a measure of the composition, for a multi-component system it is an approximate measure of the composition. (8)

In some control application, the process variable that is to be controlled cannot be conveniently measured on-line, for example, product composition measurement may require a sample be sent to the plant analytical laboratory from time to time, in this situation, measurements of the controlled variable may not be available frequently enough or quickly to be used for feedback control. One solution to this problem is to employ inferential control, where process measurements that can be obtained more rapidly are used with mathematical model sometimes called a soft sensor to infer the value of the controlled variable (see Figure (3)). [9]

LabVIEW Techninque

LabVIEW is a graphical programming language that uses icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine program execution, it uses dataflow programming, where data determine execution. A user interface was built by using a set of tools and objects. The user interface is known as the front panel then adding code using graphical representations of functions to control the front panel objects. The block diagram contains this code. If organized properly, the block diagram resembles a flowchart. This technique:

- empowers to build solutions for scientific and engineering systems.
- gives the flexibility and performance of a powerful programming language without the associated difficulty and complexity.
- gives thousands of successful users a faster way to program instrumentation, data acquisition, and control systems.
- is using to prototype, design, test, and implement instrument systems, system development time could be reduced and increased productivity by a factor of 4 to 10.
- gives the benefits of a large installed user base, years of product feedback, and powerful add-on tools. [10]

As a programming language, it is a powerful tool that can be used to help achieve these goals. LabVIEW is a graphically-based programming language developed by National Instruments. Its graphical nature makes it ideal for test and measurement, automation, instrument control, data acquisition, and data analysis applications.

Virtual Instrument (VI) is a programming element. A VI consists of a front panel, block diagram, and an icon that represents the program. The front panel is used to display controls and indicators for the user, while the block diagram contains the code for the VI. The icon, which is a visual representation of the VI, has connectors for program inputs and outputs.

LabVIEW systems are implemented in test and measurement, as well as process monitoring and control applications throughout the world. These applications vary widely from transportation systems monitoring, to university laboratory classes; from automated parts testing to industrial process control. (11)

In this work, this technique is used to control the pH of neutralization process of treatment unit automatically by on-line digital computer.

Overview of the MATLAB Environment

MATLAB is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation. Using the MATLAB product, technical computing problems could be solved faster than with traditional programming languages, such as C, C++, and FORTRAN.

This program could be used in a wide range of applications, including signal and image processing, communications, control design, test and measurement, financial modelling and analysis, and computational biology. Add-on toolboxes (collections of special-purpose MATLAB functions, available separately) extend the MATLAB environment to solve particular classes of problems in these application areas. (12)

It provides a number of features for documenting and sharing work. MATLAB code could be integrated with other languages and applications, and distributed algorithms and applications.

Process Description

As shown in Figure (4), a stirred tank vessel (Precipitator) of one litre capacity consists wastewater at concentration (C) with manipulated stream at a given flow rate (F). The pH of the mixed solution is measured by a glass electrode and transduced to the control which manipulates the base flow rate by a control valve. All signals of input and output between process and controller and date acquisition were bone using computer with LabVIEW technique. The experimental rig was designed to simulate the real process and collect the desirable data. The process consists of mainly equipments:

1. Mixing tank.
2. Chemical reagent storage for $Ca(OH)_2$.
3. Dosing pump.
4. pH glass electrode probe.
5. Motorized control valve.
6. Inputs/output interface system.
7. Computer.

Experimental Procedure

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

The desired (value) was the pH which represent the key factor for efficient treatment, so that it was monitored and controlled by manipulating the base stream of $Ca(OH)_2$ (Input variable). The pH of the wastewater was controlled within the natural to slightly alkaline range (pH 7.8) as explained in the scientific report. [(4)]

Dynamics Behavior

1. The LabVIEW program (Version 8.2) was designed to operate and control the system.
2. Filling the precipitator with one litre of the wastewater at the initial conditions of pH 7 and 25 ^{o}C.
3. Creating 100% step change in inlet flow rate (0.45 cm^3/sec) of $Ca(OH)_2$ by the manual valve V_1.
4. When reaching to the steady state value (pH 7.73), the system was automatically shutdown.
5. Recording & plotting the pH of wastewater into tank as function of time.

Control Behavior

1. Selecting the values of controller's parameters (K_c & τ_I) by directly tuning the desired knobs in the front panel appeared on the monitor.
2. Filling the precipitator with the wastewater at initial conditions of pH 7 and 25 ^{o}C (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.

Fitting of a first order plus time delay model

Sundaresan and Krishnaswamy's Method

The advantage of this method avoids use of the point of inflection construction entirely to estimate the time delay.

They proposed that two times, t_1 and t_2, be estimated from a step response curve, corresponding to the 35.3% and 85.3% response times, respectively. The time delay and time constant are then estimated from the following equations:

$$t_d = 1.3t_1 - 0.29t_2 \qquad (5)$$

$$\tau = 0.67(t_2 - t_1) \qquad (6)$$

These values of t_d and τ approximately minimize the difference between the measured response and the model, based on a correlation for many data sets. By using actual response data, model parameters k, θ and τ can vary considerably, depending on the operating conditions on the process, the size of the input step change and direction of the change. These variations usually can be attributed to process nonlinearities and unmeasured disturbances (see Figure (5)). (8)

Internal model control (IMC) method is used to find the optimal values of controller for PI feedback systems shown in Table (1). (13)

The development of IMC had begun since the late 1950s in order to design an optimal feedback controller. The first to utilize the structure of a model parallel to the process is Frank in 1974 [Brosilow and Joseph, 2002]. Then, Gracia and Morari [1982 & 1985] had introduced the IMC structure with distinct theoretical framework and application in a multivariable system. The IMC consists of three parts [Garcia and Morari, 1982]: (1) Internal Model: to predict the process response in an attempt to adjust the manipulated variable to achieve control objective; (2) Filter: to achieve certain robustness in controller design; (3) Control algorithm: to calculate the future values of manipulated variable so that the process output is within the desired value. (14)

An optimization technique was used to determine the optimum values of the controller parameters (K_C and τ_I) to give the minimum integral square of error (IAE). (15)

A suitable performance index is the integral of absolute of error, which is defined as:

$$IAE= \int_0^t |E|\, dt \quad (7)$$

The performance index of Equation (7) is easily adapted for practical measurements because an absolution is readily obtained. Furthermore, the squared error is mathematically convenient for analytical and computational purposes.

As in Equation (7), the IAE means the area under the curve between the absolute error and the time.

Results and Discussion

Because of difficulty of measuring the concentration of Cu in the solution on line, the measuring the pH of the solution was considered with aid of Figure (3) to find the values of concentration as well as to find the transfer function between the concentration and the flow rate as shown the Figures (6-a & 6-b).

It is difficult to formulate and identify a mathematical model for the pH process as small as amount of polluting element will change the process dynamics considerably [16].

The pH process was to be considered as a semi batch process with fast reaction and the pH response yield sigmoidal shape curve [17]. Precipitation was poorly known phenomenon and it was difficult to derive an accurate model [18].

The semi batch pH system is a nonlinear unsteady state process, which have several steady state (equilibrium) points at each interval of time due to the change of the tank hold up.

In this work, assumptions include perfect mixing, constant density and complete solubility of the ions involved. The concentration (C) of Cu was unmeasured controlled variable and the pH of wastewater was the measured controlled variable while the flow rate (F) of $Ca(OH)_2$ was input (manipulated) variable.

According to the Equations (5 & 6) and Figures (7-a & 7-b), the values of t_1, t_2, t_d and τ are as the following calculations:

For the pH,

t_1=2.3 sec & t_2=6.8 sec

t_d = 1.3(2.3)-0.29(6.8) = 1 sec

τ=0.67(6.8-2.3) = 3 sec

$A = 0.45\ cm^3/sec$

ultimate value of pH (B) = 0.73 pH

$K = B/A = 0.73/0.45 = 1.62\ pH/cm^3\ sec^{-1}$

While for the Cu concentration,

t_1=1.8 sec & t_2=4.8 sec

t_d = 1.3(1.8)-0.29(4.8) = 1 sec

τ=0.67(4.8-1.8) = 2 sec

ultimate value of pH (B) = -6.24 mg L^{-1}

$K = B/A = -6.24/0.45 = -13.76\ mg\ L^{-1}/cm^3\ sec^{-1}$

Therefore, the transfer function of unmeasured outputs has the form as the following:

$$G_p(s) = \frac{K}{\tau s+1}\, e^{-t_d s} \qquad (8)$$

Or

$$G_{p1}(s) = \frac{C(s)}{F(s)} = \frac{-13.76}{2s+1}\, e^{-1s} \qquad (9)$$

While the transfer function of measured Output is:

$$G_{p2}(s) = \frac{pH(s)}{F(s)} = \frac{1.62}{3s+1}\, e^{-1s} \qquad (10)$$

From technical sheets of the instruments, the transfer functions of pH electrode and control valve are:

$$G_m(s) = \frac{1}{s+1} \qquad (11)$$

$$G_v(s) = \frac{1}{6s+1} \qquad (12)$$

From Figures (6-a & 6-b), it is clear that the response of the process is dynamically behaved as a first order lag system with dead time. Dead time for both systems (G_{p1} & G_{p2}) were because of combining; pH-electrode lag, computer interface lag and bad mixing. The dynamic lags of the process caused sluggish control.

LabVIEW Technique was used in dynamic behaviour to collect the data that represent the relationship between the pH and time in order to fit and find the transfer functions.

MATLAB program was used to fit the data of pH response using Sundaresan and Krishnaswamy's Method to find the values of t_1, t_2, t_d and τ in order to find transfer functions of measured and unmeasured outputs according to inferential control. (See Appendix)

Parameters (K, τ & t_d) depends on nature of process (flow rate, mixing and pH…etc). These parameters are very important to obtain the optimum settings of the PI control using control tuning method.

IMC method was desirable method to find the initial control parameter in order to give the good specification in control system such as time constant, reducing time response and less over shoot. In this work, PI control system was used, the results are in the Table (2), and Derive action is not included in the controller because of the pH measurement time delay. [(9)]

Since the system was unsteady state semi-batch process because there are not outputs in this type of the process, so that the dynamics characteristic could be varied with time. It is difficult to be determined theoretically.

In this work, for control system, by measuring the pH response, it can measure the concentration depending on the mathematical model between the pH response and the concentration for Cu. Table (2) refers to the initial values of control parameter that obtained using IMC method and IAE value refers to the how these values are suitable for the process The performance of a tuned PI with IMC parameters was not satisfactory due to nonlinear characteristic of the process [(19)].

Generally, PI mode is the fast and with low deviation [(18, 19)] among the others controls schemes in pH control. Therefore, it was used as shown in Figure (8).

Figure (9) shows the block diagram of the process for both measured and unmeasured variables as well as controller, control valve and measuring element.

All these data were collected using LabVIEW technique and MATLAB program was used for tuned values of control parameters (see appendix)

Conclusions

1. A wastewater Treatment by hydroxyde Precipitations is active for the heavy metals.
2. Inferential control was suitable to compute the immeasurable data that is difficult to be measured on-line.
3. Sundaresan and Krishnaswamy's Method was more accurate to derive the dynamic model of the nonlinear unsteady state pH process because avoiding the inflection point.
4. The pH process was dynamically behaved as a first order system with dead time lag.
5. LabVIEW was the powerful and versatile programming language for operate and control the wastewater treatment system and MATLAB is interactive environment for algorithm development, data analysis, and numeric computation.

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Table (1): Tuning Relations Based on IMC [10]

Process Model	Controller	K_c	τ_I
$\frac{K_p e^{-t_d s}}{\tau_p s + 1}$	PI	$\frac{\tau_p}{k_p\ (\tau_c + t_d)}$	τ_p

Table (2): Initial control parameters of PI controller

Control Tuning Method	Control Parameters		IAE
	K_c	τ_I	
Internal Model Control	1	3	0.4

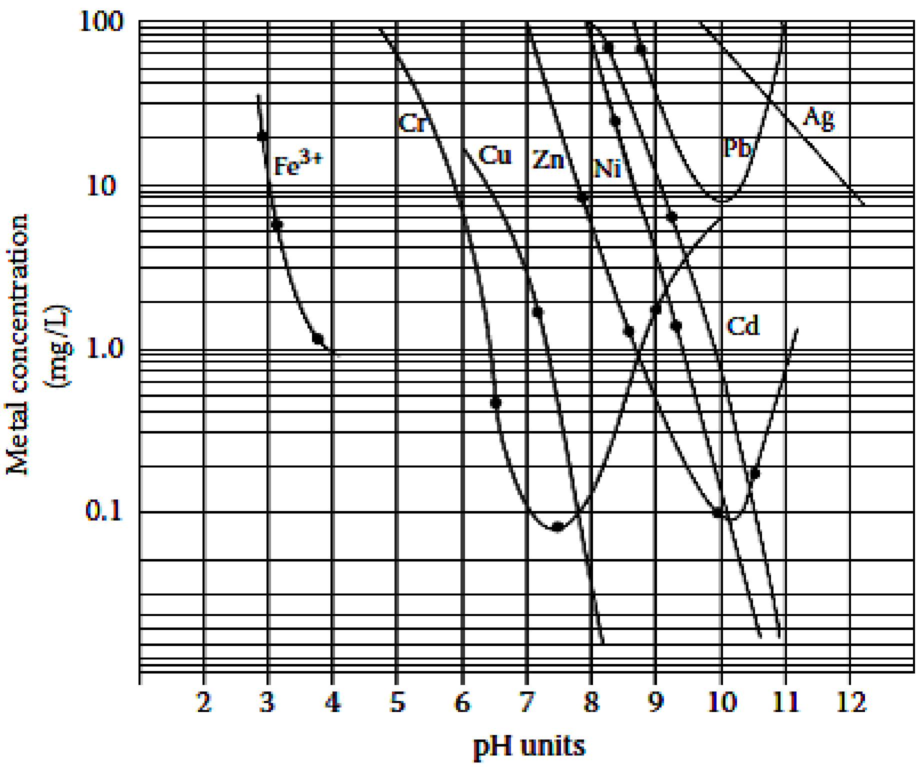


Figure (1): Solubility curves of a number of metal hydroxides at various concentrations as a function of the pH of the solution. (Courtesy of Hoffland Environmental Inc.). [7]

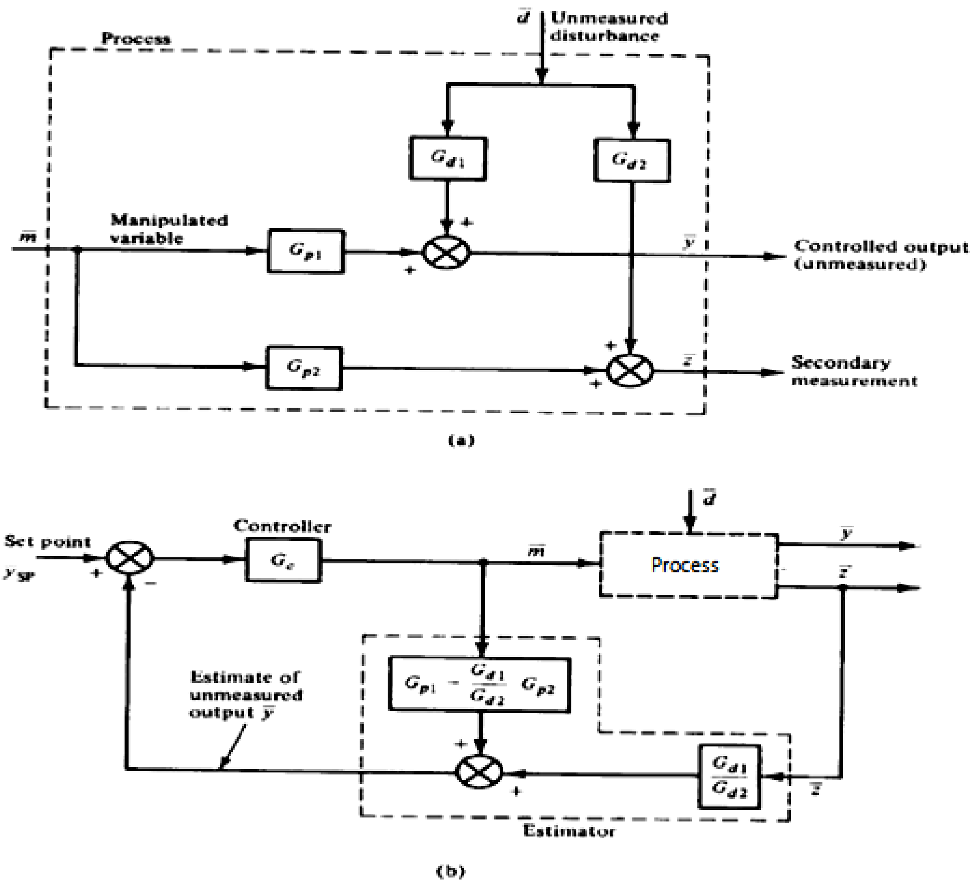


Figure (2): (a) Process with need for inferential control: (b) corresponding inferential control system.[1]

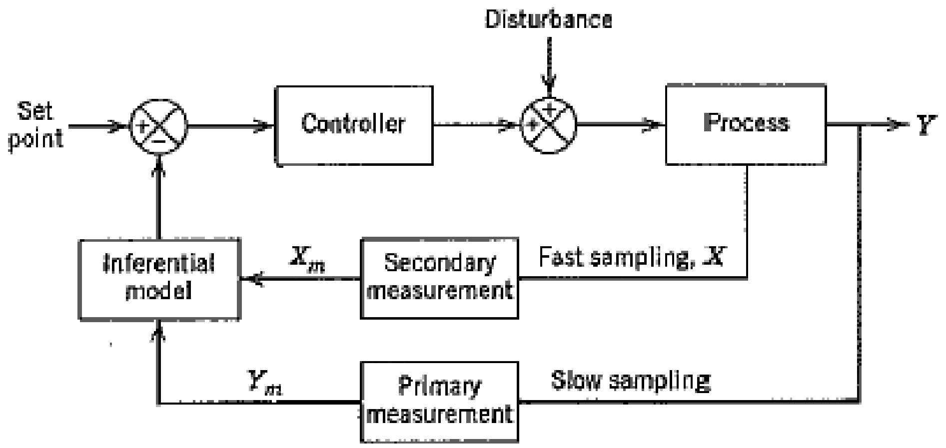


Figure (3): Soft sensor used in inferential control.[6]

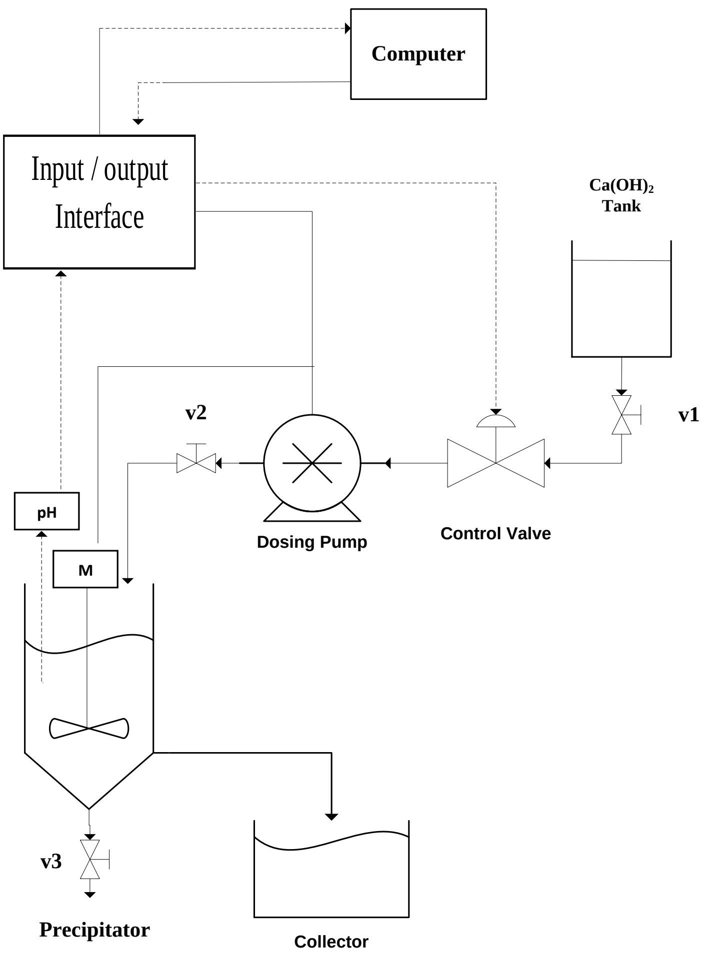


Figure (4): Schematic Diagram of On-Line Experimental Work.

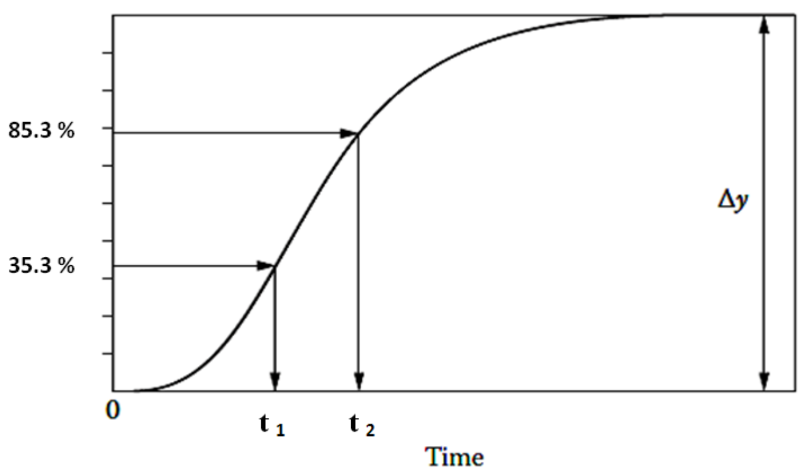
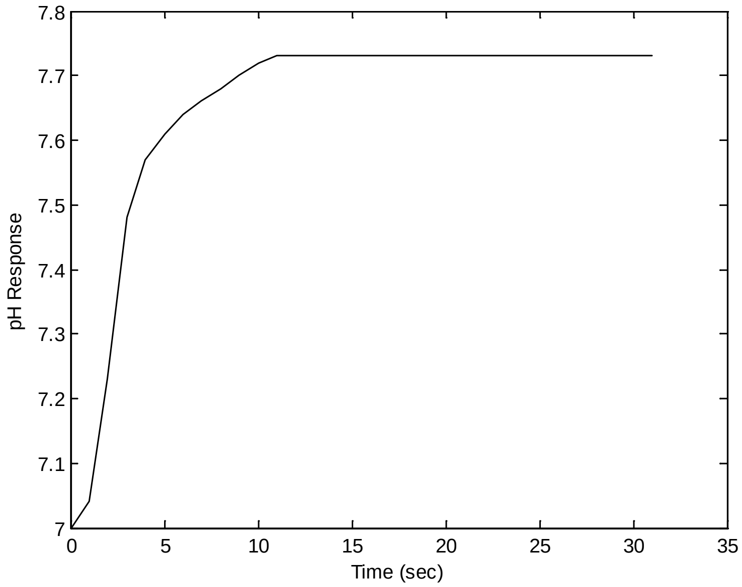
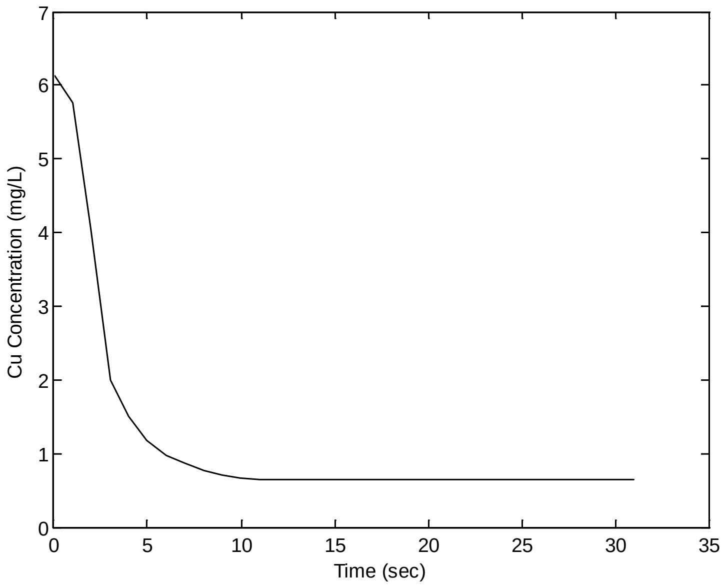


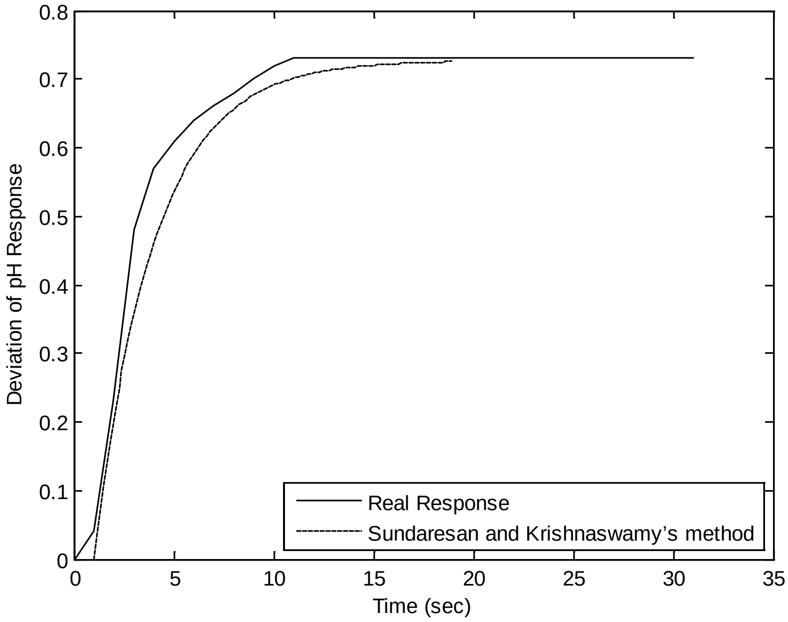
Figure (5): diagram of Sundaresan and Krishnaswamy's Method.[2]



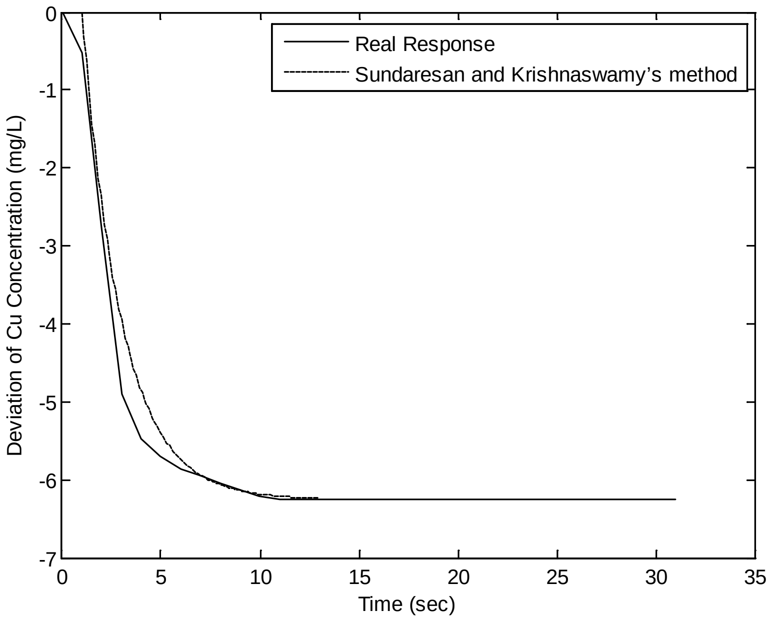
Figure(6-a): pH response with time in dynamic behavior.



Figure(6-b): Concentration response of Cu with time in dynamic behavior.



Figure(7-a): Deviation of pH response in dynamic behavior.



Figure(7-b): Deviation of Cu concentration response in dynamic behavior.

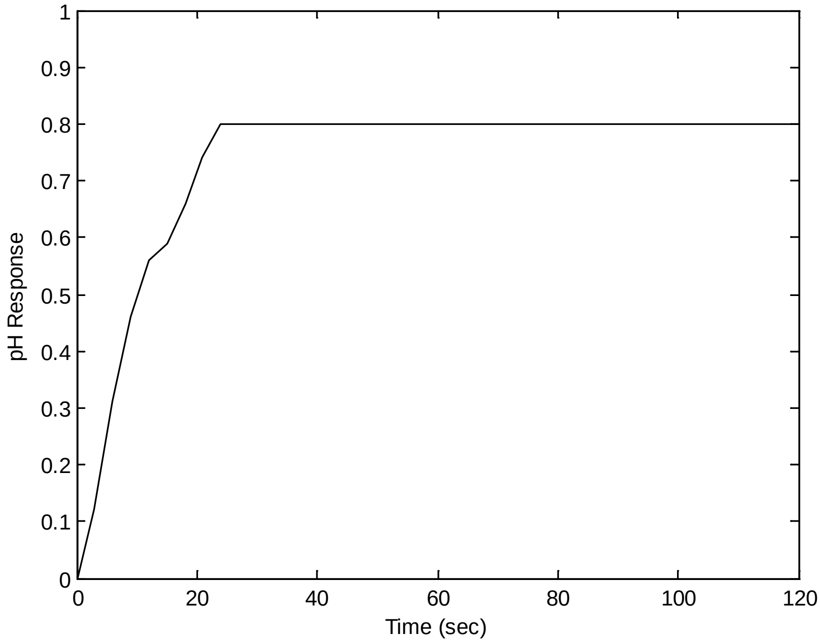


Figure (8): Control behaviour of pH using PI control.

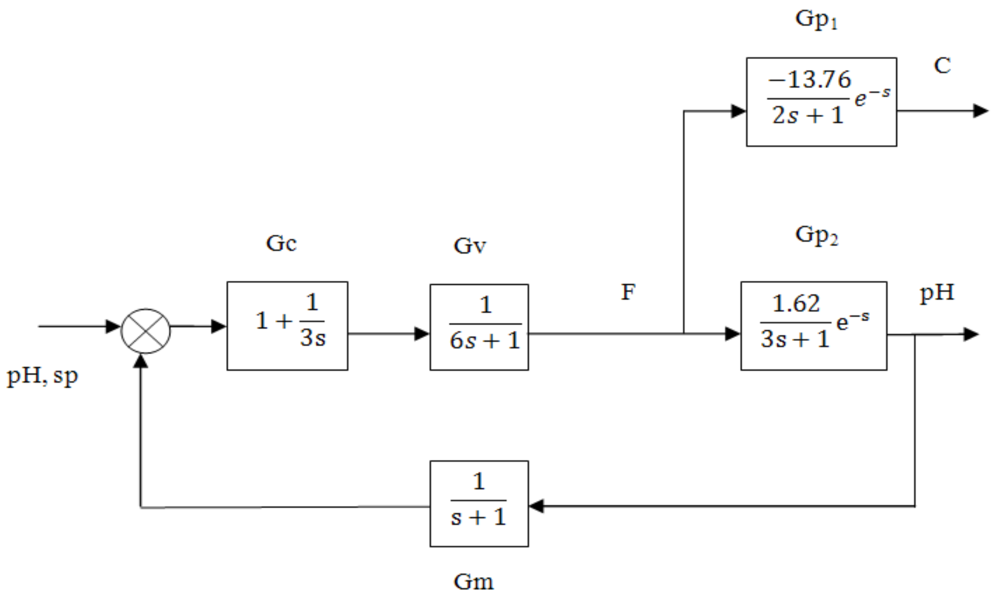


Figure (9): Diagram of control system for the process.

Appendix

MATLAB Program

```
%MATLAB program for open loop
pH=[ 0 0.04 0.23 0.48 0.57 0.61 0.64 0.66 0.68 0.7 0.72 0.73 0.73 0.73 0.73 0.73 0.73
0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.73];
t=[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
30 31 ];
figure(1) ,Plot(t,pH, 'k- '), xlabel('Time (sec)'),ylabel('pH Response')
%MATLAB program for control system (closed loop)
%Control Tuning using Internal Model Control (IMC) for PI controller
 %Define the Transfer function of process with delay time and measuring element
num=[1.62 ];,den=[3  1];,[numdt,dendt]=pade(1,1);
[nump,denp]=series(num,den,numdt,dendt);
numm=[ 1];,denm=[1  1 ]; ,k=1.62   , Tau= 3
%Calculation the adjusted parameter of PI controller
Tauc=(2/3)*td ,kc=Tau/(k*(Tauc+td)) ,ti=Tau
numc=[kc*ti  kc];,denc=[ti 0];,Gc=tf(numc,denc)
%then do colsed loop
numm=[1],denm=[1  1], numv=[1],denv=[1  1]
[numol,denol]=series(num,den,numc,denc);,Gol=tf(numol,denol)
[numcl,dencl]=feedback(numol,denol,numm,denm);
TFCL=tf(numcl,dencl) ,%where the TFCL is T.F. of close loop
[y,x,t]=step(numcl,dencl);
%plotting the step response of close loop
figure(2) ,plot(t,y,'k-'),xlabel('Time (sec)'),ylabel('pH')
%find error then IAE
```