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Determination of optimal PID control parameters by response surface methodology

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ABSTRACT

Proportional–Integral–Derivative (PID) controllers are the most widely used systems in industrial applications and in academic research regarding control engineering. In this study, the optimal PID control parameters of a liquid level control system were determined with Response Surface Methodology. Dynamic analysis was carried out on the liquid level control system to prepare the reaction curve. Accordingly, dead time, time constant and process gain values were determined as 16s, 261s and 0.842, respectively. Based on the dynamic analysis, PID parameters were calculated in accordance with the Cohen-Coon, Ziegler-Nichols, Yuwana-Seborg methods, which are the commonly used tuning methods. The Kp, τ_I, τ_D parameters were calculated as 30.77, 29.15 and 5.4 with the Cohen-Coon method, as 0.453, 30.0 and 7.5 with the Ziegler-Nichols method and as 1.63, 686.3 and 117.7 with the Yuwana-Seborg method, respectively. The PID control parameters applied for the 40cm, 50cm and 60cm set points and ISE and IAE control performance values after experiments were calculated. The Kp, τ_I and τ_D values were selected as the independent parameters, while the ISE and IAE values were chosen as the dependent variables. The numerical values of the responses for the runs in the design matrices were determined with a closed-loop PID controller with the liquid level system block diagram that was designed in MATLAB/Simulink. The simulations proposed by the trial version of Design Expert 7.0 program were performed in order and the IAE and ISE values were calculated after the simulations were processed. In this study, minimum ISE and IAE values were selected to determine the best PID parameters of a liquid level control system. The optimal PID control parameters of the liquid level system required to obtain the lowest ISE and IAE values were determined as 23.14, 28.31 and 11.50 for Kp, τ_I and τ_D, respectively.

1. Introduction

PID controllers are the most commonly used systems in the industrial field including motor drives, magnetic and optical memories, automotive and flight control, instruments and meters, robotics, and find the most research and application area in control engineering [1]. PID controller is successful design in industrial automatic control for its simple structure, stability, reliability and convenient adjustment [2-3]. PID controllers are used as pneumatic, hydraulic or mechanical controllers or had a simple interface for manual tuning of the controller. PID control output is generated by the addition of three terms called proportional, which depends on the current error, integral, which depends on the sum of past errors and derivative, which depends on future errors based on current rate of change of errors (Figure 1). Traditional methods for tuning PID controllers are divided into three categories as formula based, rule based and optimization based tuning methods [4]. Various experimental methods such as the Ziegler-Nichols and Cohen-Coon methods, have been developed to tune PID control parameters and most have been applied to real systems [5-6]. Researchers have projected experimental PID tuning approach grounded upon trial and error approach and procedure response curve approaches. These methods are time-consuming, costly and optimizing by establishing mathematical model considering the specific control mechanism, is convenient and efficient [7]. However, the parameters determined by these methods may not be effective in nonlinear, variable parameter and unstable

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systems. In such cases, it is necessary to determine the optimal control parameters. The advantages of optimal control parameters are independent problems, universal search, high robustness and multi objective orientation. In general, it is difficult to define the "optimality" of a controller, due to the fact that there are several important aspects to consider, such as set-point response, minimum error, disturbance rejection, robustness, input usage and noise sensitivity [8]. Therefore, different optimization techniques have been applied for PID tuning parameters [9].

$$C(s) = \frac{U(s)}{E(s)} = Kp + \frac{\tau_I}{s} + \tau_D s \quad (1)$$

Central Composite Design (CCD) is one of the most useful experimental planning methodologies when there are two or more factors. Thus, CCD can be used to evaluate the optimal values for a set of PID controller parameters (Kc, τ_I, τ_D) that provide the best result to performance criterion, such as the integral of square of error (ISE), integral of the absolute of the error (IAE).

There are several response surface methodology (RSM) applications that are used to determine optimal control parameters. RSM has been applied to optimize PID controller parameters for the pH and electrical conductivity values of a batch electrocoagulation process in which pulp and paper mill wastewater was treated, and to investigate the effects of control action on pollutant removal and energy consumption. ISE, IAE, ITAE and ITSE values are selected as responses which indicators of controller performance [10]. Control of the absorption column was carried out using a PID controller with the affluent water flow to the column corresponding to the manipulated variable and the component (CO_2) concentration in the gas stream effluent to the column corresponding to the controlled variable. The numerical values for proportionality constants Kp, τ_I and τ_D were defined using the experimental design of CCD, the study range of which was defined from an initial estimate. The response variable was selected the ITAE performance criteria. The experimental design runs were performed using simulations in a program developed with MATLAB software.

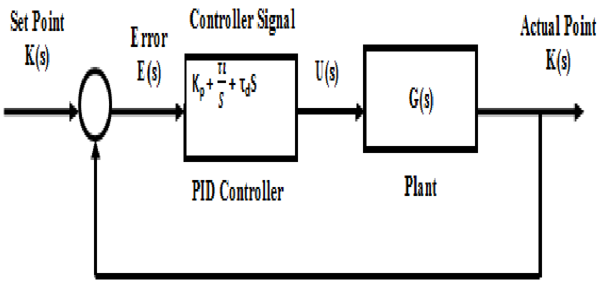

Figure 1. Diagram of feedback control with a PID controller

The responses ranged from 0.1979 to 1.1632, and the lowest value represented approximately 55% improvement in ITAE in comparison to the simulation using the initial estimated values. It was observed that the p-value for the significant terms was much lower than 0.05, which confirmed its significance [11]. The Proportional Integral (PI) control coefficients for a permanent magnet brushless direct current motor drive were determined with RSM. PI control parameters, Kp and τ_I selected input parameters and maximum overshoot with settling time selected responses. A total of 13 experiments were carried out and the optimal values of the Kp and τ_I parameters were obtained as 638.65 and 56.814, respectively. The experimental results were given to show the validity of this method [12].

Liquid level control in tanks and vessels is one of the most common controls in the process industries [13]. Level control is crucial for the successful operation of most chemical plants as the desired production rates and inventories are achieved through the proper control of flows and levels [14]. However, liquid level control is difficult due to problems such as, maximum overshoot, steady-state error and oscillating transient response [15].

The most commonly used performance indexes for PID control are ISE and IAE, which are given Equation (2) and Equation (3), respectively.

$$ISE = \int_0^\infty e(t)^2 dt \quad (2)$$

$$IAE = \int_0^\infty e|(t)| dt \quad (3)$$

In the present study, three different tuning methods applied to the liquid level experimental system under the same conditions and the on-line liquid level results of these tuning methods were compared for different set points. After the experiments, the ISE and IAE values were calculated to determine the optimal PID controller parameters of this experimental system.

2. Materials and Method

2.1 Experimental System

The liquid level control system used in this study consisted of three liquid tanks which built on mechanic assembly, a pneumatic valve connected to a regulator to adjust air pressure, an electronic panel showing liquid level and valve openings and hand valves acting at different points. The water in the storage tank was carried in pvc pipes with a submersible pump, passed through the pneumatic valve and filled into the level measuring tank. To prevent overflow, the level measuring tank was connected to a discharge tank underneath with a pvc discharge pipe located in the middle of the level measuring tank. A manually adjustable valve was located at the bottom of the level measuring tank to affect the disturbance on the system.

Discharge and storage tanks were connected to each other with a pvc pipe to balance the liquid level in them. A discharge valve was connected to the bottom of these tanks to discharge the water in them. The compressed air required for the operation of the pneumatic valve was supplied by a compressor in a laboratory and the air was sent to the valve by adjusting the desired pressure value with a regulator. The experimental liquid level control system is given in Figure 2.

The liquid level control experiments were performed with on-line computer software developed by the manufacturer of this control system. During the on-line experiments on the liquid level control system conducted with this computer software, the valve opening value which was determined as the input variable and the liquid level data which was determined as the output variable were automatically recorded on a Microsoft Excel file. The graphics of the liquid level and valve opening value changes were displayed on screen. In addition, the data acquisition time was be adjusted in seconds. The IAE and ISE values were calculated with three different set level values and measured level values after the on-line experiments. The equations of the PID control parameters for the Cohen-Coon, Ziegler-Nichols and Yuwana-Seborg tuning methods are given in Table 1.

2.2 Experimental Design and Optimization Procedure

Experiments were performed to determine the best PID control parameters for liquid level control. The PID tuning parameters (Kp, τ_I, τ_D) which values were proposed by the program recorded on the liquid level control system and on-line experiments were carried out.

Figure 2. Experimental system: on-line computer connected to the liquid level control system

Table 1. Equations of the PID controller parameters for the three tuning methods

Method	Cohen-Coon	Ziegler-Nichols	Yuwana-Seborg
Kp	$\frac{1}{K_C}\frac{\tau}{t_d}\left(\frac{4}{3}+\frac{t_d}{4\tau}\right)$	Ku/1.7	$\frac{a}{K_m}\left(\frac{d_m}{\pi_m}\right)^{-b}$
τ_I	$t_d\frac{32+6(t_d/\tau)}{13+8(t_d/\tau)}$	Pu/2.0	$\tau_m c+\left(\frac{d_m}{\tau_m}\right)^{d}$
τ_D	$t_d\frac{4}{11+2(t_d/\tau)}$	Pu/8.0	$\tau_m e\left(\frac{d_m}{\tau_m}\right)^{f}$

All other operating conditions were kept constant while the values of Kp, τ_I and τ_D were changed during the liquid level control experiments. It was expected that the liquid levels would be at a steady state by initially operating the valve opening at 10% for 300 s. At the end of 300s, the previously recorded Kp, τ_I and τ_D parameters were changed with the keys on the control panel of the experimental system and the effects of these PID parameters were observed on the liquid level control. During the experiments, liquid level and valve opening changes were continuously monitored and the values of these input and output variables were continuously recorded in seconds. The ISE and IAE values were calculated for different set level values and measured level values after the on-line experiments.

3. Results and Discussion

3.1 Dynamic Analyses for Determining the Process Parameters

Two different dynamic analyses were carried out on the liquid level control system to determine the PID control parameters.

In the first dynamic analysis, an experiment, in which a step change was applied to the valve value to prepare the reaction curve and determine the dead time, time constant and process gain values, was performed. The system was initially operated at 13% valve value and liquid level was expected to become steady state. A positive effect was given to the valve value and 70% valve opening value is provided. The liquid level that was fixed at 10 cm at the first valve value was observed to increase to 58 cm after the step change was applied to the valve value (Figure 3). The PID control parameters were calculated in accordance with the equations of the Cohen-Coon and Ziegler-Nichols methods using control coefficients that were determined from the first dynamic experiment given in Table 2.

Table 2. Coefficients of the experimental liquid level system

Parameter	τ_d	τ	Kc
Value	16s	261s	0.842

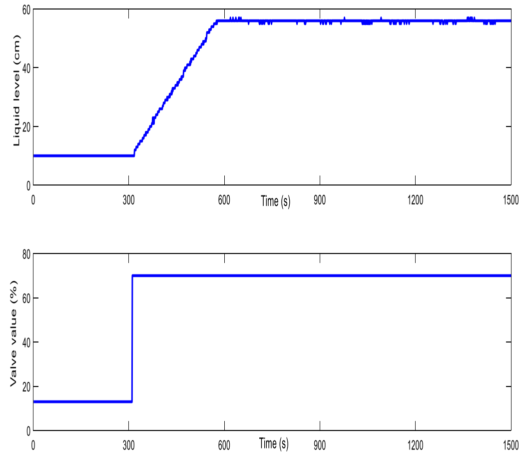

Figure 3. Liquid level changes in accordance with the step effect of valve position

In the second dynamic analysis, a proportional control value was determined by taking the integral and derivative terms as zero and a step effect was given to the set point when the system was under this proportional control action. The output variable was oscillated by changing the proportional control value. The process parameters were calculated by the oscillation of the output variable. The system was initially operated at a 13% valve value and the liquid level was fixed at 10 cm. The output variable was oscillated by changing the proportional control action after the integral and derivative terms as zero. The liquid level changed between 27 cm and 72 cm in the measuring (upper) tank (Figure 4). The PID control parameters were calculated in accordance with the equations of the Yuwana-Seborg method using control coefficients that were determined from the second dynamic experiment given in Table 3.

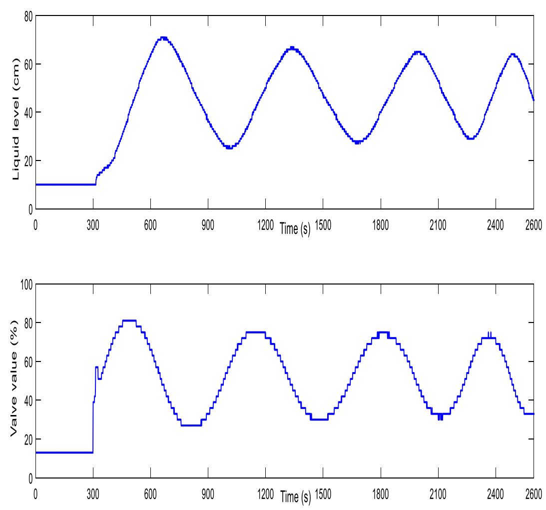

Figure 4. Liquid level changes with valve value for calculate Yuwana-Seborg constants

Table 3. Control coefficients calculated in accordance with the Yuwana-Seborg method

Parameter	Value	Parameter	Value
R_0	13 %	α_1	-0.177
R	70 %	σ	0.605
C_0	10 cm	K_m	58.74
C	60 cm	K	14.68
C_{p1}	72 cm	β_1	2.44
C_{p2}	67 cm	β_2	3.53
C_{m1}	26 cm	τ_m	925.8
C_∞	47.678	d_m	311.1

3.2 PID Control Results of The Coefficients Determined with The Cohen-Coon Method

Table 4 presents the PID control coefficients calculated using the equations of the Cohen-Coon method, which are given in Table 2. The liquid level control experiments were carried out by selecting different set points by using the PID coefficients determined in accordance with the Cohen-Coon method. In these control experiments, the changes in the valve values and liquid level profiles over time were observed and the experimental results obtained are shown in Figures 5-7. The experimental results for the different set points were investigated and it was observed that the pneumatic valve was worked on-off form irregularly. It was determined that the valve was successful for level control despite the incessant and irregular on-off operation. The same behaviour of manipulated variable was shown other studies, such as temperature control [16]. According to the experimental results, it was determined that the liquid level control using PID parameters obtained in accordance with Cohen-Coon method showed good performance and that these coefficients were suitable enough for liquid level control. Cohen-Coon parameters were achieved fast and stable regulation result. Cohen-Coon parameters work well in processes where the dead time is less than two times the length of the time constant and can even be stretched further if the process demands. One main issue with the Cohen-Coon parameters is that they tend to not be extremely robust, in other words, a small change in the process parameters can result in the closed loop system to become unstable and lead to oscillatory closed loop behaviour [17].

Table 4. PID control coefficients calculated in accordance with the Cohen-Coon method

Parameter	K_P	PB	τ_I	τ_D
Value	30.77	3.25	29.15	5.41

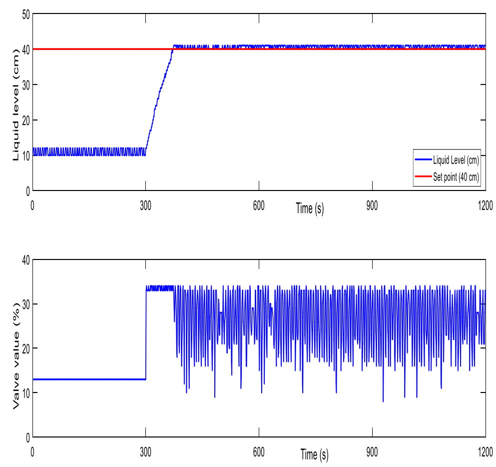

Figure 5. Liquid level changes with valve value for set point 40 cm using C-C method

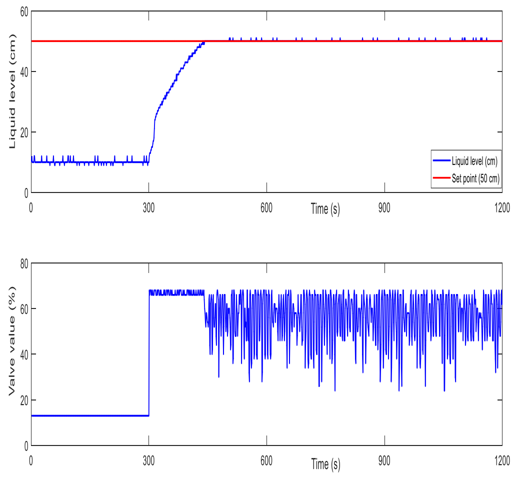

Figure 6. Liquid level changes with valve value for set point 50 cm using C-C method

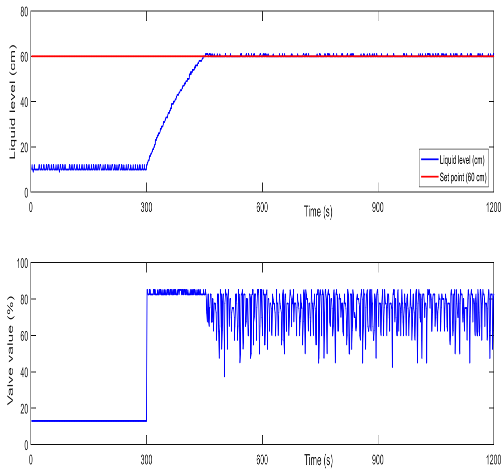

Figure 7. Liquid level changes with valve value for set point 60 cm using C-C method

3.3 PID control results of the coefficients determined with the Ziegler-Nichols method

The PID control coefficients calculated by using the values of the dead time and time constant parameters that were determined from the reaction curve are presented in Table 5. The PID control experiments were performed by selecting three different set points using the PID coefficients determined in accordance with the Ziegler-Nichols method. In these control experiments, the change in valve value and liquid level profiles over time was observed, and the experimental results are shown in Figures 8-10. According to the valve value, the liquid level was observed to be fixed at 1 cm, 2 cm and 5 cm offset for 40, 50, 60 cm set points respectively after oscillation. The experimental results for the different set points were investigated and it was observed that the valve opening value was fixed at %32, %70 and %99 for 40, 50, 60 cm set points respectively. The PID coefficients determined in accordance with the Ziegler-Nichols method were not sufficient for high level control and were not suitable for liquid level control. The parameters determined in accordance with the Ziegler-Nichols method were found to be satisfactory for first order processes with small dead times but under set point change and long dead time they failed to keep the process within an acceptable limit [18].

3.4 PID Control Results of Coefficients Determined with The Yuwana-Seborg Method

The process constants which were determined using the Figure 4 and determined PID control parameters were given in Table 6.

Table 5. PID control coefficients calculated in accordance with the Ziegler-Nichols method

Parameter	K_P	PB	τ_I	τ_D
Value	0.453	220.75	30.00	7.51

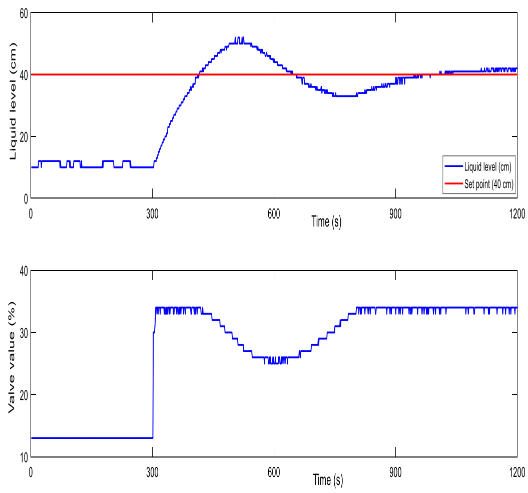

Figure 8. Liquid level changes with valve value for set point 40 cm using Z-N method

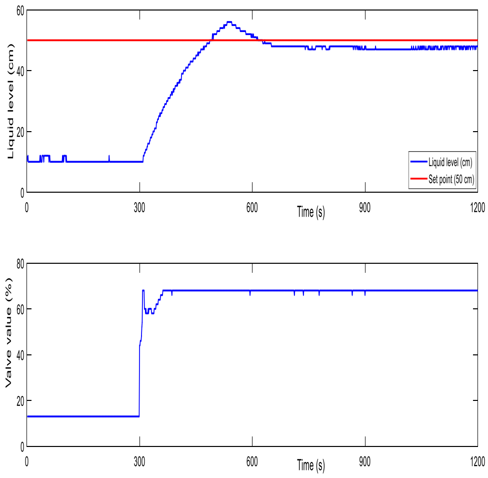

Figure 9. Liquid level changes with valve value for set point 50 cm using Z-N method

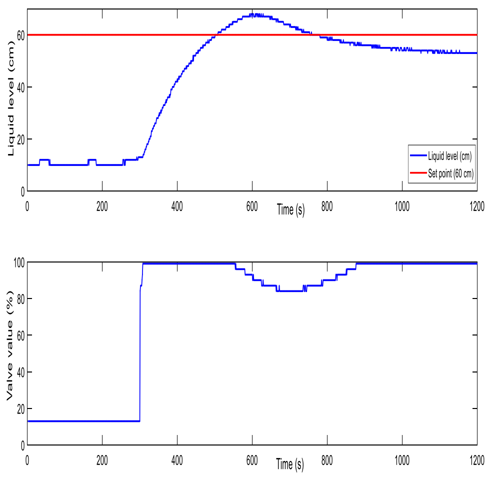

Figure 10. Liquid level changes with valve value for set point 60 cm using Z-N method

The PID control experiments were performed by selecting different set points using the PID coefficients determined in accordance with the Yuwana-Seborg method. In these control experiments, the change in the valve value and liquid level profiles over time was observed, and the experimental results are shown in Figures 11-13. According to the valve value, the liquid level was observed to be fixed at 7 cm, 15 cm and 3 cm offset for 40, 50, 60 cm set points, respectively, after oscillation. The experimental results for the different set points were investigated and it was observed that the valve opening value was fixed at 34%, 34% and 99% for 40, 50, 60 cm set points, respectively. The PID coefficients that were determined in accordance with the Yuwana-Seborg method were not sufficient for liquid level control as can be seen from Figures 11-12. The fact that it requires only a single closed-loop test and that the algorithm is simple are the practical advantages of the Yuwana-Seborg method. Its main disadvantage, on the other hand, is that the test is carried out under proportional control which introduces steady state offset during testing, which in turn creates off-specification products [19]. In addition, this method cannot be used for mildly underdamped or overdamped closed-loop responses. Furthermore, it is inaccurate, particularly when a large dead-time exists due to the use of the first order with the dead time [20].

The experimental results were investigated for the performance comparison of PID controllers using three classical tuning methods. Comparison to these methods with Cohen-Coon method were shown good performance on this experimental system for liquid level control. It was observed that the manipulated variable showed the same behavior with the Cohen-Coon and Ziegler-Nichols parameters on the liquid level control and wireless temperature control. However, the Ziegler-Nichols parameters showed better performance than the Cohen-Coon parameters on the wireless temperature control [21]. In general, it is difficult to define the “optimality” of a controller, due to the fact that there are several important aspects to consider, such as set-point response, disturbance rejection, robustness, input usage and noise sensitivity. Often, a control loop is evaluated exclusively on the basis of its response to a set point change, and in process control most important way to comparison of the PID controller performance is calculated the error values [22]. Therefore, the IAE and ISE values are the most common determinants used to determine controller performance in control engineering. The IAE and ISE values calculated using the data obtained after applying three different tuning methods with three different set points are given in Table 7 and Table 8, respectively.

Table 6. PID control coefficients determined in accordance with the Yuwana-Seborg method

Parameter	K_P	PB	τ_I	τ_D
Value	1.63	61.35	686.30	117.7

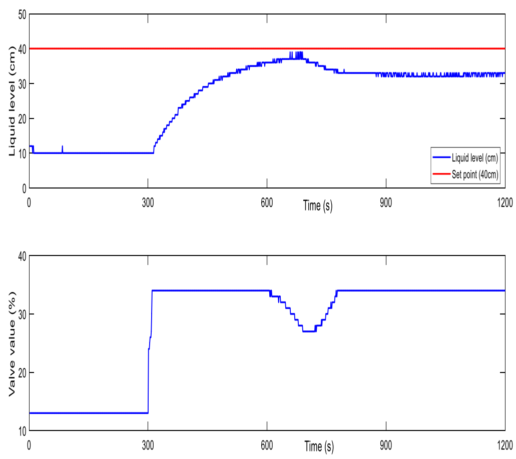

Figure 11. Liquid level changes with valve value for set point 40 cm using Y-S method

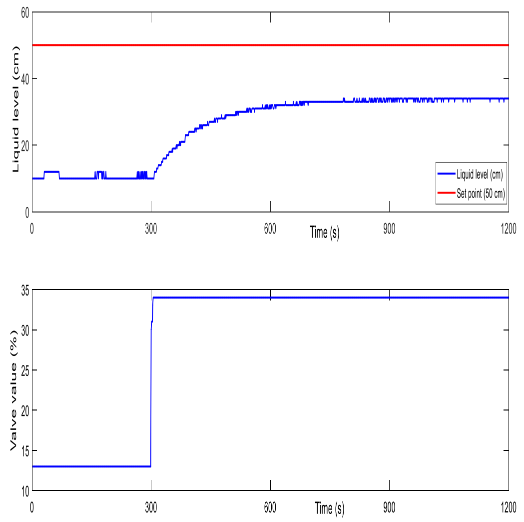

Figure 12. Liquid level changes with valve value for set point 50 cm using Y-S method

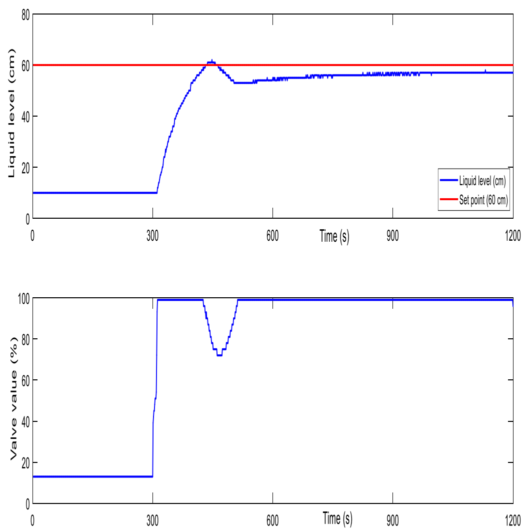

Figure 13. Liquid level changes with valve value for set point 60 cm using Y-S method

Table 7. IAE values calculated for the three PID tuning methods

Set Point	Cohen-Coon	Ziegler-Nichols	Yuwana-Seborg
40 cm	1455	4495	7714
50 cm	1983	5008	17536
60 cm	3216	7233	5796

Table 8. ISE values calculated for the three PID tuning methods

Set Point	Cohen-Coon	Ziegler-Nichols	Yuwana-Seborg
40 cm	17915	48155	93950
50 cm	41593	87640	366660
60 cm	92168	137865	104558

3.5 Preparing a Simulation Diagram and Code to Calculation of Responses

The PID parameters of Kp, τ_I and τ_D, the values of which were proposed by the program recorded on the MATLAB code, are given in Figure 14. All other simulation conditions were kept constant while the values of Kp, τ_I and τ_D were changed for the liquid level control simulations. The simulations proposed by the Design Expert 7.0 program were performed using the MATLAB/Simulink program to determining the optimum PID tuning parameters (Figure 15). The level was expected to be at a steady state by initially operating the valve opening at 10% for 300 s. At the end of 300s, the previously recorded Kp, τ_I and τ_D parameters were changed with the keys on the MATLAB program and the effect of these PID parameters were observed on the liquid level control. During the simulations, the changes in the liquid level were continuously monitored and the values of these input and output variables were continuously recorded in minutes. The ISE and IAE values were determined by using a constant set level and measured level after the simulations and these values were processed in the Design Expert 7.0 program to be analyzed.

3.6 Simulation Results and the Statistical Analysis of CCD

The Kp, τ_I and τ_D parameters of PID were selected as the independent operating variables, while the ISE and IAE values were determined as the responses. Experimental design was prepared with the Design-Expert 7.0.0 trial program and the subsequent statistical analysis was conducted by RSM. A statistical approach with CCD was applied to determine the interaction between these variables. The simulation ranges of the Kp, τ_I and τ_D parameters for CCD were determined with the parameters which determined according to the Cohen-Coon and Ziegler-Nichols parameters. The region of exploration to locate the optimum operating conditions was determined as 11.0 – 40.0, 15.0 – 45.0 and 6.0 – 20.0 for Kp, τ_I and τ_D, respectively.

```
%proportional constant Kp
Kp=0.5;
%integral constant TII
TII=1;
%derivative constant TDD
TDD=0.001;
[t,x,y]=sim('AAAyeniSim',20);
plot(t,y(:,1))
grid
title('liquid level versus time');
IAE=sum(abs(y(:,2)-y(:,1)));
ISE=sum((y(:,2)-y(:,1)).^2);
SONUC=[Kp, TII, TDD, ISE, IAE];
save PIDveriKriter.matSONUC
```

Figure 14. MATLAB code for the PID parameters to calculate the IAE and ISE values

A total of 20 experiments were conducted within the scope of the CCD and the tuning parameters at the center point were 25.50, 30.00 and 13.00 for Kp, τ_I and τ_D, respectively which were used for the optimization of PID. Simulation runs were used different PID coefficients and calculated IAE, ISE responses after simulations are given in the Table 9. The data presented in Table 9 were processed by the program to create an empirical model for the representation of the ISE and IAE values in terms of the Kp, τ_I and τ_D variables. According to the regression analysis, which was performed with a 95% confidence interval, it was determined that the lack of fit error and the p-values were significant. Quadratic models were used to fit the obtained data by least squares analysis and the empirical models obtained for ISE and IAE are given in Equation (4) and Equation (5), respectively.

$$ISE= +54058.10816 - 1977.96024 *[Kp] - 708.58871 * [T_I] - 367.21030 * [T_D] + 6.07529 * [Kp * T_I] - 2.37562 * [Kp * T_D] + 3.03929 * [T_I * T_D] + 38.40208 * [Kp^2] + 8.51565*[T_I^2]+12.39114*[T_D^2] \quad (4)$$

$$IAE = +5704.62464 - 207.56067 * [Kp] - 65.26341 * [T_I] - 81.63389 * [T_D] - 0.055172 * [Kp * T_I] + 7.38916E-003 * [Kp * T_D] - 0.040476 * [T_I * T_D] + 4.51624 * [Kp^2] + 1.18198*[T_I^2]+3.59113* [T_D^2] \quad (5)$$

The statistical significance of the quadratic model, which was applied to explain the experimental data, was tested by analysis of variance (ANOVA) results. Evaluation of models for ISE and IAE responses are given in the Table 10 and Table 11, respectively. The ANOVA results of the quadratic model for ISE and IAE responses are given in the Table 12 and Table 13, respectively. It can be seen from the tables that the regression was statistically significant at an F-value of 12.94 and 4.06 for the ISE and IAE values, respectively. Very low probability values (0.0002 for ISE and 0.0197 for IAE) were determined for the two responses. Therefore, an adequate precision of 12.426 for ISE and 7.095 for IAE was obtained with the quadratic model that described the control system used in this study, indicating a satisfactory signal for the liquid level control. The regression results are statistically significant which show that P model 0.0002 and 0.0197 for ISE and IAE, respectively. In this case Kp, Kp^2 and TI^2 were determines as significant model terms for ISE, while only Kp^2 was a significant term for IAE.

The statistical results of the ISE and IAE responses on the liquid level control are given in Table 14 and Table 15, respectively. According to the ANOVA results, the model R^2 values were determined as 92.09% and 78.52% for ISE and IAE, respectively. The adjusted R^2 values were found to be 84.98% and 59.18% for ISE and IAE, respectively. The R^2 values showed that there was a high correlation between the observed values and the predicted values. These results indicated that the regression model provided a good explanation for the relationship between the variables and the responses

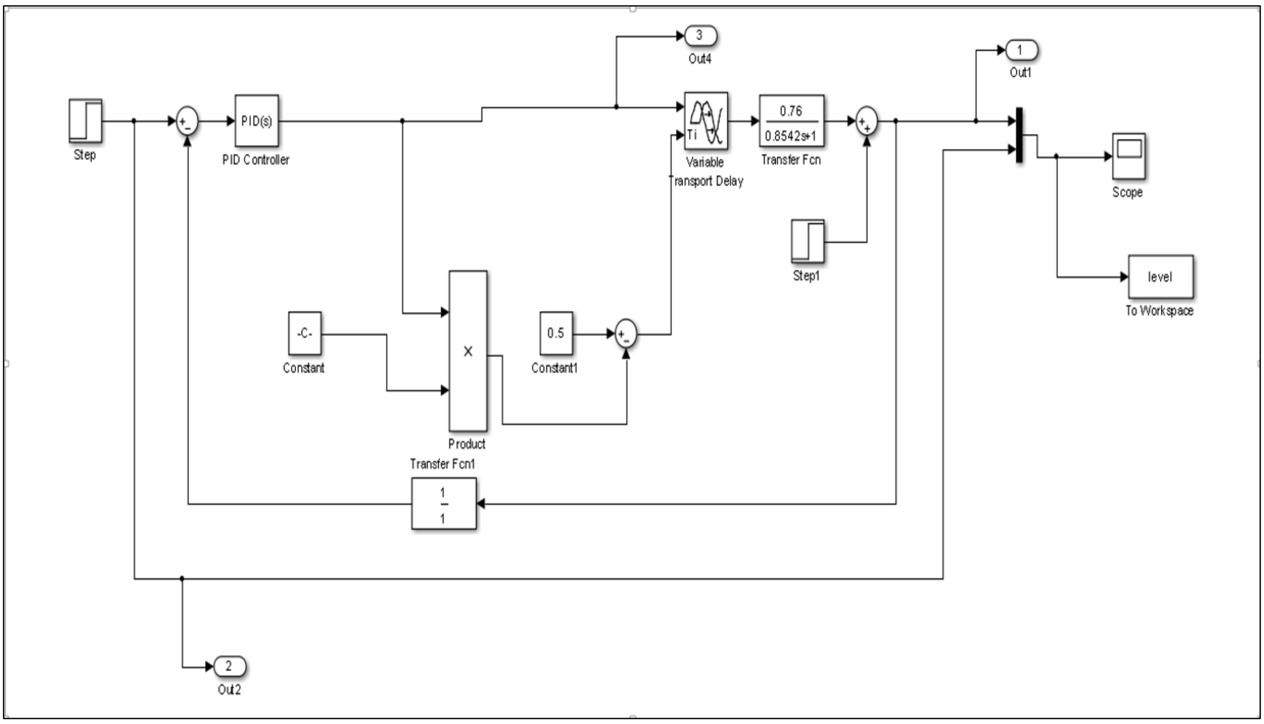

Figure 15. MATLAB/Simulink diagram of the liquid level control system

Table 9. Results of the simulation runs with the calculated two responses

Run Number	Kp (X_1)	τ_I (X_2)	τ_D (X_3)	ISE (R_1)	IAE (R_2)
1	25.50 (0)	30.00 (0)	13.00 (0)	17452	1971
2	25.50 (0)	30.00 (0)	13.00 (0)	17452	1971
3	25.50 (0)	30.00 (0)	1.23 (-α)	17489	1943
4	11.00 (-1)	45.00 (+1)	6.00 (-1)	23654	2793
5	25.50 (0)	30.00 (0)	24.77 (+α)	17569	1995
6	40.00 (+1)	45.00 (+1)	6.00 (-1)	33476	4153
7	49.89 (+α)	30.00 (0)	13.00 (0)	37645	4029
8	11.00 (-1)	15.00 (-1)	20.00 (+1)	27126	3157
9	25.50 (0)	55.23 (+α)	13.00 (0)	21898	2635
10	11.00 (-1)	45.00 (+1)	20.00 (+1)	23718	3245
11	11.00 (-1)	15.00 (-1)	6.00 (-1)	26983	3127
12	40.00 (+1)	15.00 (-1)	6.00 (-1)	32875	4096
13	25.50 (0)	4.77 (-α)	13.00 (0)	20564	1832
14	40.00 (+1)	45.00 (+1)	20.00 (+1)	33931	4169
15	1.11 (-α)	30.00 (0)	13.00 (0)	39652	4305
16	25.50 (0)	30.00 (0)	13.00 (0)	17452	1971
17	25.50 (0)	30.00 (0)	13.00 (0)	17452	1971
18	25.50 (0)	30.00 (0)	13.00 (0)	17452	1971
19	25.50 (0)	30.00 (0)	13.00 (0)	17452	1971
20	40.00 (+1)	15.00 (-1)	20.00 (+1)	30698	4568

Table 10. Evaluation of the models in terms of best fit with the results of the ISE response

Source	Sum of Squares	Degree of Freedom	Mean Square	F-value	p-value	
Mean vs Total	1.21E+010	1	1.21E+010			
Linear vs Mean	5.014E+07	3	1.671E+07	0.250	0.8589	
2FI vs Linear	1.525E+07	3	5.083E+06	0.063	0.9784	
Quadratic vs 2FI	9.588E+08	3	3.196E+08	36.35	<0.0001	Suggested
Cubic vs Quadratic	6.380E+07	4	1.595E+07	3.97	0.0656	
Residual	2.412E+07	6	4.020E+06			
Total	1.321E+10	20	6.607E+08			

Table 11. Evaluation of the models in terms of best fit with the results of the IAE response

Source	Sum of Squares	Degree of Freedom	Mean Square	F-value	p-value	
Mean vs Total	1.676E+08	1	1.676E+08			
Linear vs Mean	1.411E+06	3	4.703E+05	0.430	0.7354	
2FI vs Linear	1301.00	3	433.67	3.21E-4	1.0000	
Quadratic vs 2FI	1.349E+07	3	4.496E+06	11.03	0.0016	Suggested
Cubic vs Quadratic	1.926E+06	4	4.816E+05	1.34	0.3547	
Residual	2.15E+06	6	3.583E+05			
Total	1.866E+08	20	9.328E+06			

Table 12. ANOVA results of the ISE for liquid level control

Source	Sum of Squares	Degree of Freedom	F-value	p-value	
Model (Quadratic)	1.024E+09	9	12.94	0.0002	significant
X_1:Kp	4.997E+07	1	5.68	0.0383	
X_2:T_I	31846.64	1	3.62E-03	0.9532	
X_3:T_D	1.395E+05	1	0.016	0.9022	
X_1X_2	1.397E+07	1	1.59	0.2361	
X_1X_3	4.651E+05	1	0.053	0.8227	
X_2X_3	8.147E+05	1	0.093	0.7671	
X_1^2	9.395E+08	1	106.86	<0.0001	
X_2^2	5.291E+07	1	6.02	0.0341	
X_3^2	5.313E+06	1	0.60	0.4549	
Residual	8.792E+07	10			
Lack of Fit	8.792E+07	5			
Pure Error	0.000	5			
Cor Total	1.112E+09	19			

Table 13. ANOVA results of the IAE for liquid level control

Source	Sum of Squares	Degree of Freedom	F-value	p-value	
Model (Quadratic)	1.490E+07	9	4.06	0.0197	significant
X_1:Kp	1.292E+06	1	3.17	0.1054	
X_2:T_I	42570.21	1	0.17	0.7532	
X_3:T_D	76752.82	1	0.19	0.6736	
X_1X_2	1152.00	1	2.826E-03	0.9587	
X_1X_3	4.50	1	1.104E-05	0.9974	
X_2X_3	144.50	1	3.545E-04	0.9853	
X_1^2	1.299E+07	1	31.88	0.0002	
X_2^2	1.019E+06	1	2.50	0.1449	
X_3^2	4.462E+05	1	1.09	0.3201	
Residual	4.076E+06	10			
Lack of Fit	4.076E+06	5			
Pure Error	0.000	5			
Cor Total	1.898E+07	19			

Table 14. Statistical values of the ISE for liquid level control

Std. Dev.	2965.12	R-Squared	0.9209
Mean	24599.50	Adj R-Squared	0.8498
C.V. %	12.05	Pred R-Squared	0.3992
PRESS	6.681E+08	Adeq Precision	12.426

Table 15. Statistical values of the IAE for liquid level control

Std. Dev.	638.46	R-Squared	0.7852
Mean	2894.65	Adj R-Squared	0.5918
C.V. %	22.06	Pred R-Squared	0.6343
PRESS	3.101E+07	Adeq Precision	7.095

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Table 16. Optimization criteria of the program for studied range

Parameters	Goal	Lower limit	Upper limit
Kp (X_1)	is in range	11	40
τ_I (X_2)	is in range	15	45
τ_D (X_3)	is in range	6	20
ISE (R_1)	minimize	17452	39652
IAE (R_2)	minimize	1832	4568

Table 17. Optimum PID parameters and responses recommended by the program

PID control parameters	Numerical values	ISE (R_1)	IAE (R_2)	Desirability
Kp (X_1)	23.14			
τ_I (X_2)	28.31	17368	1908	1.00
τ_D (X_3)	11.50			

3.7 Determination the Optimum PID Parameters for Liquid Level Control

Numerical optimization was applied to determine the optimum PID parameters for liquid level control. The optimization criteria specified in the Materials and Methods section were entered into the Design Expert 7.0.0 trial program, which proposed optimization solutions. The optimization criteria of the Design Expert program for liquid level control with the PID tuning parameters are given in Table 16 and the optimization solutions proposed by the program are given in Table 17.

The optimization procedure was carried out with a desirability function. According to this function, the ISE and IAE values of every determined response were transformed into a dimensionless desirability value (d). The value of the functions ranged between 0 and 1. The value of d increased as the desirability of the corresponding response increased. In this study, the minimum ISE and IAE values are selected for the better PID parameters of liquid level control system. In order to obtain the lowest ISE and IAE values, the optimum values of the PID tuning parameters for liquid level control were determined as 23.14, 28.31 and 11.50 for Kp, τ_I and τ_D.

4. Conclusion

In this study, RSM was used for the determination of optimum PID controller parameters to minimize the ISE and IAE performance criteria after three most widely used tuning methods applied to the experimental liquid level system. Dynamic analysis carried out on the liquid level control system for prepare the reaction curve and the dead time, time constant and process gain values were determined. PID control parameters were calculated with Cohen-Coon, Ziegler-Nichols, Yuwana-Seborg which commonly used tuning methods. These parameters applied for the 40cm, 50cm and 60cm set points and after experiments ISE and IAE control performance values were calculated. Kp, τ_I, τ_D selected as independent parameters and ISE and IAE values are chosen as dependent variables (responses). Numerical values of the responses for the runs were determined using closed-loop PID controller with liquid level system block diagram which designed in MATLAB/Simulink. Simulations in the proposed list by the trial version of Design Expert 7.0 program were performed in order and the IAE and ISE values calculated after the simulations were processed by processing the results. Optimal PID control parameters of liquid level control system determined in order to obtain the lowest ISE and IAE values were Kp 23.14, τ_I 28.31 and τ_D 11.50. Although the results of this research have demonstrated the effectiveness of the proposed optimal PID parameter tuning method and its potential future, other control applications need to be implemented to test the robustness under different disturbances. As discussed in this research, for liquid level control system the PID controller with fixed PID parameters is not suitable for all conditions and it has the limitation of not dealing well with an external disturbance such as high frequency noise, and small plant parameter changes. For these systems, the proposed method is a better choice. For complex systems without an exact mathematical model, the identification scheme can be integrated into the PID control parameter tuner design to fulfill the online optimization if needed. This provides more flexibility for control system designers.

Declaration

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

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Nomenclature

e(t), ε	: error
Gs	: transfer function
IAE	: Integral of Absolute of the Error
ISE	: Integral of Square of the Error
Kp	: proportional constant
PB	: proportional band
RSM	: Response Surface Methodology
τ	: time constant
τ_d	: dead time
τ_I	: integral constant
τ_D	: derivative constant
Us	: process gain
min	: minute
t	: time (second)
cm	: centimeter

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