T.R.
VAN YUZUNCU YIL UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF CHEMICAL ENGINEERING

DETERMINATION OF PID CONTROL PARAMETERS BY RESPONSE SURFACE METHODOLOGY

M.Sc. THESIS

PREPARED BY: Mohammed Sadralddin ANWER
SUPERVISOR: Assist. Prof. Dr. Adnan ALDEMİR

VAN – 2019

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ACCEPTANCE AND APPROVAL PAGE

This thesis entitled "DETERMINATION OF PID CONTROL PARAMETERS BY RESPONSE SURFACE METHODOLOGY" presented Mohammed Sadralddin ANWER under supervision of Asst. Prof. Dr. Adnan ALDEMİR in the department of Chemical Engineering has been accepted as a M.Sc. thesis according to Legislations of Graduate Higher Education on 02/08/2019 with unanimity of members of jury.

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THESIS STATEMENT

All information presented in the thesis obtained in the frame of ethical behavior and academic rules. In addition all kinds of information that does not belong to me have been cited appropriately in the thesis prepared by the thesis writing rules.

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ABSTRACT

DETERMINATION OF PID CONTROL PARAMETERS BY RESPONSE SURFACE METHODOLOGY

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Proportional – integral-derivative (PID) controllers are the most used systems in the industrial field and find the most research and application area in control engineering. The control output is generated by the addition of three terms called proportional, integral and derivative. Some experimental methods have been developed to tuning the PID control parameters. These methods are applied to the open-line systems without control, but the parameters determined by these methods may not be effective in nonlinear, variable parameter and unstable systems. In this case, it is necessary to determine the optimal PID control parameters.

In the scope of this thesis, liquid level control system which operated in Van Yüzüncü Yıl University, Department of Chemical Engineering was used. Dynamic data for control variable was obtained with step change applied to manipulated variable. The dead time, time constant and gain values were determined with the process reaction curve was prepared using step change effect. The optimum values of the PID control parameters are determined by Response Surface Method (RSM). Kp, τ_I, τ_D as independent parameters and ISE and IAE values are chosen as dependent variables (responses). Numerical values of the responses for the runs in the design matrices 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. The models were developed through RSM in terms of related independent variables to describe the ISE and IAE as the two responses.

Keywords: IAE, ISE, Liquid level, PID control**,** Response surface methodology

ÖZET

CEVAP YÜZEY YÖNTEMİ İLE PID KONTROL PARAMETRELERİNİN BELİRLENMESİ

ANWER, Mohammed Sadralddin
Yüksek Lisans Tezi, Kimya Mühendisliği Bölümü
Tez Danışmanı: Dr.Öğr.Üyesi Adnan ALDEMİR
Ağustos 2019, 65 sayfa

PID kontrol ediciler, endüstriyel alanda halen en çok kullanılan ve kontrol mühendisliğinde en çok araştırma ve uygulama alanı bulan sistemlerdir. PID kontrol edici sinyali, oransal, integral ve türevsel olarak adlandırılan üç terimin toplanması ile kontrol çıktısı oluşturulur. PID kontrol parametrelerinin ayarlanması için bazı deneysel yöntemler geliştirilmiştir. Bu yöntemler kontrolün olmadığı açık-hat sistemlere uygulanır ancak doğrusal olmayan, değişken parametreli ve kararsız sistemlerde bu yöntemler ile belirlenen parametreler etkili olmayabilir. Bu durumda optimal PID kontrol parametrelerinin belirlenmesi gereklidir.

Bu tez kapsamında, Van Yüzüncü Yıl Üniversitesi, Kimya Mühendisliği Bölümünde bulunan sıvı seviye kontrol deney sistemi kullanılmıştır. Basamak etki değişimi ile hazırlanan reaksiyon eğrisi üzerinden deney sistemine ait ölü zaman, zaman sabiti ve proses kazancı belirlenmiştir. Optimum PID kontrol parametrelerinin değerleri, Cevap Yüzey Yöntemi (CYY) ile belirlenmiştir. Kapalı çevrim PID kontrolörü ile MATLAB/Simulink'te tasarlanan sıvı seviye deney sistemi blok diyagramı kullanılarak simülasyon sonuçlarının sayısal değerleri belirlenmiştir. Bağımsız parametreler olarak Kp, τ_I, τ_D ve bunlara karşılık deney sonrası hesaplanan ISE ve IAE değerleri bağımlı değişkenler (yanıt) olarak seçilmiştir. Design Expert 7.0 programı deneme versiyonu tarafından önerilen deney listesindeki deneyler sırasıyla gerçekleştirilmiş ve deneylerden sonra hesaplanan IAE ve ISE değerleri programa işlenerek sonuçlar değerlendirilmiştir.

Anahtar kelimeler: PID kontrol, IAE, ISE, Sıvı seviye, Cevap yüzey yöntemi

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2019
Mohammed Sadralddin ANWER

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SYMBOLS AND ABBREVIATIONS

Symbols and abbreviations used in this study are presented below, along with descriptions.

Symbols	**Explanation**
ANOVA	Analysis of Variance
CCD	Central Composite Design
e(t), ε	error
GA	Genetic Algorithm
Gs	transfer function
IAE	Integral of Absolute of the Error
ISE	Integral of Square of the Error
Kp	Proportional constant
PB	Proportional Band
PI	Proportional Integral
PID	Proportional Integral Derivative
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

1. INTRODUCTION

The most broadly utilized control strategy in processes industries such as chemical, petrochemical, pulp and paper, gas and oil, and beverage and food is PID (proportional, integral, derivative) control strategy. For controlling variables including level, temperature, flow, pressure and pH, PID controller has proven strength and reliability. Low expense, easily maintenance, simplicity in control structure and easily understood are other factors that attract industries for choosing PID controller. However, the inappropriate PID parameters may lead to poor cyclic, slow recovery as well as collapse of system operation (Åström and Hägglund, 1988). Therefore, researchers have to discover the best approach in examining optimal PID parameters. Several strategies have been projected for determining the best setting of PID parameters from the time when the PID controller is introduced.

In PID tuning approaches, the research by (Cohen, 1953); (Ziegler and Nichols, 1942) are among the pioneers. Researchers have projected experimental PID tuning approach grounded upon trial and error approach, and procedure response curve approaches. Nonetheless, when the system is intricate like time delay, high order, non-minimum phase and non-linear processes, the complications might cause to tune the PID controller. For instance, extended settling period, high oscillatory and elevated overshoots is provided by (Ziegler and Nichols, 1942) approach might for a high order system (Saravanakumar et al., 2006). In addition, in systems with S shaped stage reaction of the plant, Cohen-Coon approach is valid (Jain and Nigam, 2008). For overcoming these complications, different approaches have been utilized for obtaining best PID parameters varying between conventional approaches like pole placement (Åström and Hägglund, 1995), Refined (Ziegler and Nichols, 1942); (Åström et al., 1993) as well as applications of current heuristic enhancement method like genetic algorithms, replicated annealing, incremental learning based on population, and optimization of particle swarm (De Moura, 2005). The optimization of heuristic is an approach of examining decent solutions at a sensible expense of computation deprived of being capable to either warranty optimality or feasibility, in several circumstances to express how particular practical solution is close to optimality (Reeves, 1993).

In recent years, because of its high potential of escaping being confined a local minimum, GA has been comprehensively examined by numerous investigators in looking for ideal PID parameters. An enhanced GA approach for tuning PID controller for best control of RO plant with smallest overshoot and quick settling period in comparison to conventional approach is proposed by (Kim et al., 2008). However, for tuning PID controller for minimum damping, and slow reaction plant (Chou and Hwang, 2004) have effectively utilized GA. In addition, to optimize PID parameters, (Zain et al., 2009) employed GA for controlling a single-link bendable manipulator in perpendicular motion. The outcomes of the simulations showed that optimal parameters of PID permit the system for performing decently in decreasing vibration at the manipulators end -point. Several researchers have highlighted some shortages in GA performance in spite of the excellent performance by GA that is used in for the optimum solution in space explorations. Loss of optimum solution showed, poor premature convergence and no complete guarantee that an algorithm of the genetic could discover a global optimum (Vanitha and Thanushkodi, 2011).

(Storn and Price, 1997), projected that in numeric optimization issues DE has been discovered to be an encouraging algorithm. For fulfilling the necessity for practical minimization techniques like the global minimums reliable convergence in succeeding self-governing experimental, quick convergence, easily operated, the capability to handle non-linear, non-distinguishable and multimodal expense tasks, the DE has been designed (Storn and Price, 1997). Consequently, since the algorithm was projected, it has gained a great interest. The particle swarm optimization (PSO) and in optimizing the PID controller, the DE performance was investigated by (Dong, 2009). The investigation unveiled that in comparison to PSO, DE is commonly more robust (regarding reproducing persistent outcomes in various runs). The DE algorithm was applied in tuning the PID controller for electric-hydraulic servo system of parallel platform by (Luo and Che, 2010).

The results of simulation demonstrated that the projected parameter optimum approach is an effectual tuning technique and the controlled system has satisfactory response. DE was effective in PID controller tuning for unsteady and time delay of the integration processes, at which it generates shorter time for settling with smallest overshoot (Bingul, 2004). The information of the mechanism has been applied still unclear although several researchers have broadly investigated the PID tuning approach utilizing DE and GA. Nevertheless, better comprehensions about tuning the PID controller utilizing two prevalent heuristic methods by DE and GA. The DE and GA performance in looking for globally optimum parameters of PID and its dependability for maintaining the best value for many free experimental has been examined for non-minimum phase procedure. In addition, applying DE and GA tuning approach with Ziegler-Nichols method, this investigation make a comparison the transient systems performance.

1.1. PID (Proportional-Integral-Derivative) Controller

PID values, which are respectively indicated by Kp, τ_I, and τ_D, are basic separate parameters of PID controller parameters. The dynamic response of a system is improved, overshoot is reduced, steady state error is eliminated and stability of the system is increased by the appropriate setting of such parameters (Åström and Hägglund, 1995). The following equation represents the transfer function of a classical PID controller;

$$C(s) = \frac{U(s)}{E(s)} = K_P + \frac{\tau_I}{s} + \tau_D s \tag{1.1}$$

Figure 1 displays the fundamental structure of a PID control system. The error will be calculated between the actual output and the set point when the set point is altered. For generating the PID actions, the error signal E(s), is utilized. Then, for forming the control signal U(s), the resulting signals are weighted and summed which applied to the plant model. The new output signal is going to be obtained. Then, the actual signal directed to the controller, consequently the error signal will be calculated. Ultimately, novel control signal, U(s), will be directed to the plant. Till steady-state error, this procedure will be operated constantly.

Proportional, integral and derivative values, which are indicated by *Kp*, τ_i, and τd, are basic separate parameters of PID controller parameters. The enhancing system's dynamic response, decreasing overshoot, eliminating steady state error and increasing stability of the system are achieved by the appropriate setting of such parameters. The following equation represent the PID controller transfer function:

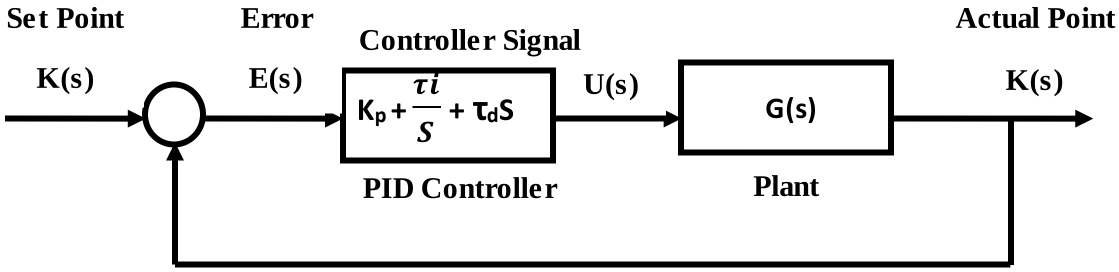


Figure 1.1. Diagram of feedback control with PID controller.

It has been discussed previously that standard PID controller has difficulties handling some systems such as nonlinear and time-varying systems. The goal of this thesis is to design optimum PID control parameters with response surface method which tunes the PID control parameters adaptively while the process is running. Here, performance of the parameters are defined to calculate how much the cost will be while the system is running during some time period t. The most commonly used performance index for PID control are integral of square of error (ISE) and integral of absolute of error (IAE) given Eq." 1.2" and "1.3", respectively.

$$ISE = \int_0^\infty e(t)^2 dt \tag{1.2}$$

$$IAE = \int_0^\infty |e(t)| dt \tag{1.3}$$

1.2. Variable-Structure PID Controller For Level Process

One of the most common controls in the process industry is the liquid level control in different vessels and tanks. It can regularly be classified into (a) the process control in that sustaining the level to a particular set point is the primary objective (boiler steam, bottom-product, drums and distillation of reflux drums columns), (b) the control where big level fluctuations are permitted and even expected the case of so called surge vessels which gather feedstock from one or more origins and deliver a flat feed proportion. The second circumstance, the primary control objective is the outflow balance. In this study, merely the first class of level control objectives will be taken into considerations. Normally a PI or PID controller, can be applied as a section of a dispersed control system or locally, regulates the level. According to the established approaches and techniques, the controllers are tuned (Astrom & Hagglund, 1984, 1995; Shinskey, 1988; Ziegler & Nichols, 1942). In several circumstances acceptable performance can barely be accomplished. Because of the fact that level process is an incorporating process, this process is occurring that in integration with the integral term of the PI/PID controller consequences in a double integrator in the loop. It is unconditionally essential for the controller integral term to be available for ensuring zero error in a steady state. Additionally, the PI controller utilization in mixture with an integrating process frequently causes oscillatory transients having low damping. To summarize, in regards of providing a decent performance, controlling level process is not as easy as it might look. For the considered process, as the performance enhancement because of introduction of the derivative term is marginal whereas the derivative term could increase the measurement noise, PID controllers are utilized more rarely in comparison to PI controllers. Thus, this study design and analysis are restricted to the circumstance of PI controllers. Nevertheless, merely by the tuning applied rules, the utilization of a PID controller would vary from the presented investigation. Several decades ago, the variable-structure (VS) control was projected and was primarily advanced as a sliding mode control (Utkin, 1992). Under the name of ‘‘variable-structure PID’’ controllers, there are several controllers illustrated in the literature. Utkin (1992) described the term ‘‘variable-structure’’ is as a kind of the switching control wherein switching happen once the state trajectory transfers from one region of the partitioned state space to another. In reliance upon the designed switching strategy, the sliding mode might or might not happen. Hence, the subsequent assets of the system of variable-structure are presumed.

1.3. Response Surface Methodology (RSM)

The RSM can be considered as a group of mathematical and statistical approach beneficial for the optimization of objective functions. This methodology is grounded upon estimation of the objective function via a low order polynomial on tiny domains of sub-region. Assumed that a response variable Y and k factors, $x_1,...,x_k$, the chief purpose of RSM is to discover the mixture of factor levels for achieving the optimal response. the variables are regularly altered to coded or design variables, $x_1,\dots,x_k$, standardized for the convenient computation so that the design centre is at the point $(x_1,\dots,x_k) = 0$. Furthermore, it is presumed that the true response is a function of the levels of the k design variables, $f(x_1, x_2,\dots,x_k)$, named the true response function. In this research, the RSM was employed for investigating/studying the influence of input variables upon the quality of coating. Subsequent the complete factorial design, twenty seven values for every response were attained and utilized for estimating the coefficients of decreased and complete second order models. Grounded upon the examination the influence (main and interaction) that were significant statistically were encompassed in the developed models. The following equation is a quadratic response surface with design variable inputs x_1 and x_2 and output variable y given Eq. (1.4).

$$y=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\cdots+\beta_kX_k \tag{1.4}$$

In which Y represents the response function and βi $(i=0,\dots,5)$ demonstrates the unidentified coefficients that were projected via minimum squares fitting of the model to the experimental outcomes attained at the design points.

The residuals analysis from the fitted model is essential for determining the sufficiency of the least squares fit, similar to fitting any regression model. By the estimation of R-squared values, this can be accomplished. Since the normal probability plot offers information regarding the absence of any critical violation of the normality assumption, it becomes necessary. The points in the plot will approximately form a straight line for the assumption to be true.

A visual explanation of the functional relations was made via utilizing various estimation and graphic illustrations of the response surfaces subsequent essential validation of the acquired models (Vitanov et al., 2010).

Oehlert (2000) declared that when discovering the optimal or describing the response is the goal, RSM designs are models for operating with constant handlings. Finding the best response is the primary goal for response surface method. Oehlert

(2000) reported that it is vital to discover the compromise optimum that does not enhance merely one response when there is more than one response. The experimental design must comply with the requirements of the limitations when there are limitations on the design data. Moreover, understanding how the response alters in a provided direction by amending the design variables is the second goal. Generally, the response surface can be visualized by graphs. To obtain the shape of a response surface; hills, valleys, and ridge lines, graphical illustrations are useful. Graphs are useful apparatuses for understanding the surface of a response. In addition, since it is beyond 3 dimension, graphs are hard or nearly impossible to utilize for illustrating the response surface when there are more than two independent variables. Thus, to analyze the unidentified function f, response surface models are vital (Elangovan et al., 2012).

1.4. MATLAB/Simulink

MATLAB solver is a component of the Simulink software solver. The Simulink buildup for the solver was developed by MathWorks Incorporation to simplify the modeling process of different systems. Simulink is integrated with MATLAB and it is a simulation environment which is used in the creation, simulation and solution of dynamic system models. Simulink supports linear or nonlinear, single or multivariate systems that are modeled at continuous time, discrete time or both. This product provides an extensive library of solvers, each of which determines the time of the next simulation step and applies numerical methods to make mathematic operations with different objects (numbers, vectors, matrices) as well as to solve the sets of ordinary differential equations that represent the model. In the process of solving this initial value problem, the solver also satisfies the accuracy requirements specified by operator. In addition, the Simulink library provides the big library of different device models with mathematic description documentation. However, during the development of control system not only control object models are required, but also the model of controlling device which complexity varies from task to task which in turn generates a challenge of universal approach for the development of controlling device model. The building structures could be simplified significantly in this case and would not contain the long line of repetitive blocks.

Operator may generate individual blocks and combine them in libraries for the further usage in Simulink. Graphical approach of Simulink allows the building of the model from standard Simulink blocks for simulating the control system functions. This approach is very useful but requires time-consuming operations for adaptation of developing control device features as the transfer of the development results on the target control system to the results of computer model built. The blocks used in the block diagram are categorized in Simulink library. Some of these categories include commonly used blocks, sinks, sources, continuous, discontinious, discrete, signal routing, indicators or outputs, math operations, model verification. The obtained data can be analyzed in MATLAB after the simulation of the system is completed.

2. LITERATURE REVIEW

2.1. Brief History of PID Controller

PID control action are combined in PIDs. In the late eighteenth century, James Watt comprised a flyball governor, which is the first mechanical feedback apparatus with merely a proportional function, into his steam engine. (Bennett, 2001) stated that the speed is controlled by the flyball governor by utilizing more steam to the engine as the speed fallen lower than a set point, and the opposite is true. In beginning of the twentieth century, the initial pneumatic controller with a completely tunable proportional controller is introduced by the Taylor Instrumental Company. Since proportional controller increases error by multiplying it by some continuous (Kp), a proportional controller is not adequate for controlling speed thoroughly. Even though the error produced is ultimately minor, however it is not zero. Obviously, every time the controller responds to the load, it produces a steady state error (VanDoren, 2000). In the mid twentieth century, control engineers found that steady state error could be eradicated via resetting the set point to some artificial bigger or smaller value, if the error not zero. PI controller is defined as resetting operation integrates the error adding the results to the proportional term. Moreover, the first PI controller Foxboro was presented in 1934-1935. Nonetheless, errors can be over-corrected and is caused closed-loop instability by PI controllers. When the controller reacts too fast and too violently, the previous circumstance occurs. It generates a fresh error sets even opposite to the real error. This case is called “hunting” problem (Chin, 2006).

There were recommendations in 1920s for embracing the rate of error alteration in combination with PI controller. The first PID pneumatic controller was produced successfully in 1940 by Taylor Instrument Companies. The derivative action was named pre-act. Issues like hunting and overshoot are decreased with an extra derivative action.

Nevertheless, problems such as discovering the suitable parameter of PID controllers were so far to be resolved. Taylor Instrument Company presented Ziegler-Nichols tuning rules in 1942. To establish the suitable parameters for PID controllers Ziegler and Nichols in their paper “Optimum settings for automatic controllers”, introduced two procedures. Nevertheless, since PID controller was not a simple concept, it was not common at that time; for the users, the parameters the manufacturers needed to be tuned did not make much sense. Automatic controllers were extensively implemented in industries in the mid twentieth century. New controlling units might be mechanically, pneumatically, electrically or hydraulically operated according to the Department of Scientific and Industrial Research of United Kingdom state. Technically, the most advanced is the pneumatic kind and several dependable designs are accessible. Moreover, it is believed that pneumatic consists more than 90% of the existing units. (Bennett, 2000). The report demonstrated the necessity for implementing controllers in electronic and electrical configuration.

The Swartwout Company presented their first electronic PID controller in 1951. The companies begun to comprehend the likelihood of the implementation of the controllers in transistors late nineteen fifties. Bailey Meter Co introduced the first solid-state electronic controller in 1959. Several years later, the benefits of utilizing electronic instrument for implementing PID controller was investigated more thoroughly. In addition to the ability of comprising the functions accessible in pneumatic instruments, more complex mathematical operation can also be carried out (Williams, 1957). Since that time, electronic PID controllers have become more usual and highly acceptable. In the 1960s, the digital computer have become involved in process control. In 1959, Texaco’s Port Arthur plant presented the first example in which closed loop control was applied by a digital computer in an industrial plant. Several companies of control instrument reacted to this novel technology and offered computer-based systems by 1960. To provide precision at low expenses Analog controllers ought to progressively evolve into digital apparatuses.

Such controllers could be comparatively modest in the combination into multipoint forms, which could be utilized for optimizing unit processes on an indigenous basis (Kumar et al., 2011). A lot of findings regarding PID controller's digitization were made. Furthermore, since microprocessors have the ability to tackle calculations directly in engineering units, discussion for the implementation of controllers on microprocessors were mentioned (Takahashi et al., 1975); (Krikelis and Fassois, 1984). Today, the PID controller is commonly and broadly utilized in aircraft systems, automobiles, process control, home appliances, equipment, and portable devices because of advances of technology. Even though the fundamental theory for designing one stays the same, things have not been similar since the introduction of several modern control theories for the complementation the PID controller.

2.2. The Future of PID Control

In the field of PID controllers, feedback is a highly influential concept. According to Bennett, (1979 and 1993), the utilization of feedback has regularly had innovative results with drastic enhancements in performance. Even though it is frequently feedback itself that provides the real advantage as well as the specific form of feedback utilized is mostly unrelated, Credit often is provided to a specific form of feedback. Undoubtedly, nowadays the PID controller is the leading form of feedback occupied. PID consists more than 90% of the total control loops. As the derivative action is not utilized very frequently, most loops are indeed PI controller. the past (I), present (P) as well as future (D) control error are the base for Proportional, integral and derivative feedback. With such a simple strategy, astonishing results can be accomplished. Dealing with significant practical problems like the saturation of actuator and integrator windup is a strength of the PID controller. Therefore, the PID controller is considered bread and butter for automatic control. When feedback is utilized, PID controller is the first solution that ought to be applied. For a broad range of issues such as motor drives, process control, magnetic and optic memories, automotive, instrumentation and flight control, the PID controller is utilized. Standard single-loop controllers, a software component in programmable logic controllers and distributed control systems, a built in controller in robots and CD players are several forms of controllers. The PID controller has continuously been significant because of its strength. The literature has not documented numerous significant problems. Consequently, as technology changed from pneumatic via electrical to digital, several mistakes have recurrent. Nevertheless, in the last ten years, there has been an augmented attention. This is because of two main reasons. The first one is the augmented utilization of model predictive control and fuzzy control methods that needs well-tuned PID controllers at the basic level. The second reason is the appearance of automatic tuning PID controllers with Ziegler–Nichols tuning as a benchmark are still utilized in most papers on single loop control. Since the Ziegler–Nichols rules are known to provide very poor outcomes in numerous circumstances, it is very unsatisfactory situation (Wang, 2009).

2.3. The Literature of RSM

In formulating, designing, developing and analyzing new products and scientific studying, the RSM is highly significant. Moreover, RSM is effective in the enhancement of present products and studies as well. Biological and Clinical Science, Industrial, Social Science, Food Science, and Physical and Engineering Sciences are the most common uses of RSM. It is vital to understand where and how response surface methodology begun in the history because RSM has a wide utilization in the real-world. In 1951, G.E.P. Box and K.B. Wilson introduced RSM method. For approximating the response variable, Box and Wilson recommended the utilization a first-degree polynomial model. It is recognized that this model is merely an estimation, not precise, however these kind of model is easy to estimate and implement, even if slight is understood on the procedure. Furthermore, Myers, Khuri, and Carter (1989) reported that the origin of RSM begins from 1930s with application of Response Curves. Myers, Khuri, and Carter (1989) also stated that the orthogonal design was encouraged by Box and Wilson (1951) in the case of the first-order model. For these models, numerous subject- matter engineers and scientists have a decent understanding of the three-level designs and central composite designs (CCDs) by Box and Behnken (1960). It was also stated that Hartley (1959), who made an effort for creating a more economical or small composite design, contributed considerably to this field. Many papers are existed in the literature on the response surface models. On the other hand, three-level fractional design has restricted operation. Therefore, three level fractional design is an exposed subject for research. A useful source carrying out this type of design is Fractional Factorial Design (FFD) for Factor at 3-Levels of (Connor and Zelen 1959). This study include numerous three- level fractional factorial designs and their alias tables. Subsequent the Word World II, an imperative progress of theory of the optimal design in the field of experimental design appeared (Myers, Khuri, and Carter (1989). Numerous authors, who published their studies about optimality are Elfving (1952, 1955, 1959), Chernoff (1053), Kiefer (1958, 1959, 1960, 1962), and Kiefer and

Wolfowitz. The RSM comprises a maximum, a minimum or a saddle point, which has a broad attention in industry. Thus, the system is being progressively utilized in the industry. Myers, Khuri, and Carter (1989) stated that recently the chemical and processing field placed more emphasis to find regions where there is an enhancement in response rather than discovering the optimum response. In conclusion, in the future, RSM application and development will continue to be utilized in numerous fields.

The selection of the variables is the first difficulty. As an experimental design dedicated to response surface requires more experiences than thus dedicated to parameter effects, the factor number must then be reduced. The results of the first experimental design revealed that PVSde, PVSe and dem are main factors. These factors have strong positive effects and immaterial interaction. Consequently, values of these factors are fixed to low level. Secondary influent factors ought to be chosen for response surface variables as interaction between them ought to be varied from zero by separating the preponderant parameters. After that, three parameters remain influent: PVSs, PSs and g. Furthermore, the functions of the membership, the duality between PSs and PVSs, on one side and gm, the denormalisation gain, on the other side presents tough interactions.

3. MATERIALS AND METHODS

In a liquid level control, the manipulated flow is often situated upstream of a critical unit. In this case, controlling the behavior of the outlet flow is as important as controlling that of the liquid level itself, in order to avoid rapid variations with significant magnitude. Therefore, a level controller is required to provide nonaggressive and smooth control action as well minimizing the deviation of the level. Furthermore, a level loop normally has two important requirements: (1) the rate of change of the outlet flow should be kept below a specified allowable limit, and (2) the deviation of the level should also be within a specified allowable limit. For this reason, level control problems can be considered as a typical constrained optimal control problem. Optimal control strategy has been employed in practical level loops because of its industrial and economic importance.

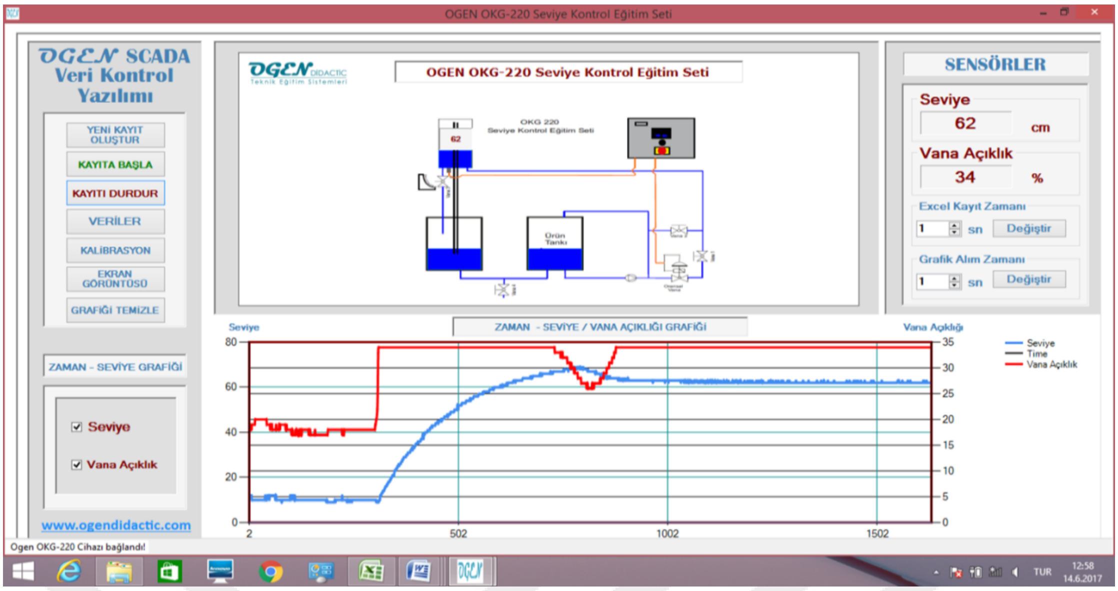
This section contain the details of experimental system and procedure of this thesis. There is a liquid level control system that can be used for liquid level control and dynamic data for control variable was obtained with step change applied to manipulated variable. The dead time, time constant and gain values were determined with the process reaction curve was prepared using this step change effect. Design Expert 7.0 program (trial version) used for design the tuning of the PID control parameters and MATLAB/Simulink program used for recorded only one set point of PID control simulation results. Optimal PID control parameters are determined with Response Surface Methodology (RSM) based on calculated ISE and IAE values after simulation results.

3.1. Experimental Liquid Level Control System

The liquid level control system consists of three liquid tanks built on mechanic assembly, a pneumatic valve connected a regulator for adjust the air pressure, an electronic panel showing liquid level and valve openings and hand valves acting at different points. The water in the storage tank is carried in pvc pipes with submersible pump and passes through pneumatic valve and filled into the level measuring tank. To prevent overflow, the level measuring tank is connected to a discharge tank underneath by a pvc discharge pipe in the middle of the level measuring tank. A manually adjustable valve is located at the bottom of the level measuring tank for effect the disturbance on this system. Discharge and storage tanks are connected to each other with pvc pipe to balance the liquid level in these tanks. A discharge valve is connected to the bottom tanks for discharging the water in these tanks. In the system, the compressed air required for the operation of the pneumatic valve is supplied by the compressor in the laboratory and the air is sent to the valve by adjusting the desired pressure value with the regulator. Experimental liquid level control system is given in Figure 3.1.

Liquid level control experiments were performed with on-line computer software which developed by the manufacturer of this control system. During the on-line experiments on the liquid level control system with this computer software, the valve opening value which is the input variable and the liquid level data which is the output variable are automatically recorded on the excel file. The graphics of liquid level and valve opening value changes are displayed on the screen. In addition, the data acquisition time can be adjusted in seconds. The computer software of the liquid level control system is given in Figure 3.2.

Figure 3.1 Experimental system: on-line computer connected liquid level control system.



Seviye 62 cm

Vana Açıklık 34 %

Excel Kayıt Zamanı 1 sn

Grafik Alım Zamanı 1 sn

Ogen OKG-220 Cihazı bağlandı!

Figure 3.2 Control software of liquid level and valve opening changes.

3.2. Selection of Variables for Optimal PID Control

In this subsection, Kp, τ_I, τ_D which are the PID tuning parameters are determined as independent variables effecting liquid level control. Optimum values of these control parameters have been obtained with the minimum IAE and ISE values which used for controller performance criteria.

RSM was used for determining the optimum values for the PID tuning parameters with Design-Expert 7.0 program (trial version). This program is used to design the liquid level simulations which make these experiments on the MATLAB/Simulink respectively, to create a mathematical model using the simulation results and to determine the optimum values of the PID tuning parameters according to the selected criteria. The main reason of using this program is perform the least number of experiments with see the integrated response of the system as a function and realize the optimization. In the general operation of this program, the response from the system is provided by changing the effective parameters at the same time. Thus, it is also examined whether there is an internal effect of the influencing factors taken from the system.

In this study, the basic criteria have been followed which given below for determining optimum values of PID tuning parameters on the liquid level control system;

1) Parameters are considered that are independently influence the control of experimental system and can be changed or adjusted by the researcher. In order to determine these parameters, literature review was performed and it was decided to select Kp, τ_I, τ_D parameters used in PID control as independent variables.
2) Measuring the response of the system to each changed the independent variable has been taken into account the basic factor for determining and detection range of the independent variables.
3) It has been emphasized that the interval of the independent variables should be selected in the working interval of the experimental system.
4) The CCD level control simulations were carried out in sequence with all other conditions (compressor pressure, etc.) kept constant in order to correctly determine the relationship between the dependent and independent variables.
5) Two important controller performance criteria values (ISE, IAE) were selected as dependent variables (response), which were calculated based on the difference between the set value and the measured value, in order to correctly determine the relationship between the dependent and independent variables.

In order to determine the optimal PID control parameters according to these criteria, K_P, τ_I, τ_D PID tuning parameters were chosen as independent variables and the change intervals for these three parameters were determined using literature searches and preliminary experiments. The ISE and IAE values which were calculated after the simulations were evaluated as the dependent variables (response). The intervals of the independent variables for the CCD simulations were processed into the Design Expert 7.0 program and a list of 20 PID control simulations which of 6 simulations were located in the center point and 2 simulations were located $+\alpha$, $-\alpha$, respectively, proposed by this program. The design summary of the Design Expert program, the ranges of independent variables and the design with levels of independent variables based on CCD given in Table 3.1, Table 3.2 and Table 3.3, respectively.

Table 3.1 Design summary of Design Expert 7.0 program

Design Type	**Response Surface Method (RSM)**
Design Name	Central Composite Design (CCD)
Design Model	Quadratic
Run Number (N= $2^3+2*3+6$)	20
Response	ISE (response 1), IAE (response 2)

Table 3.2 Operation levels of independent variables based on CCD

Variables	**-α**	**-1**	**0**	**+1**	**+α**
Kp	1.11	11.00	25.50	40.00	49.89
τ_I	4.77	15.00	30.00	45.00	55.23
τ_D	1.23	6.00	13.00	20.00	24.77

Table 3.3 CCD simulation list for optimization of PID tuning parameters

Run Number	**Kp (X_1)**	**τ_I (X_2)**	**τ_D (X_3)**
1	25.50 (0)	30.00 (0)	13.00 (0)
2	25.50 (0)	30.00 (0)	13.00 (0)
3	25.50 (0)	30.00 (0)	1.23 (-α)
4	11.00 (-1)	45.00 (+1)	6.00 (-1)
5	25.50 (0)	30.00 (0)	24.77 (+α)
6	40.00 (+1)	45.00 (+1)	6.00 (-1)
7	49.89 (+α)	30.00 (0)	13.00 (0)
8	11.00 (-1)	15.00 (-1)	20.00 (+1)
9	25.50 (0)	55.23 (+α)	13.00 (0)
10	11.00 (-1)	45.00 (+1)	20.00 (+1)
11	11.00 (-1)	15.00 (-1)	6.00 (-1)
12	40.00 (+1)	15.00 (-1)	6.00 (-1)
13	25.50 (0)	4.77 (-α)	13.00 (0)
14	40.00 (+1)	45.00 (+1)	20.00 (+1)
15	1.11 (-α)	30.00 (0)	13.00 (0)
16	25.50 (0)	30.00 (0)	13.00 (0)
17	25.50 (0)	30.00 (0)	13.00 (0)
18	25.50 (0)	30.00 (0)	13.00 (0)
19	25.50 (0)	30.00 (0)	13.00 (0)
20	40.00 (+1)	15.00 (-1)	20.00 (+1)

3.3. Experimental Procedure of Dynamic Analysis

Dynamic data of control variable was obtained with a positive step change applied to manipulated variable. In the dynamic analysis where the step effect is applied, the liquid level is stabilized in a fixed pneumatic valve value and it was observed that the liquid level becomes retention after different values are given to the valve. The dead time, time constant and gain values were determined with the process reaction curve was prepared using data of this step change effect.

The experiments were performed for comparison the conventional PID tuning techniques for liquid level control. PID control parameters Kp, τ_I and τ_D which values were recorded on the control panel of liquid level control system and on-line experiments were carried out. All other operating conditions were kept constant while the values of Kp, τ_I and τ_D were changed at the liquid level control experiments and it was expected that level would be steady state by initially operating the valve opening at 10% for 300s. At the end of 300s, previously recorded Kp, τ_I and τ_D parameters were changed with the keys on the control panel of the experimental system and the effect 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. IAE and ISE values were calculated with three different set level values and measured level values after on-line experiments. Equations of PID control parameters for Cohen-Coon, Ziegler-Nichols and Yuwana-Seborg tuning methods are given in the Table 3.4. Required coefficients for calculation of PID controller parameters with Yuwana-Seborg method given in Eq. (3.1) to Eq. (3.10).

The simulations which proposed by the Design Expert 7.0 program were performed respectively with MATLAB/Simulink to determining the optimum PID tuning parameters for liquid level control. PID tuning parameters Kp, τ_I and τ_D which values were proposed by the program recorded on the MATLAB/Simulink program and on-line simulations were carried out. All other simulation conditions were kept constant while the values of Kp, τ_I and τ_D were changed at the liquid level control simulations and it was expected that level would be steady state by initially operating the valve opening at 10% for 300 s. At the end of 300s, previously recorded Kp, τ_I and τ_D

parameters were changed with the keys on the MATLAB/Simulink program and the effect of these PID parameters were observed on the liquid level control. During the simulations, liquid level changes were continuously monitored and the values of these input and output variables were continuously recorded in minutes. ISE and IAE values were determined by using a constant set level and measured level after simulations and these values were processed in Design Expert 7.0 program for analyzing.

Table 3.4 Equations of PID controller parameters for 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	$\tau_m e\left(\frac{d_m}{\tau_m}\right)^{f}$

$$e^{-d_m s}=\frac{1-0.5d_m s}{1+0.5d_m s} \tag{3.1}$$

$$C_\infty=\frac{C_{p2}*C_{p1}-(C_{m1})^2}{C_{p1}+C_{p2}-2C_{m1}} \tag{3.2}$$

$$\alpha_1=\frac{C_\infty-2C_{m1}}{C_{p1}-C_\infty} \tag{3.3}$$

$$\sigma=\frac{-\ln(\alpha_1)}{\left[\pi^2+(\ln\alpha_1)^2\right]^{\frac{1}{2}}} \tag{3.4}$$

$$K_m=\frac{\left|C_\infty-C_o\right|}{K_c\left[\left|R-R_o\right|-\left|C_\infty-C_o\right|\right]} \tag{3.5}$$

$$K = K_c * K_m \tag{3.6}$$

$$\beta_1 = (K+1)^{\frac{1}{2}} + \left[\sigma^2 (K+1) + K\right] \tag{3.7}$$

$$\beta_2 = \left[(1-\sigma^2)(K+1)\right]^{\frac{1}{2}} \tag{3.8}$$

$$\tau_m = \frac{\Delta t \beta_1 \beta_2}{\pi} \tag{3.9}$$

$$d_m = \frac{2\Delta t \beta_2}{\pi \beta_1} \tag{3.10}$$

Table 3.5 Coefficients of PID controller parameters for Yuwana-Seborg

Criteria	**a**	**b**	**c**	**d**	**e**	**f**
IAE	1.086	-0.869	0.740	-0.130	0.348	0.914
ITAE	0.965	-0.850	0.769	0.146	0.308	0.929

3.4. Determination of Optimum PID Tuning Parameters

CCD was applied using Design-Expert 7.0 program (trial version). The total number of experiments for three variables were 20 (=2k+2k+6), where k is the number of independent variables. Fourteen simulations were augmented with six replications at the center values (zero level) to evaluate the pure error. In the regression equation, the test variables were coded according to the Eq. (3.11).

$$X_i = \frac{X_i - X_0}{\Delta X} \tag{3.11}$$

where, X_i is the dimensionless coded value of the i_{th} independent variable, X_0 is the value of X_i at the center point and ΔX is the step change value. The behavior of system is explained by the following second-order polynomial model Eq. (3.12).

$$y=\beta_0+\sum_{i=1}^{3}\beta_i X_i+\sum_{i=1}^{3}\beta_{ii} X_j^{2}+\sum_{i\le 1}^{3}\sum_{j=1}^{3}\beta_{ij} X_i X_j+e \tag{3.12}$$

where, y is the response, β_0 is the constant coefficient, X_i (i=1–3) are non-coded variables, β_is are the linear, and β_{ii}s are the quadratic, and β_{ij}s (i and j=1–3) are the second-order interaction coefficients. The residuals for each experiment were computed as in Eq. (3.13), where, ε_i, y_i and $y^\wedge_i$ are the residual of i_{th} experiment, observed response and predicted response, respectively.

$$e_i=y_i-\hat{y}_i \qquad i=1, 2, \ldots ,n \tag{3.13}$$

Data were processed for Eq. (3.12) using Design-Expert 7.0 program including ANOVA to obtain the interaction between the process variables and the response. The quality of the fit of polynomial model was expressed by the coefficient of determination (R^2), and its statically significance was checked by the F-test in the same program.

The second-order model determined from Eq. (3.12) is adequate for the optimal points. A general mathematical solution can be obtained by Eq. (3.14) for the location of the stationary point (Myers and Montgomery, 2002). Writing the second-order model in matrix notation,

$$y=\beta_0+x^I b+x^I B x_S \tag{3.14}$$

where,

$$x_S\,(stationary\ points)=\begin{bmatrix} X_1 \\ X_2 \\ X_k \end{bmatrix},\ \mathrm{b}=\begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_{\mathrm{k}} \end{bmatrix}\quad and\quad B=\begin{bmatrix} \beta_{11} & \beta_{12}/2 & \beta_{1k}/2 \\ & \beta_{22} & \beta_{2k}/2 \\ Sym & & \beta_{kk} \end{bmatrix}$$

That is, *b* is a (kx_1) vector of the first order regression coefficient and *B* is a (kx_k) symmetric matrix whose main diagonal elements are the pure quadratic coefficients (β_{ii}) and whose off-diagonal elements are one half of the mixed quadratic coefficients (β_{ij}, $i \neq j$). The stationary points (x_s) are the solution of Eq. (3.15).

$$x_S = -\frac{1}{2} B^{-1} b \tag{3.15}$$

The optimum points of the PID tuning parameters to minimize the ISE and IAE values were evaluated by application of Eq. (3.15). X_S, b and B matrixes in Eq. (3.15) were arranged which derivated by Design Expert 7.0 program, includes coded values of the parameters. The optimum points of the PID tuning parameters were determined with solving the matrices in Eq. (3.15) in the MATLAB program. Also this design program that can perform three different optimizations; ‘Numerical optimization’, ‘Graphical optimization’ and ‘Point Prediction’. The purpose of optimization; to determine the exact values of the parameters that will provide the desired response. In addition, numerical optimization results proposed by the program for different conditions were used. As optimization criteria;

- Proportional value: ‘in range’ (operating range)
- Integral value: range in range ’(operating range)
- Derivative value: range in range ’(operating range)
- ISE (Integral of Square of The Error): ‘minimize’ (minimum value)
- IAE (Integral of Absolute of The Error): ‘minimize’ (minimum value)

While determining the best solution, the solution that provides the lowest ISE and lowest IAE values with desirability = 1 was chosen among the solutions given. Design Expert 7.0.0 program was used for statistical analysis of the data. While making this determination; For each function 'Sequential Model Sum of Squares (Type I)' and 'Lack of fit' tests were performed and standard deviation, R2 (R squared), adjusted R2 (adjusted R squared) and predicted R2 (for each function) predicted R squared values were calculated. In the next stage, the model that best represents the studied system is determined by ANOVA table. When selecting the model representing the system, it is requested to meet the following criteria.

- Model; 'Significant'
- Lack of fit; Insignificant
- All model terms; 'Values of (Probe> F) <0.05' (95% confidence interval),
- R_squared; ~ 1,
- Adjusted R_squared; ~ 1,
- Predicted R_squared; ~ 1,
- Adjusted R_squared; ~ Predicted R_squared,
- Coefficient of variation (C.V.%); minimum (lowest)

After determining the best representation model of this system, three dimensional response surface graphs were generated by Design Expert 7.0.0 program.

4. RESULTS AND DISCUSSION

PID controllers are the most widely used systems in the industrial applications and the academic research in control engineering. The control output of the PID controller signal is generated by collecting three terms, proportional, integral and derivative. Some experimental methods have been developed to determine the PID control parameters. These methods are applied to open-loop systems where there is no control, but the parameters which determined by these methods may not be effective in non-linear, variable parameters and unstable systems. In such cases it is necessary to determine the optimal PID control parameters. In this thesis, optimum PID control parameters for a liquid level control system were determined by the Response Surface Methodology (RSM). Kp, τ_I, τ_D were selected as the independent parameters and the ISE and IAE values calculated after simulations were selected as dependent variables (responses). Dynamic data for control variable was obtained with step change applied to manipulated variable. The dead time, time constant and gain values were determined with the process reaction curve was prepared using this step change effect. Simulations in the list proposed by the trial version of Design Expert 7.0 program were performed respectively and then the calculated IAE and ISE values were processed into this program. and the results were evaluated.

4.1. Dynamic analysis for determining process reaction curve parameters

Dynamic analysis carried out on the liquid level control system for determining PID control parameters. Two different dynamic analysis carried out on the liquid level control system for determining PID control parameters. The first type dynamic experiment is performed in which a step change is applied to the valve value for prepare the reaction curve and determine the dead time, time constant and process gain values. A step change is applied to the valve value for prepare the reaction curve and determine the dead time, time constant and process gain values. The system was initially operated at 13% valve value and liquid level was expected to become steady state. A positive effect of 57 unit was given to the valve value and 70% valve opening value is provided. Liquid level is fixed 10 cm at the first valve value was observed to increase at 58 cm after the step effect given to the valve value (Figure 4.1). PID control parameters are calculated with Cohen-Coon and Ziegler-Nichols method equations using control coefficients which determined from first dynamic experiment given in the Table 4.1.

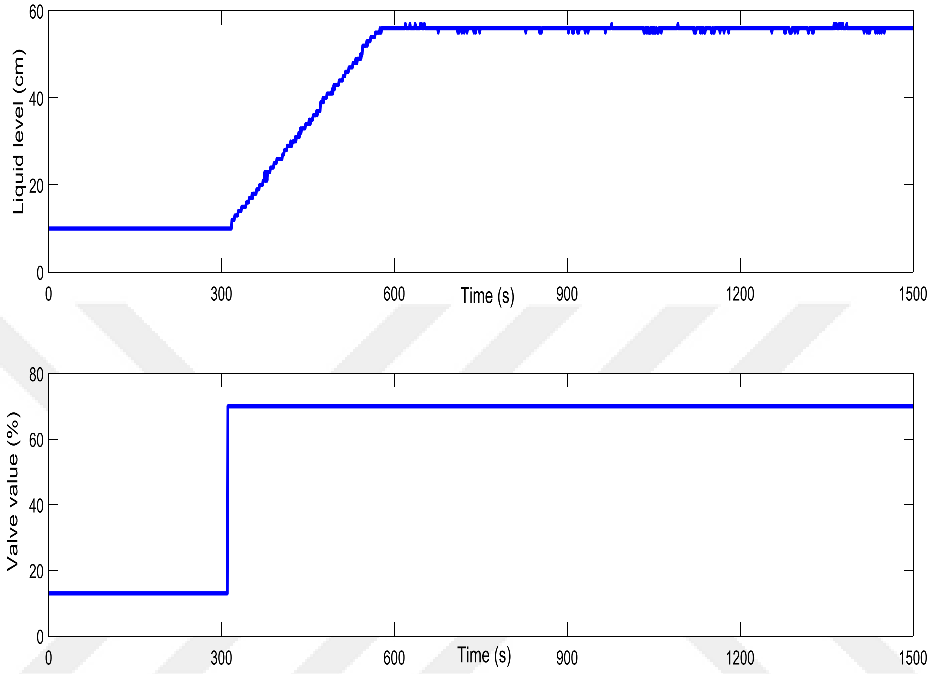


Figure 4.1. Liquid level changes with valve position of step effect.

Table 4.1. Process control coefficients of experimental liquid level system

Parameter	τ_d	τ	**Kc**
Value	16s	261s	0.842

The second type dynamic experiment applied to the system for output variable is made steady state at the desired value. A proportional control value is determined by taking the integral and derivative terms as zero and a step effect is given to the set point when the system is under this proportional control action. The output variable is oscillated by changing the proportional control value. The process parameters are calculated by the oscillation of the output variable.

The system was initially operated at 13% valve value and liquid level is fixed 10 cm. The output variable is oscillated by changing the proportional control action after the integral and derivative terms as zero. Liquid level changes between 27 cm and 72 cm in the measuring (upper) tank which given in the Figure 4.2. PID control parameters are calculated with Yuwana-Seborg method equations using control coefficients which determined from second dynamic experiment given in the Table 4.2.

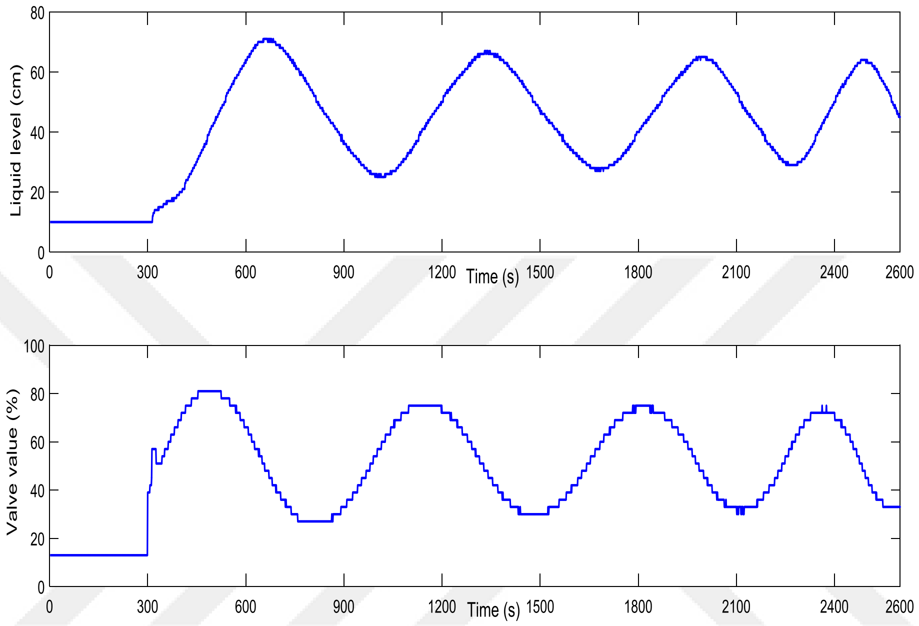


Figure 4.2. Liquid level changes with valve value for calculate Yuwana-Seborg constants.

Table 4.2. Determined control coefficients for 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
$C_{\square}$	47.678	d_m	311.1

4.2. PID control results of coefficients determined with Cohen-Coon method

The PID control coefficients calculated using the equations in Table 4.1 for the Cohen-Coon method are given in Table 4.3. Liquid level control experiments were carried out by selecting different set points using PID coefficients determined by Cohen-Coon method. In these control experiments, the changes of valve value and liquid level profiles over time was observed and the experimental results obtained are shown in Figures 4.3-4.5. Experimental results for different set points are investigated and it has been observed that the pneumatic valve is irregularly works on-off form. It has been observed that the valve is successful on level control despite the incessant and irregular on-off operation. The same behaviour of manipulated variable shown another studies such as temperature control (Jin et all., 2018). According to experimental results, it was determined that the liquid level control using PID parameters obtained by Cohen-Coon method was show the good performance and these coefficients were enough suitable for liquid level control. Cohen-Coon method parameters provide experimentally to achieve a fast and stable regulation result. The Cohen-Coon method parameters work well on processes where the dead time is less than two times the length of the time constant and can even be stretched further if process demands. A major problem with the Cohen-Coon parameters is that they tend not to be very robust; that is, a small change in the process parameters can cause the closed loop system to become unstable and lead to oscillatory closed loop behaviour (Mehta and Swarnalatha, 2018).

Table 4.3. Calculated PID control coefficients with Cohen-Coon method

Parameter	**K_P**	**PB**	**τ_I**	**τ_D**
Value	30.77	3.25	29.15	5.4

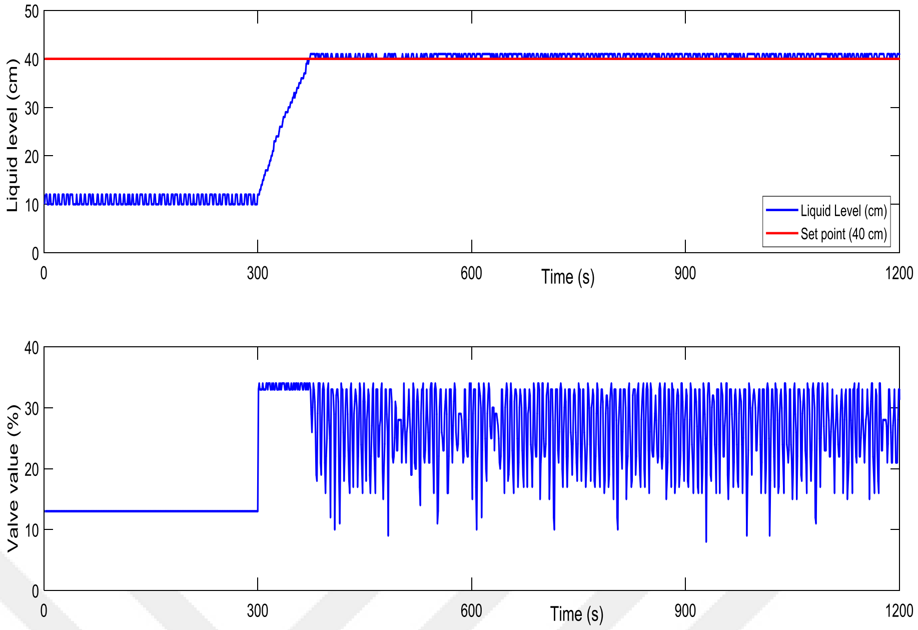


Figure 4.3. Liquid level changes with valve value for set point 40 cm using C-C method.

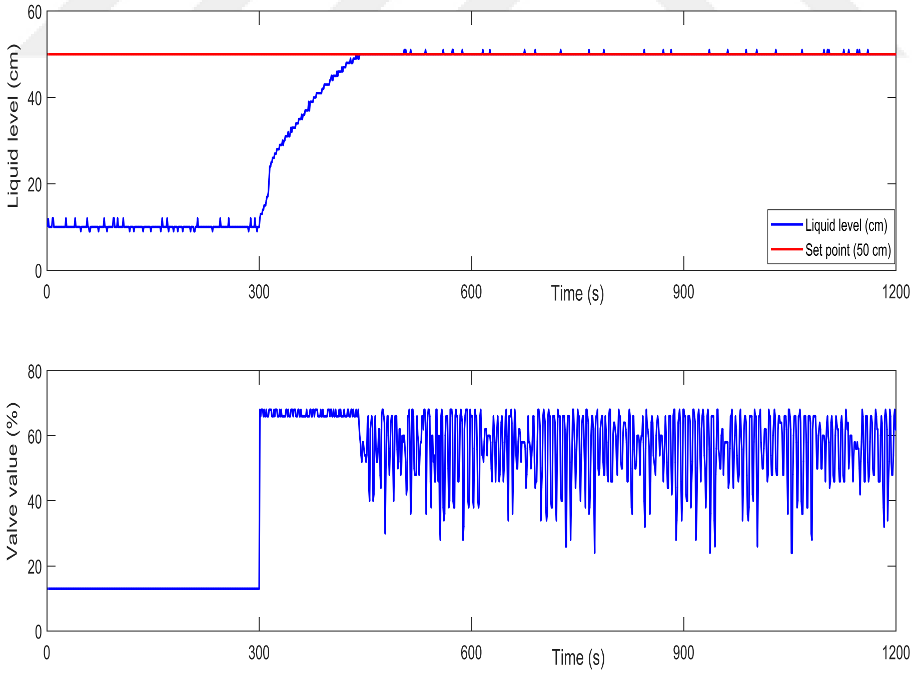


Figure 4.4. Liquid level changes with valve value for set point 50 cm using C-C method.

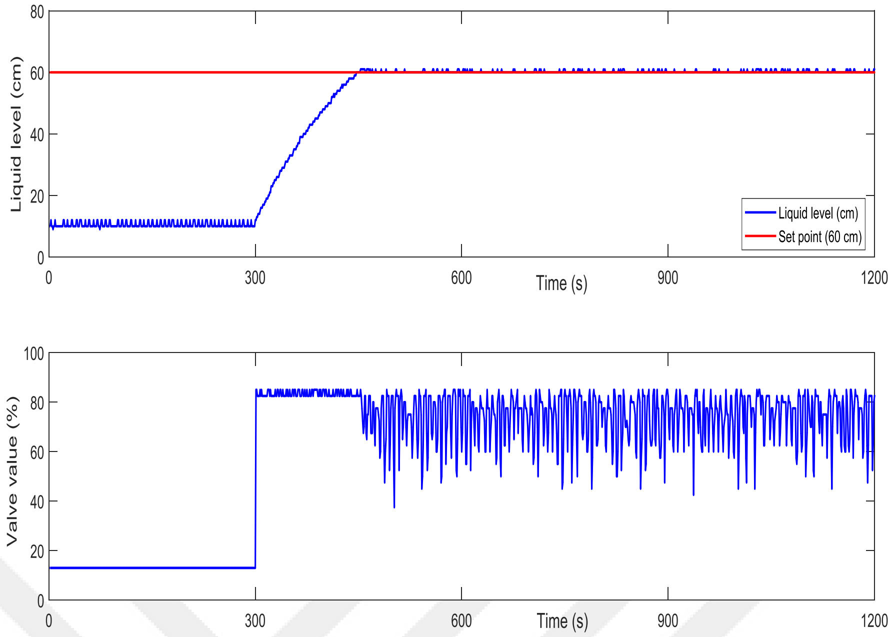


Figure 4.5. Liquid level changes with valve value for set point 60 cm using C-C method.

4.3. PID control results of coefficients determined with Ziegler-Nichols method

The PID control coefficients calculated by using the values of the dead time and time constant parameters which determined from the reaction curve are given in Table 4.4. PID control experiments were performed by selecting three different set points using the PID coefficients found by 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 4.6-4.8. According to the valve value, the liquid level was observed to be fixed with 1 cm, 2 cm and 5 cm offset for 40, 50, 60 cm set points respectively after an oscillation. Experimental results for different set points are investigated and it has been observed that the valve opening value is fixed with %32, %70 and %99 for 40, 50, 60 cm set points respectively. PID coefficients which determined by Ziegler-Nichols method were not sufficient for high level control and these coefficients were not suitable for liquid level control. Z-N parameters are found to be satisfactory for first–order processes with small dead–time but under set–point change and long dead–time it fails to keep the process within acceptable limit (Selvaraj and Nirmalkumar, 2015).

Table 4.4. Calculated PID control coefficients with Ziegler-Nichols method

Parameter	**K_P**	**PB**	**τ_I**	**τ_D**
Value	0.453	220.75	30.0	7.5

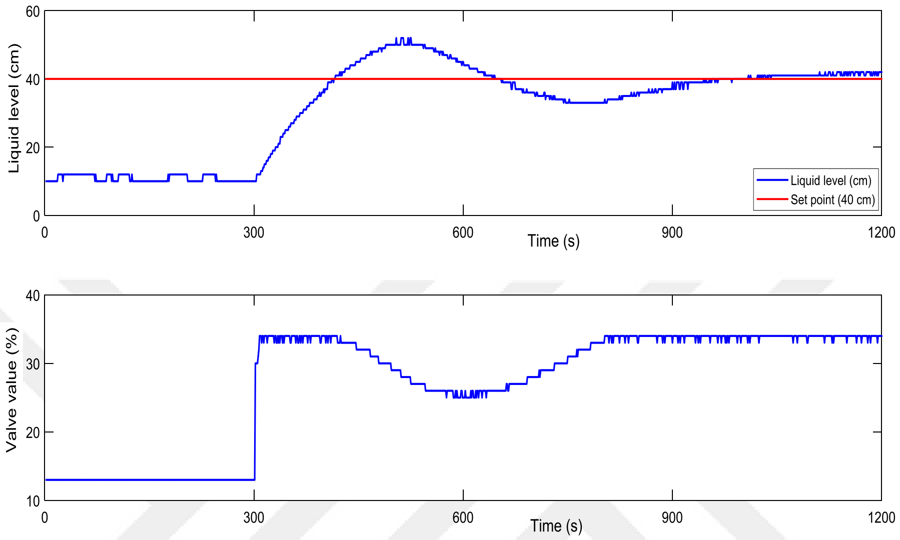


Figure 4.6. Liquid level changes with valve value for set point 40 cm using Z-N method.

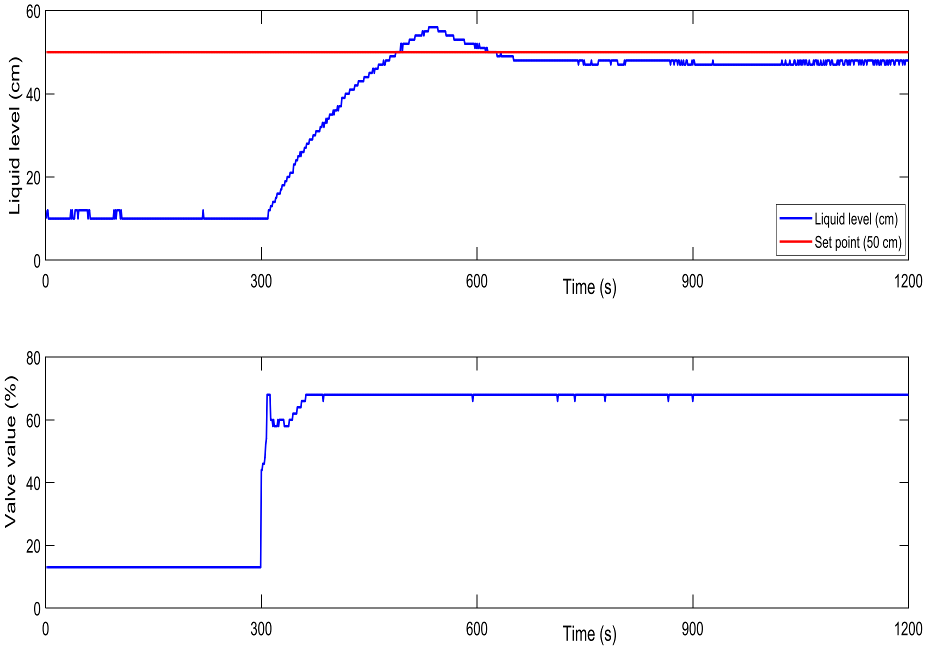


Figure 4.7. Liquid level changes with valve value for set point 50 cm using Z-N method.

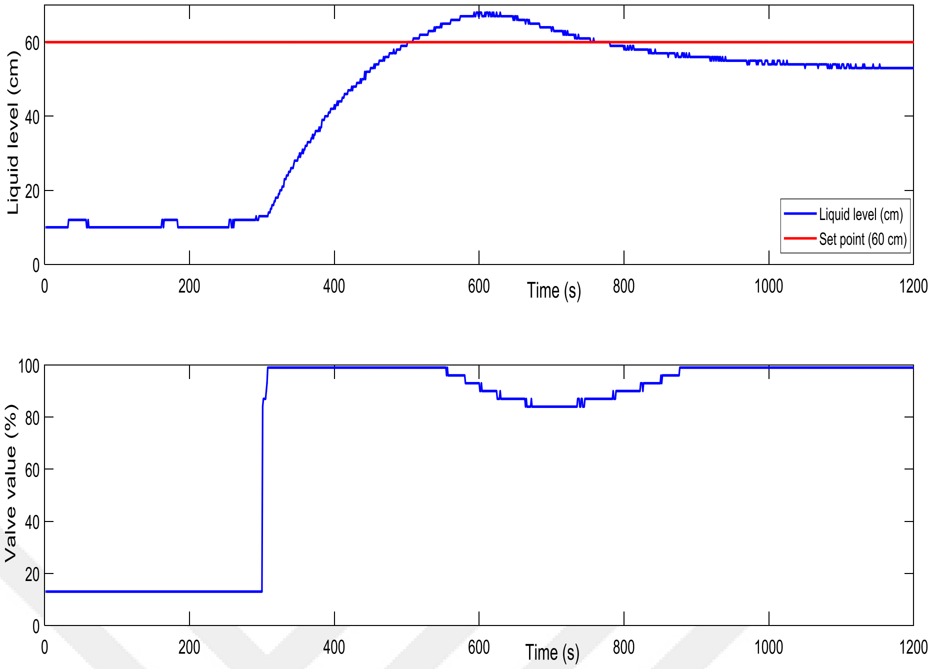


Figure 4.8. Liquid level changes with valve value for set point 60 cm using Z-N method.

4.4. PID control results of coefficients determined with Yuwana-Seborg method

The process constants which parameters are determined using the Fig. 4.3 and PID control coefficients values of the dead time and time constant parameters determined from the shown in are given in Table 4.5. PID control experiments were performed by selecting different set points using the PID coefficients found by the Yuwana-Seborg 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 4.9-4.11.

Table 4.5. Calculated PID control coefficients with Yuwana-Seborg method

Parameter	**K_P**	**PB**	**τ_I**	**τ_D**
Value	1.63	61.35	686.3	117.7

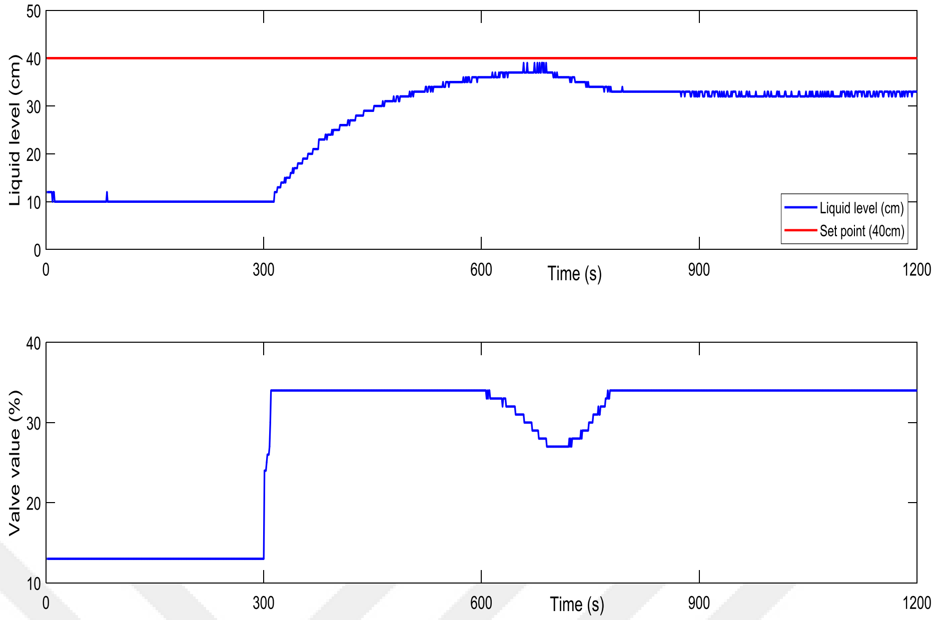


Figure 4.9. Liquid level changes with valve value for set point 40 cm using Y-S method.

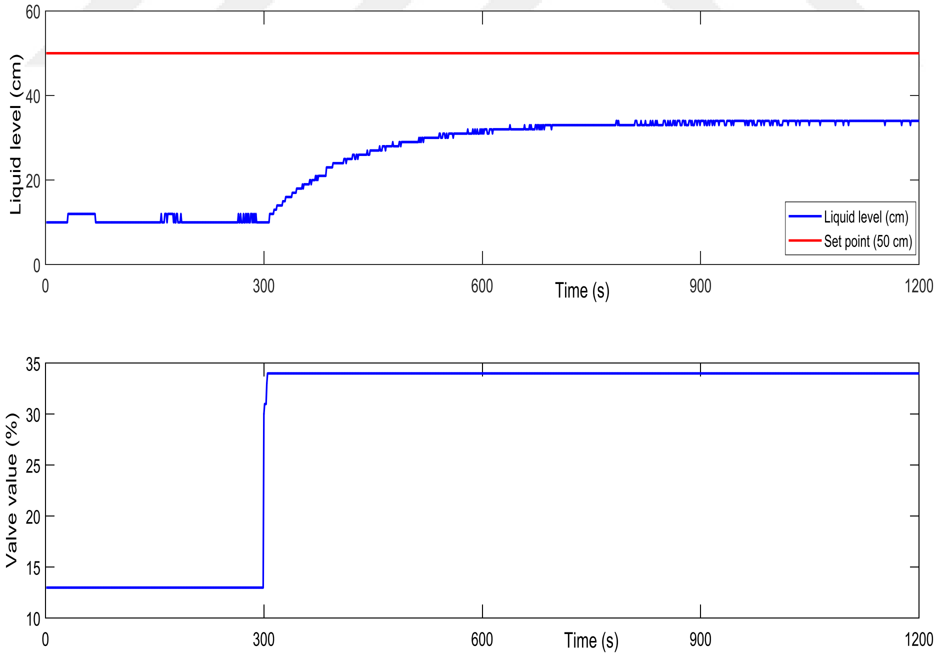


Figure 4.10. Liquid level changes with valve value for set point 50 cm using Y-S method.

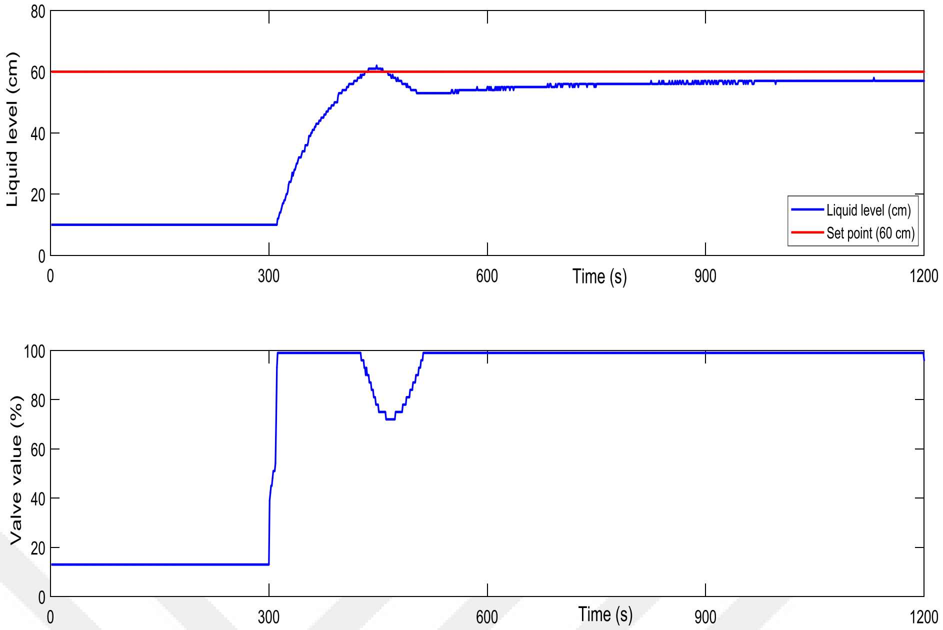


Figure 4.11. Liquid level changes with valve value for set point 60 cm using Y-S method.

According to the valve value, the liquid level was observed to be fixed with 7 cm, 15 cm and 3 cm offset for 40, 50, 60 cm set points respectively after an oscillation. Experimental results for different set points are investigated and it has been observed that the valve opening value is fixed with %34, %34 and %99 for 40, 50, 60 cm set points respectively. PID coefficients which determined by Yuwana-Seborg method were not sufficient for liquid level control according to Figure 4.9 and Figure 4.10. The practical advantages of the Yuwana-Seborg method are that it requires only a single closed-loop test and the algorithm is simple. The main disadvantage is that the test is performed under proportional control which introduces steady state offset during testing and consequently produces off-specification products (Mamat and Fleming, 1995). Also this method cannot be applied to mildly underdamped or overdamped closed-loop response. Moreover, it is inaccurate, especially when a large dead-time exists due to the use of the first order Páde approximation for the dead-time (Wang et. all., 2001).

The experimental results are investigated for the performance comparison of PID controller using three classical tuning methods. Comparison to these methods control parameters which determined with Cohen-Coon method were shown good performance on this experimental system for liquid level control. It was observed that manipulated variable showed the same behavior for Cohen-Coon and Ziegler-Nichols parameters on the liquid level control and wireless temperature control. But Ziegler-Nichols parameters were shown better performance than Cohen-Coon parameters on the wireless temperature control (Aldemir and Hapoğlu, 2016). Generally, it is difficult to define “optimality” of a controller, as there are many important aspects to take into consideration, including set-point response, disturbance rejection, robustness, input usage, and noise sensitivity. Often a control loop is evaluated solely 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 (Grimholt and Skogestad, 2018). Therefore IAE and ISE values are the most common used for determine controller performance in control engineering. Calculated IAE and ISE values using the data obtained after three different tuning methods with three different set points were given in Table 4.6 and Table 4.7 respectively.

Table 4.6. Calculated IAE values for 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 4.7. Calculated ISE values for 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

4.5. Preparing Simulation Diagram and Code for Calculation of Responses

Determining the optimum PID tuning parameters with simulations which proposed by the Design Expert 7.0 program were performed respectively by MATLAB/Simulink program, Figure 4.12. PID tuning parameters Kp, τ_I and τ_D which values were proposed by the program recorded on the MATLAB program, Figure 4.13. All other simulation conditions were kept constant while the values of Kp, τ_I and τ_D were changed at the liquid level control simulations and it was expected that level would be steady state by initially operating the valve opening at 10% for 300 s. At the end of 300s, 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, liquid level changes were continuously monitored and the values of these input and output variables were continuously recorded in minutes. ISE and IAE values were determined by using a constant set level and measured level after simulations and these values were processed in Design Expert 7.0 trial program for analyzing.

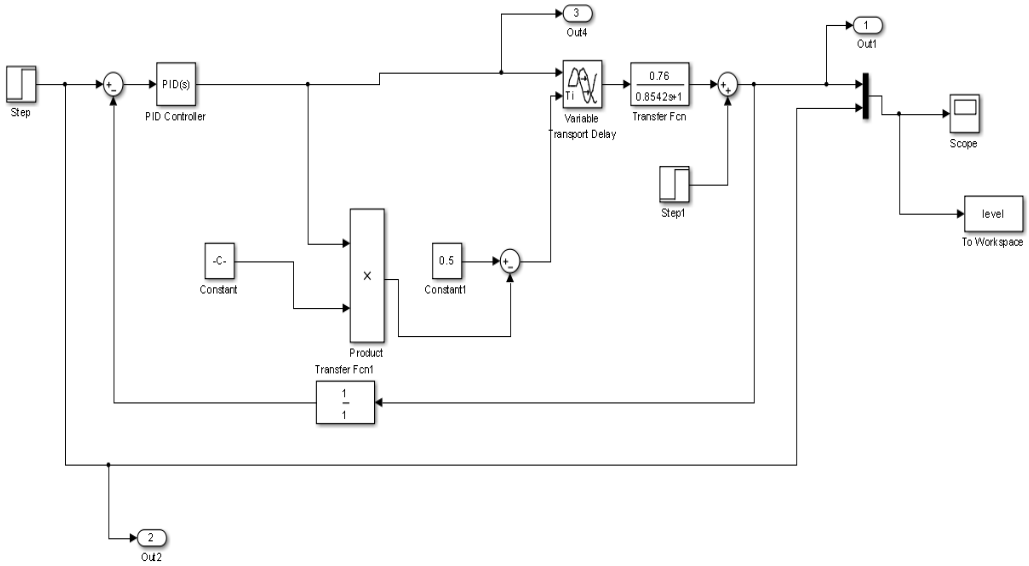


Figure 4.12. MATLAB/Simulink diagram of liquid level control system.

```
clc
%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.mat SONUC
```

Figure 4.13. MATLAB code of PID parameters for calculate IAE and ISE values

4.6. Simulation Results and Statistical Analysis of CCD

Kp, τ_I and τ_D tuning parameters of PID were chosen as the independent operating variables while ISE and IAE were the responses in the light of screening experiments and the literature research. The effects of three parameters, Kp, τ_I and τ_D were studied with the help of Design-Expert 7.0.0 trial program and the subsequent statistical analysis was performed by RSM. A statistical approach with a CCD was used for determining the interaction between these factors. The ranges of Kp, τ_I and τ_D parameters for CCD operating conditions were determined with Cohen-Coon and Ziegler-Nichols parameters. The region of exploration to locate the optimum operating conditions was decided 11.0 -40.0, 15.0 – 45.0 and 6.0 – 20.0 as Kp, τ_I and τ_D, respectively. The CCD was conducted with 20 experiments, including 8 star points, 6 axial points corresponding to the alpha value and 6 replicates at the center points. The tuning parameters at the center point were Kp 25.50, τ_I 30.00 and τ_D 13.00, which have been used for optimization of PID. Simulation runs which used different PID coefficients and calculated IAE, ISE responses after simulations given in the Table 4.8.

Table 4.8. Results of simulation runs with calculated 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 ($-\alpha$)	17489	1943
4	11.00 (-1)	45.00 (+1)	6.00 (-1)	23654	2793
5	25.50 (0)	30.00 (0)	24.77 ($+\alpha$)	17569	1995
6	40.00 (+1)	45.00 (+1)	6.00 (-1)	33476	4153
7	49.89 ($+\alpha$)	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 ($+\alpha$)	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 ($-\alpha$)	13.00 (0)	20564	1832
14	40.00 (+1)	45.00 (+1)	20.00 (+1)	33931	4169
15	1.11 ($-\alpha$)	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 4.8 presents the data resulting from investigation of the effect of three independent variables, Kp (X_1), τ_I (X_2) and τ_D (X_3) on the two responses ISE (R_1) and IAE (R_2). The data in Table 4.8 were run through RSM to construct an empirical models for the representation of ISE and IAE in terms of Kp, τ_I and τ_D tuning parameters of PID. Based on regression analysis at 95 % of confidence interval, the lack of fit error and p-values of parameter estimations were found to be significant. This indicates that a model except linear would better fit the data. The quadratic models were used to fit the observed data by least squares analysis and the following empirical models were obtained for ISE and IAE as Eq 4.1 and Eq 4.2, respectively.

$$ISE= +54058.10816 - 1977.96024 *[Kp] - 708.58871 * [T_I] - 367.21030 * [T_D] + 6.07529 * [Kp * T_I] - 2.37562 * [Kp * T_D] + 3.03929 * [T_I * T_D] + 38.40208 * [Kp^2] + 8.51565 * [T_I^2] + 12.39114 * [T_D^2] \qquad 4.1$$

$$IAE = +5704.62464 - 207.56067 * [K_p] - 65.26341 * [T_I] - 81.63389 * [T_D] - 0.055172 * [K_p * T_I] + 7.38916E{-}003 * [K_p * T_D] - 0.040476 * [T_I * T_D] + 4.51624 * [K_p^2] + 1.18198 * [T_I^2] + 3.59113 * [T_D^2] \qquad 4.2$$

In order to ensure the statistical significance of the quadratic model employed for explaining the experimental data at a 95% confidence level, the model was tested by analysis of variance (ANOVA) results. Evaluation of models for best fit with simulation results were given in the Table 4.9 and Table 4.10 for ISE and IAE responses, respectively. The ANOVA results of the quadratic model for the controller parameters of PID were given in the Table 4.11 and Table 4.12 for ISE and IAE responses, respectively. On the basis of the simulation values, statistical testing was carried out using Fisher's test for ANOVA.

Table 4.9. Evaluation of models for best fit with results on 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 4.10. Evaluation of models for best fit with results on 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 4.11. ANOVA results of 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 4.12. ANOVA results of 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			

From Table 4.11 and Table 4.12 there were observed that the regression was statistically significant at an F-value of 12.94 for ISE and 4.06 for IAE values with a very low probability value (P model 0.0002 for ISE and 0.0197 for IAE) on the liquid level control. Therefore, in the quadratic model that describes our process, an adequate precision of 12.426 for ISE and 7.095 for IAE values, indicates a satisfactory signal for the process. The statistical significance of the second-order equation revealed that the regression is statistically significant (P model 0.0002 for ISE and 0.0197 for IAE). In this case Kp, Kp^2 and T_I^2 are significant model terms for ISE but only Kp^2 is significant term for IAE. The results indicate that the response equation proved to be suitable for the CCD experiments.

Table 4.13. Statistical values of ISE on the 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 4.14. Statistical values of IAE on the 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

The statistical results of ISE and IAE responses on the liquid level control were given in the Table 4.13 and Table 4.14, respectively. The fit of the model was controlled by the coefficient of determination R^2. Based on the ANOVA results, the model reports high R^2 values of 92.09% for ISE and 78.52% for IAE were found. Also, an acceptable agreement with the adjusted determination coefficient is necessary. In this study, the adjusted R^2 values of 84.98% for ISE and 59.18% for IAE were found. The values of R^2 are advocates a high correlation between the observed values and the predicted values. This indicates that the regression model provides a good explanation of the relationship between the three independent variables and the two responses (Aldemir et all., 2015).

4.7. Response surface plots of PID control parameters for ISE and IAE

Figure 4.14 – 4.16 and Figure 4.17 - 4.19 describes the response surface profiles for the calculated ISE and IAE values of liquid level control with PID tuning parameters, respectively. The curvatures nature of 3D surfaces showed that there is significant and moderate interactions among the variables considered for the ISE and IAE values. Figure 4.14 – 4.16 indicates the mutual interaction of ISE with Kp, τ_I, ISE with Kp, τ_D, and ISE with τ_I, τ_D and Figure 4.17 – 4.19 indicates the mutual interaction of IAE with Kp, τ_I, IAE with Kp, τ_D and IAE with τ_I, τ_D, respectively. The plot for the interaction between Kp (X_1), τ_I (X_2) and τ_D (X_3) Figure 4.14 and Figure 4.15 shows that increasing two independent variables above and below the center points increases the ISE values. Similarly in Figure 4.17 and Figure 4.19 two independent variables above and below the center points increases the IAE values.

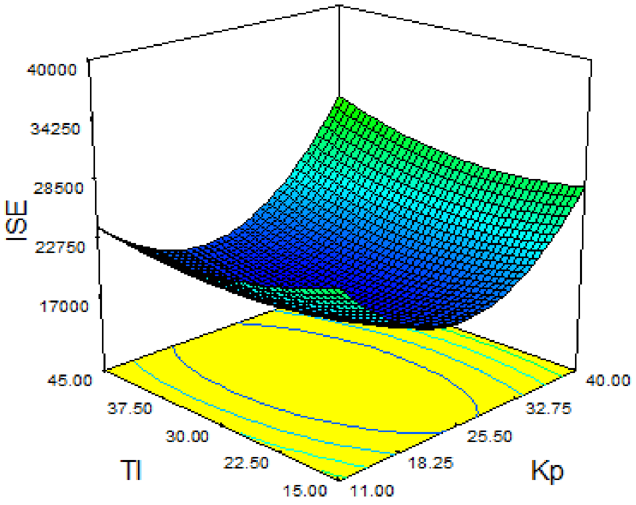


Figure 4.14. Response surface plot of interaction between Kp and T_I on ISE.

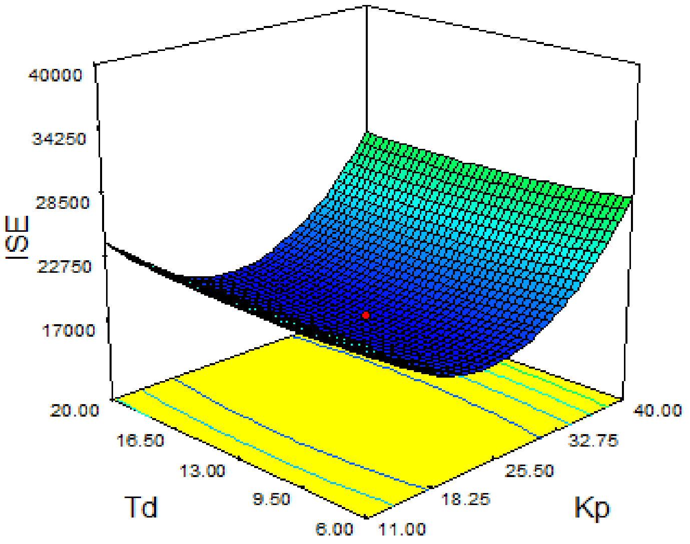


Figure 4.15. Response surface plot of interaction between Kp and Td on ISE.

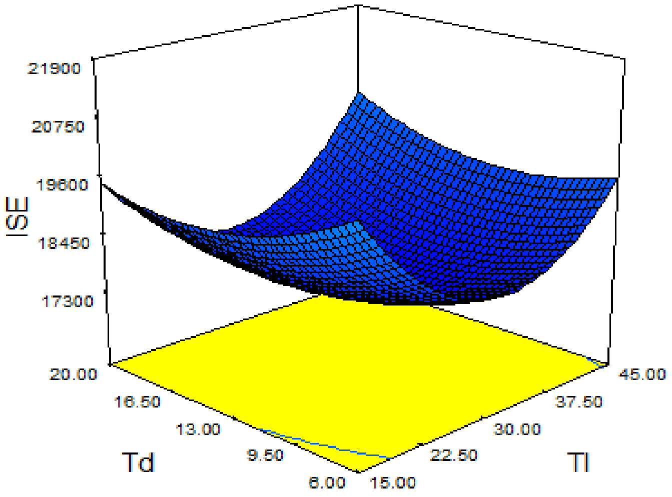


Figure 4.16. Response surface plot of interaction between TI and Td on ISE.

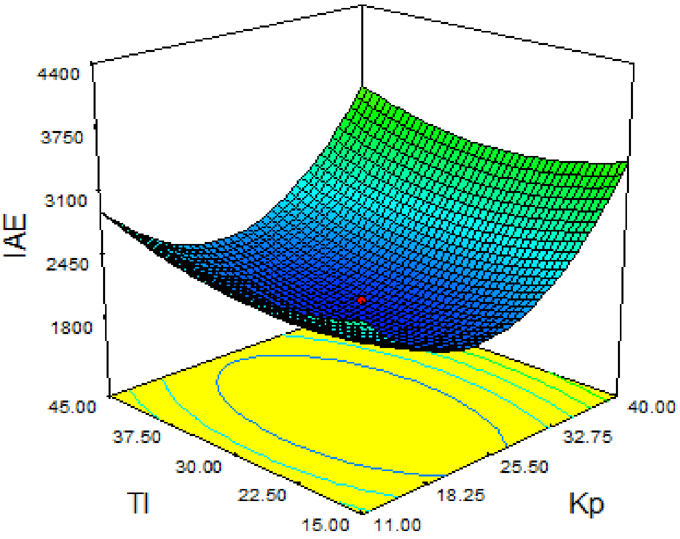


Figure 4.17. Response surface plot of interaction between Kp and Tı on IAE.

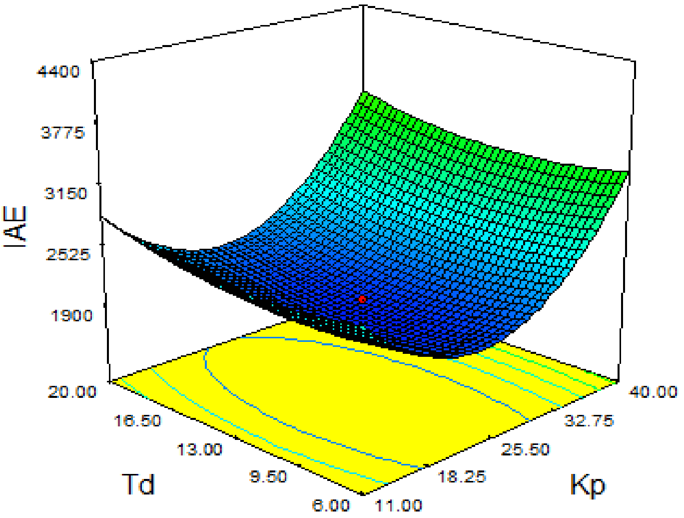


Figure 4.18. Response surface plot of interaction between Kp and Td on IAE.

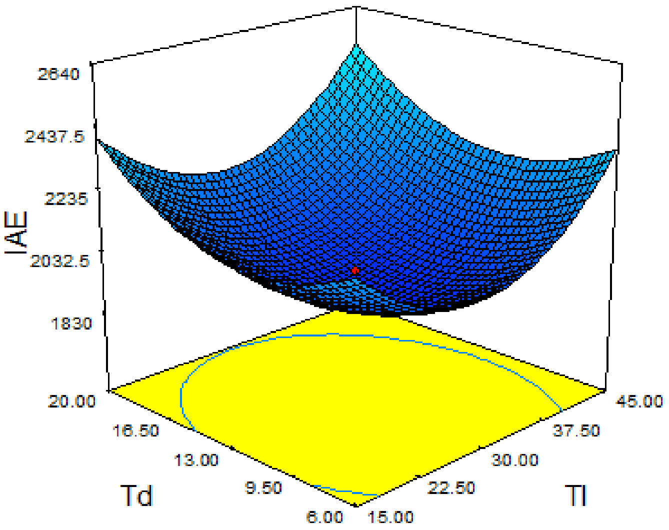


Figure 4.19. Response surface plot of interaction between T_I and Td on IAE.

4.8. Determination of optimum PID control parameters for liquid level control

The optimum magnitudes of the most significant parameters to minimize the ISE and IAE values for liquid level control with PID control parameters were evaluated by application of Equation (8). The *xs*, *b* and *B* matrices in Equation (8) were arranged by Equation (9) and Equation (10), for ISE and IAE respectively, which includes the effects of the tested parameters. *xs*, *b* and *B* matrices were formed as follows [18]:

$$x_S = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \quad , \quad b = \begin{bmatrix} -1977.96024 \\ -708.58871 \\ -367.21030 \end{bmatrix}$$

$$B = \begin{bmatrix} +38.40208 & +6.07529/2 & -2.37562/2 \\ +6.07529/2 & +8.51565 & +3.03929/2 \\ -2.37562/2 & +3.03929/2 & +12.39114 \end{bmatrix}$$

Optimum values of Kp (X_1), τ_I (X_2) and τ_D (X_3) for minimize the ISE were calculated to be 23.7319, 30.7627 and 13.3197, respectively.

$$x_S = \begin{bmatrix} \mathrm{X}_1 \\ \mathrm{X}_2 \\ \mathrm{X}_3 \end{bmatrix} \quad , \quad b = \begin{bmatrix} -207.56067 \\ -65.26341 \\ -81.63389 \end{bmatrix}$$

$$B = \begin{bmatrix} +4.51624 & +0.055172/2 & (+7.38916{*}\mathrm{E}{-}3)/2 \\ +0.055172/2 & +1.18198 & -0.040476/2 \\ (+7.38916{*}\mathrm{E}{-}3)/2 & -0.040476/2 & +3.59113 \end{bmatrix}$$

Optimum values of Kp (X_1), τ_I (X_2) and τ_D (X_3) for minimize the IAE were calculated to be 22.8034, 27.2723 and 11.4963, respectively.

In addition, numerical optimization was used to determine the optimum PID tuning parameters for the liquid level control as indicated in Section 3.4. The optimization criteria specified in the Materials and Methods section were entered into the Design Expert 7.0.0 trial program. Optimization solutions proposed by the program were obtained. The optimization criteria of the Design Expert program for liquid level control with PID tuning parameters were given in Table 4.15 and the optimization solution proposed by the program are given in Table 4.16.

Table 4.15. Optimization criteria of program for the studied range

Parameters	**Goal**	**Lower limit**	**Upper limit**	**Importance**
Kp (X_1)	is in range	11	40	3
τ_I (X_2)	is in range	15	45	3
τ_D (X_3)	is in range	6	20	3
ISE (R_1)	minimize	17452	39652	3
IAE (R_2)	minimize	1832	4568	3

Table 4.16. Optimum PID parameters and responses recommended by the program

Parameters		**ISE (R_1)**	**IAE (R_2)**	**Desirability**
Kp (X_1)	23.14	17368	1908	1.00
τ_I (X_2)	28.31			
τ_D (X_3)	11.50			

Optimization procedure carried out with desirability function. The desirability function technique is one of the most widely used engineering applications for the parameter optimization. According to this function, the ISE and IAE values of every determined response is transformed to a dimensionless desirability value (d). The value of the function is ranges between 0 and 1. The value of d increase as the desirability of corresponding response increases. In this work, ISE and IAE values are selected minimum for the better PID parameters of liquid level control system. In order to obtain the lowest values of ISE and IAE optimum values of PID tuning parameters studied for liquid level control were Kp 23.14, τ_I 28.31 and τ_D 11.50.

Determining PID control parameters have been divided mainly into three categories: formula based, rule based and optimization based tuning. Several tuning methods were developed for PID control and most of them applied to the real systems. There are a few applications of RSM for determining optimal control parameters. RSM applied to optimize PID controller parameters for pH and electrical conductivity values of an batch electrocoagulation process in which pulp and paper mill wastewater was treated, and to determine 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 (Camcıoğlu et. all., 2017). Control of the absorption column was carried out using a PID controller with the manipulated variable is the affluent water flow to the column, and the controlled variable corresponds to the component (CO_2) concentration in the gas stream effluent to the column. The numerical values for proportionality constants Kp, τ_I and τ_D were defined using the experimental design through a CCD whose study range 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 on the MATLAB software. Responses ranged from 0.1979 to 1.1632, and the lowest found value represents about 55% improvement in ITAE in comparison to the simulation using the initial estimated values. It is observed that the p-value for the significant terms was much lower than 0.05, confirming its significance (Gasparovic et. all., 2018). Proportional Integral (PI) control coefficients for a permanent magnet brushless direct current motor drive were determined with RSM. The system has the properties of stability, low overshoot level and fast response. PI control parameters, Kp and τ_I selected input parameters and maximum overshoot with settling time selected responses. Totally 13 experiments carried out which include standard eight experiments for cube and axial points and five experiments (as default) for the center points. The optimal values of Kp and τ_I parameters were obtained as 638.65 and 56.814. Experimental results were given to show the validity of this method (Demirtaş and Karaoglan, 2012).

In this thesis, RSM was used for determination of optimum PID controller parameters to minimize the ISE and IAE performance criteria after three most widely used PID tuning methods applied to the experimental liquid level system. Although the experimental and simulation results in this thesis 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 kind of disturbances. As discussed in this thesis, 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 optimal PID parameter tuner design to fulfill the online optimization if needed. This provides more flexibility for control system designers.

5. CONCLUSION

PID controllers are the most used systems in the industrial field and find the most research and application area in control engineering. The control output is generated by the addition of three terms called proportional, integral and derivative. Some experimental methods have been developed to tuning the PID control parameters. These methods are applied to the open-loop systems without control, but the parameters determined by these methods may not be effective in nonlinear, variable parameter and unstable systems. Also it is desirable for control systems to be able to meet servo and regulatory problems; however, each of applications will have an optimal set of values for the parameters, requiring a global optimum solution. In this case, it is necessary to determine the optimal control parameters.

- In this thesis, an experimental liquid level control system was used for determining the optimal PID control parameters. Two different dynamic analysis carried out on the liquid level control system for determining PID control parameters. Based on these dynamic effects PID parameters were calculated with three commonly used methods (Cohen-Coon, Ziegler-Nichols, Yuwana-Seborg). PID control parameters applied for the 40cm, 50cm and 60cm set points and after experiments ISE and IAE control performance values were calculated.
- The first dynamic experiment was performed in which a step change was applied to the valve value for determine the dead time, time constant and process gain values on the process reaction curve. The dead time, time constant and gain values were calculated to be 16s, 261s and 0.842, respectively. PID control parameters were calculated with Cohen-Coon and Ziegler-Nichols equations using control coefficients which determined from first dynamic experiment.
- Cohen-Coon method which the first of the classical methods used in the thesis and Kp, τ_I, τ_D parameters were calculated to be 30.77, 29.15 and 5.4, respectively. After experiments IAE and ISE values were calculated 1455, 1983, 3216 and 17915, 41593, 92168 for the 40cm, 50cm and 60cm set points, respectively. According to experimental results it has been observed that the pneumatic valve is irregularly works on-off form

but the valve is successful on level control despite the incessant and irregular on-off operation.

- Ziegler-Nichols method which the second of the classical methods used in the thesis and Kp, τ_I, τ_D parameters were calculated to be 0.453, 30.0 and 7.5, respectively. After experiments IAE and ISE values were calculated 4495, 5008, 7233 and 48155, 87640, 137865 for the 40cm, 50cm and 60cm set points, respectively. According to the valve value, the liquid level was observed to be fixed with 1 cm, 2 cm and 5 cm offset after an oscillation for 40, 50, 60 cm set points, respectively. The valve value is fixed with %32, %70 and %99 for 40, 50, 60 cm set points respectively. PID coefficients which determined by Ziegler-Nichols method were not sufficient for high level control and these coefficients were not suitable for liquid level control.
- Yuwana-Seborg method which the third of the classical methods used in the thesis and Kp, τ_I, τ_D parameters were calculated to be 1.63, 686.3 and 117.7, respectively. After experiments IAE and ISE values were calculated 7714, 17536, 5796 and 93950, 366660, 104558 for the 40cm, 50cm and 60cm set points, respectively. According to the valve value, the liquid level was observed to be fixed with 7 cm, 15 cm and 3 cm offset for 40, 50, 60 cm set points respectively after an oscillation. Experimental results for different set points are investigated and it has been observed that the valve opening value is fixed with %34, %34 and %99 for 40, 50, 60 cm set points respectively. PID coefficients which determined by Yuwana-Seborg method were not sufficient for 40cm and 50cm control.
- Comparison to these methods control parameters which determined with Cohen-Coon method were shown best performance on this experimental system for liquid level control. Another way to comparison of the controller performance is calculated the error values. Therefore ISE and IAE values are the most common used for determine controller performance in control engineering.
- The optimum values of the PID control parameters are determined by Response Surface Method (RSM). Kp, τ_I, τ_D as independent parameters and ISE and IAE values are chosen as dependent variables (responses). Numerical values of the responses for the runs in the design matrices 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. The models were developed through RSM in terms of related independent variables to describe the ISE and IAE as the two responses.

- The optimum PID control parameters of liquid level control system for minimize the ISE and IAE values were evaluated by matrix equations. Optimum values of Kp, τ_I and τ_D for minimize the ISE were calculated to be 23.7319, 30.7627 and 13.3197, respectively. Optimum values of Kp, τ_I and τ_D for minimize the IAE were calculated to be 22.8034, 27.2723 and 11.4963, respectively. In order to obtain the lowest values of ISE and IAE optimum of PID tuning parameters determined for liquid level control were Kp 23.14, τ_I 28.31 and τ_D 11.50 with numerical optimization of Design Expert 7.0 trial program. It is seen that these determined optimum PID controller parameters are close to each other.

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EXTENDED TURKISH SUMMARY
(GENİŞLETİLMİŞ TÜRKÇE ÖZET)

CEVAP YÜZEY YÖNTEMİ İLE PID KONTROL PARAMETRELERİNİN BELİRLENMESİ

ÖZ

PID kontrol ediciler, endüstriyel alanda halen en çok kullanılan ve kontrol mühendisliğinde en çok araştırma ve uygulama alanı bulan sistemlerdir. PID kontrol edici sinyali, oransal, integral ve türevsel olarak adlandırılan üç terimin toplanması ile kontrol çıktısı oluşturulur. PID kontrol parametrelerinin ayarlanması için bazı deneysel yöntemler geliştirilmiştir. Bu yöntemler kontrolün olmadığı açık-hat sistemlere uygulanır ancak doğrusal olmayan, değişken parametreli ve kararsız sistemlerde bu yöntemler ile belirlenen parametreler etkili olmayabilir. Bu durumda optimal PID kontrol parametrelerinin belirlenmesi gereklidir.

Bu tez kapsamında, Van Yüzüncü Yıl Üniversitesi, Kimya Mühendisliği Bölümünde bulunan sıvı seviye kontrol deney sistemi kullanılmıştır. Basamak etki değişimi ile hazırlanan reaksiyon eğrisi üzerinden deney sistemine ait ölü zaman, zaman sabiti ve proses kazancı belirlenmiştir. Optimum PID kontrol parametrelerinin değerleri, Cevap Yüzey Yöntemi (CYY) ile belirlenmiştir. Kapalı çevrim PID kontrolörü ile MATLAB/Simulink'te tasarlanan sıvı seviye deney sistemi blok diyagramı kullanılarak simülasyon sonuçlarının sayısal değerleri belirlenmiştir. Bağımsız parametreler olarak Kp, τ_I, τ_D ve bunlara karşılık deney sonrası hesaplanan ISE ve IAE değerleri bağımlı değişkenler (yanıt) olarak seçilmiştir. Design Expert 7.0 programı deneme versiyonu tarafından önerilen deney listesindeki deneyler sırasıyla gerçekleştirilmiş ve deneylerden sonra hesaplanan IAE ve ISE değerleri programa işlenerek sonuçlar değerlendirilmiştir.

Anahtar kelimeler: cevap yüzey yöntemi, IAE, ISE, PID kontrol, sıvı seviye

1. GİRİŞ

PID kontrol ediciler, kolay temin edilebilmeleri, düşük maliyetleri, hem ayrı sistem olarak hem de algoritma şeklinde gömülü olarak kullanılabilmeleri, kontrol hassasiyeti, uygulama prensiplerinin anlaşılır olması ve kontrol parametrelerinin ayarlama kolaylığı nedeniyle günümüzde halen en yaygın kullanılan kontrol sistemleridir. PID kontrol sistemi proses çıkışındaki ölçülen değer ve set değeri arasındaki fark olan hatayı üç ayrı matematiksel işlemden geçirilip toplanması ile kontrol çıktısını oluşturur. Buna bağlı olarak PID kontrolün proses üzerindeki etkisi oransal-integral-türevsel olarak üç temel parametrenin etkileri verildiği şekilde ayrıştırılır: Oransal etki, kontrol edici çıkışına hatanın belirli bir "Kazanç" değeri ile çarpımı kadar etki gösterir. İntegral etki, kontrol edici çıktısında kontrol işlemi başladığı andan etkinin hesaplandığı zamana kadar geçen tüm zamanlardaki hatanın toplamına orantılı olarak etkisini gösterir. Bu integral etkisi sistemin geçmişteki yaptığı hataların toplamını ifade eder. Türevsel etki, kontrol edici çıktısına hatanın değişimi ile doğru orantılı olarak etkisini gösterir.

PID kontrol edici parametrelerinin ayarlanması için uygulanabilecek çeşitli yöntemleri geliştirilmiştir. Bu yöntemler parametrik veya parametrik olmayan yapıda tasarlanabilirler ve deneysel olarak sistemin giriş ve çıkış değişken değerlerini kullanırlar. PID parametrelerinin ayarlama yaklaşımlarında, (Cohen ve Coon 1953); (Ziegler ve Nichols, 1942) öncüler arasındadır. Bu araştırmacılar proses reaksiyon eğrisine bağlı belirlenen proses değerlerini kullanarak geliştirdikleri eşitliklerin kurulu deneysel PID ayarlama yaklaşımını öngörmüşlerdir. Bununla birlikte, değişken zaman gecikmesi, yüksek mertebeden, minimum olmayan faz ve doğrusal olmayan prosesler gibi sistemler olduğunda bu yöntemler yetersiz olabilir. Bu nedenle farklı yöntemler geliştirilmeye devam etmektedir. Bu yöntemlerin bazıları çıkış ve set değeri arasındaki fark olarak hesaplanan hata değerlerine bağlı olarak geliştirilmektedir.

Sıvı seviye kontrolünde, set noktası sapmasını en aza indirmek ve salınımsız kontrol sağlamak için iyi bir kontrol edici tasarlamak gerekir. Ayrıca, seviye kontrolün iki önemli gereksinimi vardır: (1) çıkış akışındaki değişim oranı, izin verilen bir sınırın altında tutulmalı ve (2) seviye sapması izin verilen bir sınır dahilinde olmalıdır. Bu nedenle, seviye kontrol problemleri tipik bir optimal kontrol problemi olarak düşünülebilir. Endüstriyel ve ekonomik önemi nedeniyle bu tez kapsamında sıvı seviye kontrolü için CYY ile optimum PID kontrol parametrelerinin belirlenmesi hedeflenmiştir.

2. KAYNAK BICDIRSLERI

PID kontrol parametrelerinin belirlenmesi formül temelli, kural temelli ve optimizasyon temelli olarak üç kategoriye ayrılmıştır. PID kontrolü için çeşitli ayar yöntemleri geliştirilmiştir ve çoğu gerçek sistemlere uygulanmıştır. Optimum PID kontrol parametrelerini belirlemek için bazı CYY uygulaması vardır. Kağıt fabrikası atık suyunun işlendiği bir elektrokoagülasyon prosesinde kirletici maddelerin uzaklaştırılması ve enerji tüketimi üzerindeki etkilerini belirlemek için pH ve elektriksel iletkenlik değerleri ile PID kontrolör parametrelerini optimizasyonu ve kontrol etkisi için CYY uygulanmıştır. ISE, IAE, ITAE ve ITSE değerleri PID kontrol performans göstergeleri cevaplar olarak seçilmiştir (Camcıoğlu ve ark., 2017). Absorpsiyon kolonunun kontrolü, bir PID kontrol kullanılarak gerçekleştirildi ve kolonda çıkan su akışı ayarlanabilen değişken ve kolona akan gaz akışındaki bileşen (CO_2) konsantrasyonu kontrol edilen değişken, karşılık gelir. PID kontrol parametreleri Kp, τ_I ve τ_D için sayısal değerler, çalışma aralığı başlangıçtaki bir tahminden tanımlanmış bir CCD aracılığıyla deney tasarımı kullanılarak tanımlanmıştır. Yanıt değişkeni olarak ITAE performans kriteri seçilmiş ve deney tasarım çalışmaları, MATLAB yazılımı üzerinde geliştirilen bir programdaki simülasyonlar kullanılarak gerçekleştirildi. Yanıtlar 0.1979 ile 1.1632 arasında değişmiştir ve bulunan en düşük değer, ilk tahmini değerleri kullanan simülasyona kıyasla ITAE'de yaklaşık% 55 iyileşme göstermektedir. Anlamlı terimler için p değerinin anlamlılığını teyit ederek 0.05'ten daha düşük olduğu gözlenmiştir (Gasparovic ve ark., 2018). Sabit mıknatıslı bir fırçasız doğru akım motor sürücüsü için PI kontrol katsayıları CYY ile belirlenmiştir. Sistem kararlılık, düşük aşma seviyesi ve hızlı tepki özelliklerine sahiptir. PI kontrol parametreleri, Kp ve τ_I seçili giriş parametreleri ve yerleştirme süresi seçilen yanıtlarla maksimum aşma. Küp ve eksenel noktalar için sekiz ve merkez noktada beş deney içeren toplam 13 deney yapıldı. Kp ve τ_I parametrelerinin optimal değerleri 638.65 ve 56.814 olarak elde edildi.

Bu yöntemin geçerliliğini göstermek için farklı deneysel sonuçlar verilmiştir (Demirtaş ve Karaoğlan, 2012).

3. MATERYAL ve YÖNTEM

Sıvı seviye kontrolü için kullanılan bir sıvı seviye kontrol deney sisteminde ve ayarlanabilen değişken olan vana açıklığına uygulanan basamak etki ile sıvı seviyesinin zamanla değişimini gösteren dinamik veriler elde edildi. Ölü zaman, zaman sabiti ve kazanç değerlerinin belirlenmesi için proses reaksiyon eğrisi hazırlandı. Cohen-Coon, Ziegler-Nichols ve Yuwana-Seborg yöntemleri ile PID kontrol parametreleri belirlendi. Bu parametreler ile farklı set değerleri için sıvı seviye kontrol deneyleri yapıldı. Bu deneylerin ardından ISE ve IAE değerleri hesaplandı. Deney sisteminin proses ekipmanlarını içeren MATLAB/Simulink programında blok diyagramı hazırlandı. Ayrıca sıvı seviye kontrol deneylerinden sonra ISE ve IAE değerlerini hesaplayacak MATLAB kodu yazıldı. PID kontrol parametrelerinin optimum değerlerini belirlemek için klasik yöntemler ile belirlenen kontrol parametrelerinin değerlerini içeren çalışma aralığında Design Expert 7.0 programı ile simülasyon tasarımı yapıldı. Simülasyon sonrasında hesaplanan ISE ve IAE değerleri programa kaydedilerek optimal PID kontrol parametreleri belirlendi.

3.1. Sıvı Seviye Kontrol Deney Sistemi

Sıvı seviye kontrol sistemi, mekanik bir düzenek üzerine kurulmuş üç sıvı tankından, hava basıncını ayarlamak için bir regülatöre bağlı pnömatik bir vanadan, sıvı seviyesini gösteren bir elektronik panelden oluşur. Depolama tankındaki su, dalgıç pompa ile pvc borularda taşınarak pnömatik vanadan geçirildikten sonra seviye kontrol tankına doldurulur. Taşmayı önlemek için, seviye kontrol tankının ortasındaki bir pvc boşaltma borusu ile altındaki boşaltma tankına bağlanır. Boşaltma ve depolama tankları, bu tanklardaki sıvı seviyesini dengelemek için pvc boru ile birbirine bağlanmıştır. Bu tanklardaki suyu boşaltmak için alt tanklara bir tahliye vanası bağlanmıştır. Sistemde, pnömatik vananın çalışması için gerekli olan basınçlı hava, kompresör tarafından sağlanır ve vanaya istenen basınç değeri regülatör ile ayarlanarak gönderilir.

3.2. Yöntem (Deneysel Prosedür)

Sıvı seviye kontrol deneyleri, bilgisayar bağlantısı olan seviye kontrol deney sistemi ile çevrimiçi olarak yapıldı. Sıvı seviye kontrol sisteminde yapılan deneyler sırasında, giriş değişkeni olan vana açıklık değeri ve çıkış değişkeni olan sıvı seviye verileri otomatik olarak kaydedilir. Deneyler esnasında sıvı seviyesi ve vana açıklık değerlerinin zamanla değişimini gösteren grafikler ekranda görüntülenir.

4. BULGULAR TARTISMA VE SONUC

Bu tez çalışmasında, optimum PID kontrol parametrelerinin belirlenmesi için deneysel bir sıvı seviye kontrol sistemi kullanılmıştır. PID kontrol parametrelerinin belirlenmesi için sıvı seviye kontrol sisteminde iki farklı dinamik analiz yapılmıştır. Bu dinamik etkilere dayanarak PID parametreleri üç yaygın yöntemle (Cohen-Coon, Ziegler-Nichols, Yuwana-Seborg) hesaplandı. 40cm, 50cm ve 60cm ayar noktaları ve deneylerden sonra uygulanan PID kontrol parametreleri ISE ve IAE kontrol performans değerleri hesaplandı.

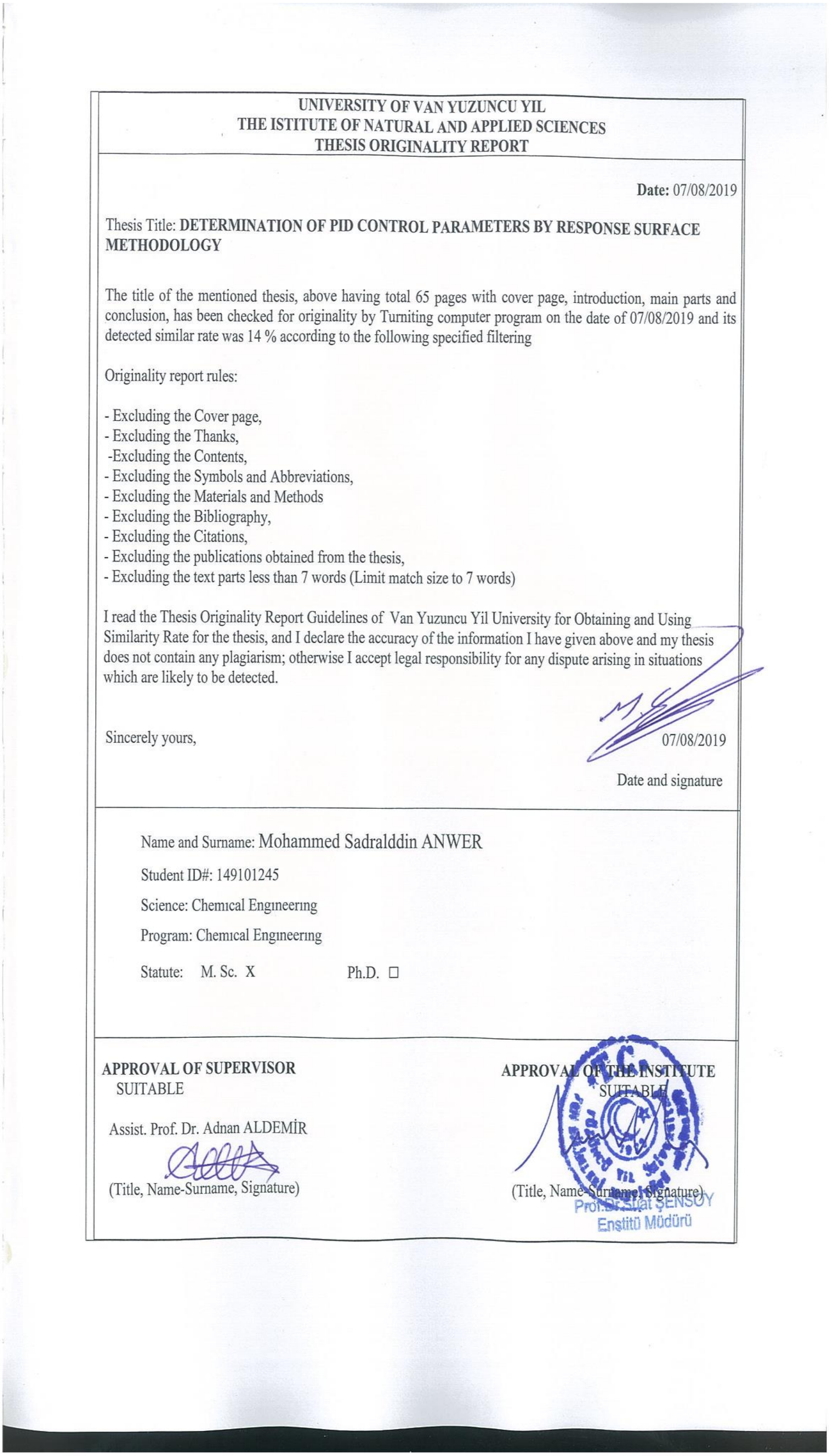
- İlk dinamik deney, proses reaksiyon eğrisi üzerindeki ölü zaman, zaman sabiti ve proses kazanç değerlerini belirlemek için vana açıklık değerine bir basamak etki uygulandı. Ölü zaman, zaman sabiti ve kazanç değerleri sırasıyla 16s, 261s ve 0.842 olarak hesaplandı. PID kontrol parametreleri, ilk dinamik deneyden belirlenen katsayılar kullanılarak Cohen-Coon ve Ziegler-Nichols denklemleri ile hesaplandı.
- Tezde kullanılan klasik yöntemlerden ilki olan Cohen-Coon yöntemi ile Kp, τ_I, τ_D parametreleri sırasıyla 30.77, 29.15 ve 5.4 olarak hesaplandı. Deneylerden sonra IAE ve ISE değerleri sırasıyla 40cm, 50cm ve 60cm set noktaları için 1455, 1983, 3216 ve 17915, 41593, 92168 olarak hesaplandı. Deneysel sonuçlara göre, pnömatik vananın düzensiz olarak açık-kapalı formunda çalıştığı, ancak sürekli ve düzensiz açık-kapalı işlemine rağmen seviye kontrolü üzerinde başarılı olduğu görüldü.
- Tezde kullanılan klasik yöntemlerden ikincisi olan Ziegler-Nichols yöntemi ile Kp, τ_I, τ_D parametreleri sırasıyla 0.453, 30.0 ve 7.5 olarak hesaplandı. Deneylerden sonra IAE ve ISE değerleri, 40cm, 50cm ve 60cm set noktaları için sırasıyla 4495, 5008, 7233 ve 48155, 87640, 137865 olarak hesaplandı. Vana açıklık değerine göre, sırasıyla 40, 50, 60 cm set noktaları için bir salınımdan sonra sıvı seviyesinin 1 cm, 2 cm ve 5 cm

offset ile sabitlendiği görülmüştür. Vana açıklıkları sırasıyla 40, 50, 60 cm ayar noktaları için % 32, % 70 ve % 99 değerlerinde sabitlenmiştir. Ziegler-Nichols yöntemi ile belirlenen PID katsayıları yüksek seviye kontrolü için yeterli olmadığı belirlendi.

- Tezde kullanılan klasik yöntemlerin üçüncüsü olan Yuwana-Seborg yöntemi ve Kp, τ_I, τ_D parametreleri sırasıyla 1.63, 686.3 ve 117.7 olarak hesaplandı. Deneylerden sonra IAE ve ISE değerleri sırasıyla 40cm, 50cm ve 60cm set noktaları için 7714, 17536, 5796 ve 93950, 366660, 104558 olarak hesaplandı. Vana değerine göre, sıvı seviyesinin bir salınımdan sonra sırasıyla 40, 50, 60 cm set noktaları için 7 cm, 15 cm ve 3 cm offset ile sabitlendiği gözlenmiştir. Farklı set noktaları için deneysel sonuçlar araştırılmış ve vana açılış değerinin sırasıyla% 40,% 50,% 34 ve% 99 ile 40, 50, 60 cm ayar noktalarında sabit olduğu görülmüştür. Yuwana-Seborg metodu ile belirlenen PID katsayıları 40cm ve 50cm kontrolü için yeterli olmadığı belirlendi.
- Bu yöntemlerle karşılaştırıldığında, Cohen-Coon yöntemiyle belirlenen kontrol parametrelerinin, sıvı deney kontrolü için bu deneysel sistemde en iyi performansı gösterdiği görülmüştür. Denetleyici performansının karşılaştırılmasının bir başka yolu hata değerleri hesaplanır. Bu nedenle, ISE ve IAE değerleri kontrol mühendisliğinde kontrol edici performansını belirlemek için en yaygın kullanılanlardır.
- PID kontrol parametrelerinin optimum değerleri Cevap Yüzey Yöntemi (CYY) ile belirlenmiştir. Bağımsız değişkenler olarak Kp, τ_I, τ_D ve ISE, IAE değerleri de bağımlı değişkenler (yanıtlar) olarak seçilmiştir. MATLAB / Simulink'te tasarlanan sıvı seviye sistem blok diyagramında kapalı devre PID kontrol kullanılarak Design Expert 7.0 programının deneme sürümünde önerilen simülasyonlar sırasıyla gerçekleştirildi ve sonuçlar işlenerek simülasyonlardan sonra IAE ve ISE değerleri hesaplandı.
- En düşük ISE ve IAE değerleri için sıvı seviye kontrol sisteminin optimum PID kontrol parametreleri matris denklemleriyle değerlendirildi. En düşük ISE için optimum Kp, τ_I ve τ_D değerleri sırasıyla 23.7319, 30.7627 ve 13.3197 olarak ve en düşük IAE için optimum Kp, τ_I ve τ_D değerleri sırasıyla 22.8034, 27.2723 ve 11.4963 olarak hesaplandı. Ayrıca en düşük ISE ve IAE değerlerinde sıvı seviye kontrolü için PID kontrol parametrelerinin optimum değerleri, Design Expert 7.0 deneme programının sayısal optimizasyonuyla Kp 23.14, τ_I 28.31 ve τ_D 11.50 olarak belirlendi ve bu optimum PID kontrol parametrelerinin birbirine çok yakın olduğu görülmüştür.

CURRICULUM VITAE

He was born in Erbil in 1985. He completed his primary and secondary education in Erbil-Iraq. He educated from the Chemical Science Department University of Salahaddin - Erbil in 2009-2010. The has been employed in a Ministry of Health in Erbil.



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