Application of Self-Tuning Fuzzy PID (STFPID) Controller on Industrial Essential Oil Extraction System Using System Identification Approach

Zuraida Muhammad[1], Khalili Afandi Jamil[1], Zakiah Mohd Yusoff[2], Mohd Hezri Fazalul Rahiman[3]
[1]*Faculty of Electrical Engineering, UiTM Pulau Pinang, Malaysia*
[2]*Faculty of Electrical Engineering, UiTM Johor, Kampus Pasir Gudang, Malaysia*
[3]*Faculty of Electrical Engineering, UiTM Shah Alam, Selangor, Malaysia*
zuraida321@ppinang.uitm.edu.my

***Abstract*—Most of the preferred technique used in the industry for the extraction of essential oil is the steam distillation. The main factors are the system cost, cleanliness, productivity, operational cost and maintenance cost. In extracting the essential oils, few factors have been identified and involved in order to get great quality on the extraction yields. Temperature of extraction is the most significant parameter, which gives impact to the amount of output yield and quality of the oil. The extraction temperature in steam distillation must not be too high to avoid thermal degradation to the oil production. From the previous research, PID controller has been proposed for controller steam temperature in the extraction of essential oil. However, PID controller has some disadvantages in performance during the process to control steam temperature that may reduce the yield and quality of the oil. Therefore, self-tuning fuzzy PID controller (STFPID) is proposed to overcome the problem of the PID controller. This research is aimed to propose an application system of STFPID that integrates the induction based on steam distillation system and regulates the steam temperature during the essential oil extraction process. The autoregression exogenous (ARX) structure with the first order model has been done to represent the plant during the controller design. Both STFPID controllers with different shapes of membership functions of the generalized bell and Gaussian performed very well in relation to the settling time, rise time and percentage of overshoot. STFPID controllers with different shapes membership functions of generalized bell performed with 127.3889 seconds in rise time, 162.5660 second in settling time, and 0% of overshoot.**

***Index Terms*—Self-Tuning Fuzzy-PID; ARX model; Steam Temperature Control**

I. INTRODUCTION

The steam distillation is the most preferable technique to extract essential oil. However, this technique is found to have several weaknesses: Firstly, the system is not alert or quick to react to the change of the parameter in terms of the control response. Secondly, it lacks precision, and thirdly the characteristic of steam temperature is highly nonlinear and ambiguous that cause the robust controller becomes nontrivial. The volatile material presented in the plant is referred to essential oil [1]. The essential oil is mostly used for flavorings, particularly when making perfume or fragrance [2]. They are generally distilled from various parts of the plant that have strong aromatic component. The plant essential oil is usually isolated by steam distillation or hydrodistillation and solvent extraction [3]. The proportion difference of the essential oil extracted by steam distillation is 93% and the remaining 7% is extracted by the other method [4]. The extracted essential oil for the plant used is the steam distillation technique although there are several other methods used, such as solvent extraction and supercritical CO_2 extraction. This steam distillation method is one of the inexpensive processes to control at the basic level. Besides, this method does not absolutely change the oil properties but provides quick responses in comparison to other methods. Countless researchers have emphasized that temperature has effects on the production of essential oil, indicating the importance of controlling it in the extraction process [5]. Therefore, every extraction method has focused on temperature extraction either as fixed [6] or varying temperature [7], and from the analysis, it shows that temperature will affect the yield of essential oil [6][8]. Besides, this method has always been made as a benchmark technique to other techniques [7][8]. System identification approach is a technique that requires a relationship between input and output of the data process [9] for designing performance control system. There are many approaches used for modeling, such as black box [10][11], white box [10] and grey box [10][12] modeling. Many model structures are being referred to when performing the black box modeling that gives an efficient way of modeling the system. Mathematical models involve a large number of trial-and-error for modelers [13]. Therefore, black box approach is applied for performing system identification. In an effort to design and implement a control system, it needs to use efficient techniques. The technique provides a simple and practical solution that can cater the performance requirement if the system disturbances and uncertainties happened. Most physical systems have inherently intractable characteristics, such as non-linear and high order. Ziegler Nichols method is a well-known method that provides a good tuning method for the PID parameter. Besides, for load disturbance attenuation, this method is a good method [14]. Aspects, such as rise time overshoots of the integral absolute error and fuzzy logic is particularly appropriate to improve the performance system. Fuzzy PID Controller has a relatively uniformed performance no matter how large is the set point or load disturbance; hence, resulting in a more robust system.

II. SYSTEM INTEGRATION

A. Steam Distillation Theoretical

Figure 1 is a set up of the steam distillation process. The proposed distillation process includes a column, still pot, condenser and module of induction heating system. The heating element of an induction heating system is a powerful high-frequency system that heats up the water in the pot to produce steam. The strength of the electromagnetic field is controlled so that the amount generated by heat in the pot can be controlled [15]. The steam temperature is measured by a resistive temperature detector (RTD). This detector has the advantages, such as high accuracy, low drift, wide operating range and suitable precision applications. A personal computer (PC) and a digital multi-meter are connected to a set of RTD to display the output voltage. The water temperature increases in proportion to the output voltage. The condensation process takes place through the condenser that reforms from steam form and back into water form: It is a looping process to reuse the water back into the column of the plant.

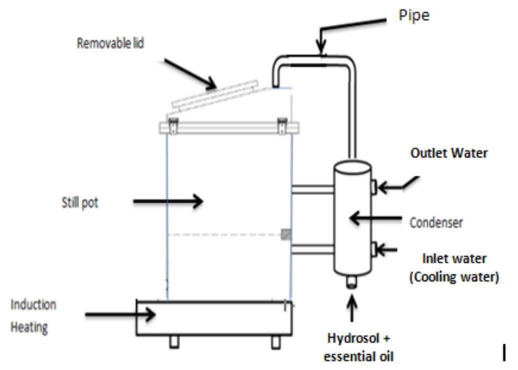

Figure 1: Sketch of steam distillation process for essential oil extraction

B. System Configuration

A configuration was set up for the arrangement of elements in controlling the steam temperature for the process to extract essential oil. A personal computer (PC) was included in this plant system as the based control unit and the software MATLAB as a controller programming tool to control the process and monitor the responses from the system. Figure 2 shows the process that regulates the temperature of the plant using induction heater of the controller to produce control signals via a digital-to-analog converter (DAC) and input of heating element as the actuator of the plant.

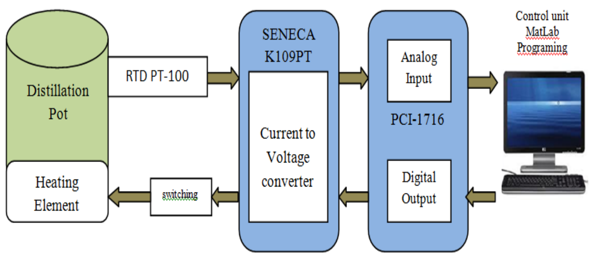

Figure 2: Block diagram of the induction-based steam distillation system

III. System Identification

A. Linear System Identification

System identification is defined as a mathematical model desired in certain system dynamic from the measured and collected data. A dynamic model is required for the design and performance control system. Figure 3 shows the system identification process approach utilized for the observation of data from the dynamical system, model structure selection, model estimation and model validation. For this work, a model required to validate the verification of preciseness was used. The data set used were collected from the experiment at the plant of steam distillation from the starting of the ambient temperature at 90°C.

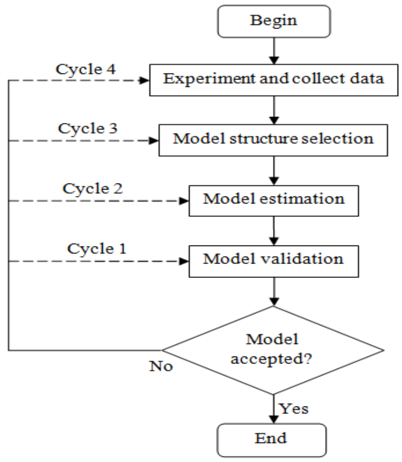

Figure 3: System Identification approaches

B. ARX Model and Data Selection

After a model has been selected, estimated and validated, it was applied to represent the process. In this work, a description of the behavior of the global model [16] based on the relationship between input and output data Auto Regressive Exogenous (ARX) model was chosen because it is the simplest model that incorporates the stimulus signal [17]. Moreover, the estimation of ARX model is the most efficient for polynomial estimation method to get the result of solving linear regression equation analysis. From Figure 4, *u(t)*, *e(t)* and *y(t)* represent the input, error and output respectively. Further, the input of pseudo-random binary sequence (PRBS) perturbation and output (temperature) is shown in Figure 5 and the error is varied from -0.5 to 0.5. The model selection was based on the high percentage value of their best fit, which is above 90%. The analysis from this dataset shown 92.2% of the best fits. Therefore, it is sufficient to proceed to the simulation work.

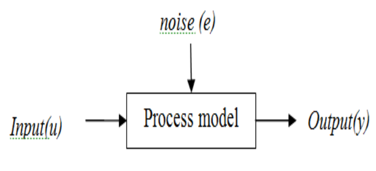

Figure 4: ARX Model structure

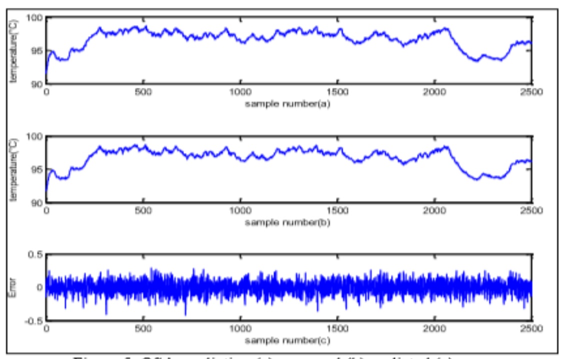

Figure 5: OSA prediction, (a) measured, (b) predicted, (c) error

The representative of *A* and *B* is the estimated polynomials that represent the overall system dynamic. The polynomials are given as:

$$y(t) = q^{-nk}\frac{B(q)}{A(q)}u(t) + \frac{1}{A(q)}e(t) \quad (1)$$

where the polynomials *A(q)* and *B(q)* are given by:

$$A(q) = 1 + a_1 q^{-1} + \cdots + a_{na} q^{-na} \quad (2)$$

$$B(q) = b_0 + b_1 q^{-1} b_{nb} q^{-na} \quad (3)$$

From Equation (2) and (3), q^{-1} is the delay operator. The variables $a^1 \ldots n^a$ $b^1..n^b$, 1.. and $c^1..n^c$ are the parameters to be estimated. This work focused on the first order of ARX model and the results were obtained from the data represented in the transfer function, as shown in Equation (4).

$$tf(z) = \frac{0.1127z^{-1}}{1-z^{-1}} \quad (4)$$

IV. METHODOLOGY

A. *PID Controller*

PID Controller is a simple structure of a control system that is easy to handle and implement. Initially, all parameters gain K_p, K_i and K_d should be tuned to perform the Simulink simulation on PID. In this work, Ziegler-Nicholas method was used to tune all the parameters gained. However, there is a need to find the fine-tuning to get an optimum performance. Besides, the PID controller has some disadvantages in performance during the process to control steam temperature that may reduce the yield and the quality of the oil. Equation (5) is the representative of the proportional (P), integral (I) and derivative (D) action:

$$G_c = K_p e(t) + K_1 \int e(t)dt + K_d \frac{de(t)}{dt} \quad (5)$$

B. *Self-tuning Fuzzy PID (STFPID)*

The controller of self-tuning fuzzy PID (STFPID) in this study is to improve the performance of the plant system, which is to remove overshoot and to produce fast settling time and fast time response. A fuzzy logic controller is automatically tuned on to their gain of K_p, K_i, and K_d during the process. In this study, two shapes of the membership function, which are the Generalized bell and the Gaussian with 3, 5, and 7 memberships function for each of the shapes are implemented to obtain the result. The purpose of using these shapes is to determine whether the variance in the number and shape of the four memberships function can give better performance in STFPID controller. Based on the simulation work, the rules designed of STFPID are based on the plant characteristic and the properties of PID controller itself. The fuzzy implication relation used is the Mamdani implication. With regard to the fuzzy structure, there are two inputs, which are errors *e(t)* and derivative of error *de(t)/dt*, and three output for each PID controller parameter for K_p, K_i, and K_d. The Simulink block diagram in Figure 6 shows the simulation STFPID controller.

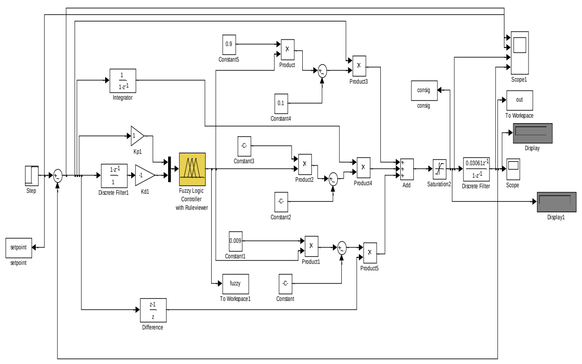

Figure 6: Simulink block diagram for simulation STFPID

The fuzzy system contains the interpretation of the structure in fuzzy. There are two inputs to fuzzy inference, which are error *e(t)* and derivative of error *de(t)/dt*, and output as defined in Figure 7. The aggregation chosen is the max-min and defuzzification is achieved by using the center of the centroid method.

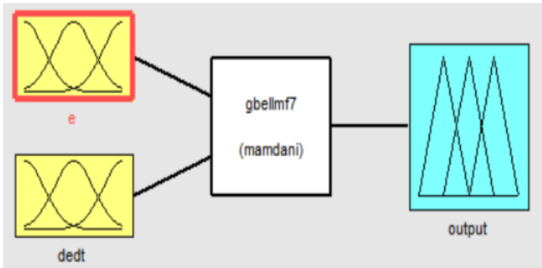

Figure 7: Self-tuning fuzzy PID

Both ranges of the error and derivative of error have been set between -100 to 100, based on the absolute error and derivative error of the plant. The linguistic variable used to classify the error and derivative of error are as shown in Figure 8 and 9. The work of fuzzy set is based on the shape of membership (mf) functions, which are the Generalized bell mf and the Gaussian mf. The levels of the membership function are in 3, 5 and 7.

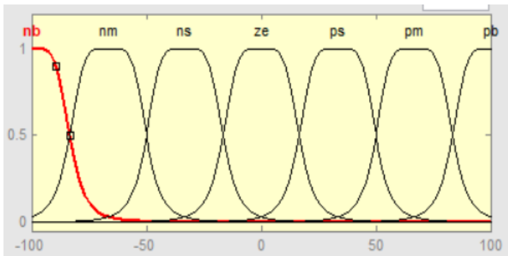

Figure 8: Input variable *'e'* for shape gbellmf 7 membership function

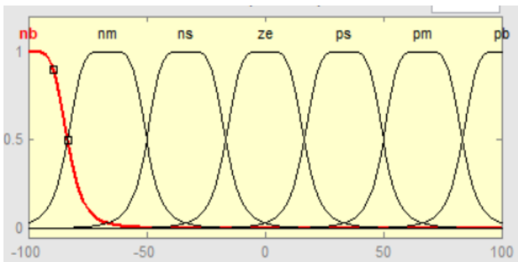

Figure 9: Input variable *'de/dt'* for shape gbellmf 7 membership function

The range for output membership function is from 0 to 1, as shown in Figure 10.

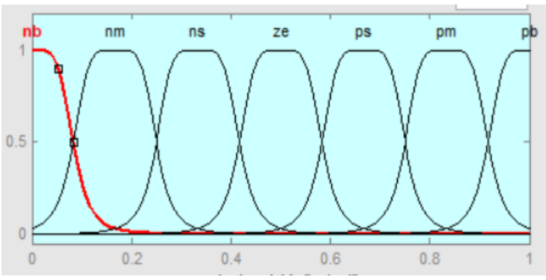

Figure 10: Output for shape Generalized bell mf 7 membership function

Table 1 shows the matrix rules for 7 membership function of fuzzy with two input, which are error, *e(t)* and derivative error, *de(t)/dt*. The linguistic variable levels based on the seven levels are nb: negative big; nm: negative medium; ns: negative small; ze: zero; ps: positive small; pm: positive medium; pb: positive big. Each rule contains two antecedents and one consequence.

Table 1
Fuzzy rules

e	***de/dt*** **nb**	**nm**	**ns**	**ze**	**ps**	**pm**	**pb**
nb	nb	nb	nb	nb	nm	ns	ze
nm	nb	nb	nb	nm	ns	ze	ps
ns	nb	nb	nm	ns	ze	ps	pm
ze	nb	nm	ns	ze	ps	pm	pb
ps	nm	ns	ze	ps	pm	pb	pb
pm	ns	ze	ps	pm	pb	pb	Pb
pb	ze	ps	pm	pb	pb	pb	pb

V. RESULT AND DISCUSSION

The result discusses the experimental evaluation and application of conventional PID and STFPID controller, which includes the use of certain transient performance to evaluate the performance of controller, namely the rise time, settling time, and percent overshoot.

A. *PID Controller*

Figure 11(a) shows the control signal is able to control the simulation output process by injecting the control signal in the range of 0-5 V. This procedure prevents the input from going outside the input limit. Figure 11(b) illustrates the PID output controller 5.

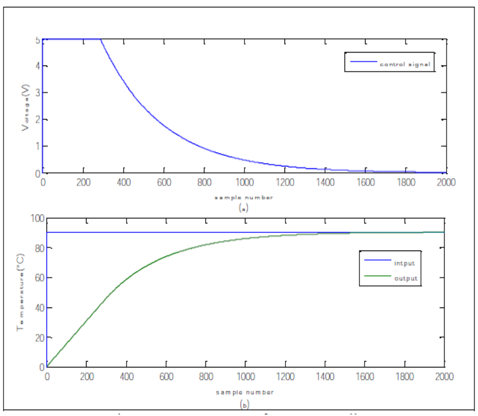

Figure 11: Step response for PID controller

Table 2
Output Controller Performance Using PID Controller

Controller	Rise time	Settling time(s)	Overshoot (%)
PID	473.70	661.16	0

B. *Self-Tuning Fuzzy PID controller*

The STFPID controller is applied to control the steam temperature at the desired point. The temperature is controlled using STFPID, whereas the signal and the actual steam temperature are controlled based on the simulation in software Matlab. Several shapes of the membership function of the fuzzy method were conducted, such as the shape of Gaussian mf and Generalized bell mf. Each shape has a different number of the membership function. There are three membership functions (3mf), five membership functions (5mf) and seven membership functions (7mf), which require parameters adjustment. This process is determined either by varying the number and shape of membership function to produce better performance in STFPID controller.

Based on Figure 12(a), the control signal is between 0-5V. As shown in Figure 12(b), the STFPID shape Generalized bell mf of three membership functions (3mf) produces no overshoot with a rise time of 127.1655s and a settling time of 173.6578s. The simulation was continued by applying five membership functions (5mf). The controller produced no overshoot and the rise time was 127.2611s with a settling time of 165.2156s. Additionally, the use of seven membership functions (mf7) resulted in no overshoot with the rise time of 127.3889s and settling time of 162.5660s. While, the PID controller shows that it can be used or suitable for controlling the output at the set point temperatures, which result in no percent of overshoot, with a rise time of 473.7075s and a settling time of 661.1570s.

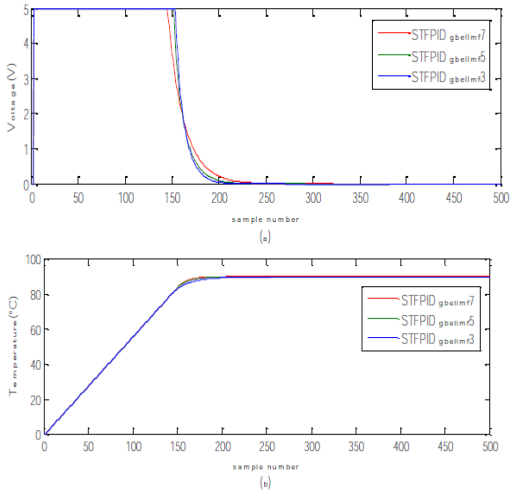

Figure 12: Step response of STFPID type Generalized bell mf

Figure 13 shows the step response of STFPID shape Gaussian mf. From Figure 13 (a), the control signal started to decrease when the output rise time was achieved. Based on Figure 13(b), the STFPID shape Gaussian mf three membership functions (3mf) produced no overshoot and its rise time was 126.6740s and settling time was 172.1866s. The five membership functions (mf5) contributed no overshoot when the rise time was 127.3696s and settling time was 162.2023s. Then, for seven membership functions (7mf), the controller design produced no overshoot and the rise time was 127.5123s and settling time was 159.9071s.

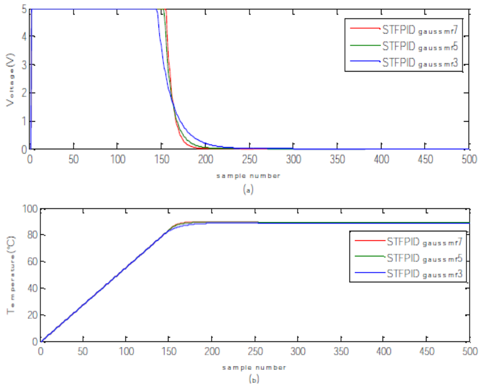

Figure 13: Step response of STFPID type Gaussian mf

The results of the transient response of all the controller performance are tabulated in Table 3 based on the rise time, settling time and the percentage of overshoot. The controller design focused on achieving a faster response and their settling time. Three types of controller, which are the conventional PID controller, STFPID with Generalized bell mf shape and STFPID with Gaussian mf shape have been simulated.

Based on Table 3, the STFPID controller proved that it can improve the performance in terms of the rise time and the settling time. The conventional PID controller has slower rise time and settling time. The result of this study showed that the different shape of membership function and the increment in membership function did not significantly improve the rise time and settling time.

Table 3
Controller Performance of PID and STFPID

Controller	Rise time(s)	Settling time(s)	Overshoot(%)
Gbellmf3	127.17	173.66	0
Gbellmf5	127.26	165.22	0
Gbellmf7	127.39	162.57	0
Gaussmf3	126.67	172.19	0
Gaussmf5	127.37	162.20	0
Gaussmf7	127.51	159.91	0
PID	473.71	661.16	0

VI. Conclusion and Recommendation

This study has produced a successful model and control using STFPID. The STFPID performed better than the conventional PID controller. Both the membership function shape performed well during the simulation. However, the results of this study showed that the different shape of membership function and the increment in membership function did not significantly improve the rise time and settling time

From the system identification result, the ARX model has satisfactorily represented the plant dealing simulation work. The simulation of STFPID controller has the ability to perform well to regulate the steam temperature at the desired point with fast rise time and settling time compared to the conventional PID controller.

The development of work can be applied based on the result achieved. In this study, the simulation work has been done for induction-based steam distillation. In future, the simulation work is continued by implementing the STFPID controller to the real-time application.

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