Temperature regulation for distillation process using self-tuning fuzzy plus PID controller

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Abstract. This paper presents a self-tuning fuzzy logic controller plus PID controller that applied for essential oil extraction process. The most popular technique in extraction essential oil is using steam distillation. This method is lack to the process requirement and also towards parameter change. In order to regulate the steam distillation at desired extraction condition, the controller needs to integrate to the plant. By using auto regressive model with external input (ARX) model structure, the temperature of steam was successfully modelled with best fit 98.42%. This model was successfully representing the system during controller simulation work. There are several controllers that demonstrated in this project which are self-tuning fuzzy PID controller (STFPID) and conventional PID. Both controller will compare their performance in terms of system response which are percent overshoot (%OS), settling time (Ts) and also rise time (Tr). As the result, the STFPID with seven membership function gives the best performance compared to PID controller.

1. Introduction
Many purposes have been used for essential oil in our daily life for examples food, cosmetics product, perfumes and traditional medicines [1]. Essential oil is implemented by plant parts which are wood, bark, flowers, and leaves and also seed [2-4] and it always in highly demand from users and also will give positive affect for our economy. The advantages of essential oils are their flavor concentrations with similarity to their sources [5]. Nevertheless, with age essential oil may oxidize which resulting the color becomes darker [5]. Thus, there are several methods to extract the essential oil is steam distillation, solvent extraction, absolute oil extraction and expression process [6]. Steam distillation is the common conventional method for isolation of essential oils from plant materials [5, 7]. Steam distillation is a type of distillation process for a temperature sensitive plant such as natural aromatic compounds. These methods have some disadvantages preservation of essential oil from its environment [8] and lack to change parameters in step response. Therefore, steam distillation still important in certain industrial sectors (Fahlbusch et al., 2003)[5] due to several factors such as operational cost, productivity and cleanliness [9]. The temperature regulation is needed in this process because to achieve and maintain the desired input and produce the best quality of essential oil. The physical color of essential oil will reduce if essential oil is exposes to high temperature in a long time heating process [6]. Thus, to control the temperature in extraction process the controller needs to integrate to the plant. Many types of controller that used to control the temperature for heating process which are PID controller, Fuzzy logic controller, Neural Network controller and Model Reference
Adaptive Controller (MRAC) also Model Predictive Controller (MPC) [10]. In fact, more than 95% of the PID controller are employed today and still continue to dominate in control industry [11]. The conventional PID controller was used in industrial application because of simple and easy to control the system. Ziegler Nichols method it is one of the most popular technique [12] to tune the PID controller in the system tuning compared the other technique and provides a good tuning for PID controller [13]. But this controller, does not provide a good transient response while set point is changed [14]. However, a self-tuning fuzzy PID (STFPID) controller is proposed in this process. This controller is expected to execute a better performance for achieving the desired set points. Thus, in this study a model and STFPID plus conventional controller of this process are developed. The comparison performance between both controllers are evaluated in terms of Tr, Ts and %OS. Then, the STFPID controller is tested with varies the set points and injected load disturbance. The purpose of this test to analyze the ability of the robustness controller towards set point. This paper organized as follow. Section II explains on the overall experiment and methodology for this study. The analysis part in Section III provides the comparison of both controller. Finally, Section IV is presented conclusion.

2. Methodology

Figure 1 shows the overall experiment to develop this system. Start with ARX modelling, design controller and followed by analyse and compare the performance controller.

![Figure 1. Overall experiment of this system](image)

2.1. System identification

System identification is a mathematically models of dynamic system using measurements of the system. A dynamic is needed for the design and performance in plant system. The set point of the heating process is set at 90°C. The system start from model structure selection, model estimation and the last is model validation.

2.2. ARX modelling

ARX model is an Auto-Regressive with Exogenous Input. In this study, ARX modelling is chosen as a modelling in the heating process because it is a simply and efficiency model to get the result from the process. So that, the model will represent the plant and used during controller simulation. Equation (1) and (2) show the ARX model from system identification with best fit 98.42%:

\[
\begin{align*}
A(q)y(t) &= B(q)u(t) + e(t) \\
A(q) &= 1 - q^{-1} \\
B(q) &= -0.005054(\pm0.004087)q^{-1}
\end{align*}
\]
A (q) and B (q) are polynomials equations, y (t) as an output while u (t) as an input terms and e (t) as a white noise towards the system. This study is used first order model of ARX model. Thus, the transfer function for this system was obtained in terms of discrete time as shown in equation (3):

\[ tf (z) = \frac{-0.00554z^1}{1-z^{-1}} \] (3)

2.3. PID controller

PID is a universal controller and most commonly used it in industrial application because is simple and easy to handle in a control system. Ziegler Nichols method was used in this controller for tune all parameters gain such Kp, Ki, Kd. The parameters in PID controller can be tuned by using theoretical, numerical calculation or experimental [15]. For this study, PID controller was tuned automatically in Simulink simulation by PID tuner. The formula of the controller can be shown in equation (4) and equation (5)[16]:

\[ u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \] (4)

\[ e(t) = r(t) - y(t) \] (5)

Where e (t) is a feedback error, r (t) is desired set point and y (t) is an actual set point [16]. The effect of PID controller on system response can been see in table 1:

| Parameter | Rise Tim, Tr | Overshoot, (\%OS) | Settling Time Ts | Steady state error, e_{ss} |
|-----------|--------------|--------------------|------------------|---------------------------|
| Kp        | Reduce       | Increase           | Small change     | Reduce                    |
| Ki        | Small change | Reduce             | Reduce           | Small change              |
| Kd        | Reduce       | Increase           | Increase         | Eliminate                 |

2.4. Self-tuning PID fuzzy logic controller(STFPID)

Using the self-tuning fuzzy PID controller in this process is an accurately choice to give the best performance of the plant system. STFPID produce three output gained which are Kp’, Ki’ and Kd’ and this gained will change the values to improve the step response of system [18]. The gain will automatically tuned by fuzzy logic controller. In this work, the 3,5 and 7 membership function (mf) was used to produce the optimum STFPID scheme [19].

Next, triangular and trapezoidal shapes were used in this controller by using 3, 5 and 7 rules. This rules is implement for each shapes to produce the result. This type of shape is simple and easy to implement to the rules and produce better performance for this process. Regarding the fuzzy logic controller structure, it have two an input and one output which are error e(t) , and derivative error de(t) as show in figure 3(a)

Besides that, the value of gain parameters (Kp,Ki and Kd) gets from simulate of PID controller in Simulink/ Matlab [14]. This values are vary between [Kpmin,Kpmax], [Kimin,Kimax] and [Kdmin, Kdmax]. So, the range values of Kp’, Ki’ and Kd’ are [1, 10], [0.009, 0.0009] and [0.1, 0.01] and can be obtained based on equation (6) until (8) [16, 20]:

\[ Kp' = \frac{K_p - K_{pmin}}{K_{pmax} - K_{pmin}} = \frac{K_p - 1}{10 - 1} \] (6)

\[ Ki' = \frac{K_i - K_{i min}}{K_{i max} - K_{i min}} = \frac{K_p - 0.00009}{0.009 - 0.0009} \] (7)
\[ K_d' = \frac{K_d - K_{d_{\text{min}}}}{K_{d_{\text{max}}} - K_{d_{\text{min}}}} = \frac{K_d - 0.01}{0.1 - 0.01} \]  

(8)

The parameters of PID (Kp, Ki and Kd) can be determined by equation (9) until (11) [16]:

\[ K_p = 9K_p' + \]  

(9)

\[ K_i = 0.0081 Ki' + 0.0009 \]  

(10)

\[ K_d = 0.9K_d' + 0.01 \]  

(11)

In this work, the fuzzy set for both input is used 7 membership function and used triangular and trapezoidal shapes. The range values for both input is between -100 to 100 and output is from 0 to 1. This figure 2(b) and 2(c) shows the input of membership function.

![Membership Function Images](image)

**Figure 2.** (a) Fuzzy inference of STFPID, (b) The input of membership function e (t), (c) The input of membership function de (t), (d) The output of membership function

From the figure 2(b) and (c), the seven levels of linguistic variables are determined such as NB(negative below), NM(negative medium), NS(negative small), ZE(zero), PB(positive below), PM(Positive medium), PB(positive big). Next, the figure 2(d) defined the linguistic variables are VS(very small), SM_small), MS(medium small), MD(medium), MB(medium big), BG(big), VB(very big). Summarize of this rules is shown in table 2. The input and output of linguistic variable are
defined based on plant criteria [14]. Thus, the relation of 49 rules is used IF-AND-THEN connection. The simulation structure of STFPID shown in figure 3.

2.5. Robustness test with different set points
The purpose of this tested to analyze the ability of the robustness controller towards different set point. The performance STFPID will be evaluated based on rise time, settling time and percent overshoot. The set point test was set from 88°C, 90°C and 85°C [13].

Table 2. The summarize of 7 membership function

| Fuzzy rule matrix | CE | Nb | nm | Ns | ze | Ps | pm | Pb |
|-------------------|----|----|----|----|----|----|----|----|
| E                 | Nb | nb | Nb | Nb | Nb | Nb | Nb | Nb |
| Nh                | Nb | nb | Nb | Nm | Nm | Nm | Nm | Nm |
| Nm                | Nb | nb | Nm | ns | ns | ns | ns | ns |
| Ns                | Nb | nb | Nm | ze | Ps | Ps | Ps | Ps |
| ze                | Nb | nb | Nm | ze | Ps | Ps | Ps | Ps |
| Ps                | Nm | ns | Ze | ps | Pm | Pm | Pm | Pm |
| Pm                | Nm | ze | Ps | Pm | Pb | Pb | Pb | Pb |
| Pb                | Ze | ps | Pm | Pb | Pb | Pb | Pb | Pb |

2.6. Load disturbance
In this study, the load disturbance is used to test the controller how low the temperature drop and the period of controller return back to the desired set point during running process. The disturbance will have injected at 5°C and 500s since the process in achieve the stable condition at 90 °C[13]. The performance of each controller will be observed and analyzed.
3. Experimental results and discussion

3.1. Step response performance of controller

The output performance of STFPID by using 3, 5 and 7 membership function (mf) and PID controller details of both controllers were recorded in table 3. By referring the data recorded, STFPID controller was achieved the desired set point that is short of rise time and settling time also give low the percent overshoot. Comparing with PID controller, the performance is not achieved the desired set point with long of rise and settling time and give higher the percent overshoot in this process.

As shown in table 3, the STFPID-3 produce 6.975s of rise time to achieve the desired set point while 300s to settle the heating process and 0.068% of overshoot. While, STFPID5 show the values of rise time, settling time and overshoot are 6.975s, 243.3s and 0.068% respectively. Next, STFPID-7 obtained value 6.975s of rise time to reach the desired set point temperature, 203s of settling time and 0.176% of overshoot. Lastly, PID controller shows the result 13s of rise time, 455.5s of settling time and 0.176% of overshoot. However, between the both controller the STFPID using 7(mf) displayed the better performance in term of settling time.

| Controller | Rise Time (s) | Settling Time (s) | Overshoot (%OS) |
|------------|--------------|-----------------|-----------------|
| STFPID-3   | 6.975        | 300             | 0.068           |
| STFPID-5   | 6.975        | 243.3           | 0.068           |
| STFPID-7   | 6.975        | 203             | 0.176           |
| PID        | 13           | 455.5           | 0.176           |

3.2. Robustness test with different set points

On the first set point temperature is 88°C the rise time of the self-tuning fuzzy PID (STFPID) controller using 7 membership functions produce 5 second, settling time is 203 second and percent overshoot is 0.95%. While increasing the set input temperature to 90°C the rise time and percent overshoot is same but different settling time is 63 second. Lastly, the set input temperature is 85°C is produce rise time and percent overshoot is same with first set point temperature value and settling time is 185 second. However, this controller across all the set points with short rise time compared with STFPID 3 and 5 membership functions. As mentioned previous, the higher number of membership function can affect the better performance of step response. Thus, this test is to analyse the robustness controller to achieve and maintained the desired input temperature. So that, STFPID-7 controller is suitable to implement in this process. All the data STFPID-7 are tabulated in table 4.

| Time (s) | Temperature (°C) | Rise Time (s) | Settling Time (s) | Overshoot (%OS) |
|----------|------------------|---------------|-----------------|-----------------|
| 400      | 88               | 5             | 203             | 0.95            |
| 800      | 90               | 5             | 63              | 0.95            |
| 1200     | 85               | 5             | 185             | 0.95            |

For PID controller, the result shows it took a very long duration to reach the desired input temperature compared to the STFPID controller. Reviewing the first set point at 88°C the rise time is 15 second, settling time and percent overshoot is 1.829%. This controller is not achieved the desired input and unable to determine the settling time for each set input point. The second set point temperature at 90°C, the rise time and percent overshoot is same with the first set point temperature and settling time is 166 second. Lastly, set input temperature is 85°C, then the values of rise time is same with first input temperature while settling time is unable to determine. All the performance of step response are tabulated in table 5.
Table 5. The Conventional PID Controller with Varies Set Point

| Time (s) | Temperature (°C) | Rise Time (s) | Settling Time (s) | Overshoot (%OS) |
|----------|------------------|---------------|-------------------|-----------------|
| 400      | 88               | 15            | -                 | 1.829           |
| 800      | 90               | 15            | 166               | 1.829           |
| 1200     | 85               | 15            | -                 | 1.829           |

3.3. Load disturbance
This test was conduct to observe the ability of the designed controller to return to the set point. The time taken by the controller to return the process output back at desired point will determine the robustness of the controller designed. Based on the analysis, STFPID-3 shows the output temperature drop is 85°C and took 826s to return back to the desired input. While STFPID-5 also drop 85°C and takes 827s to recover. STFPID-7 drop 85°C and 761s to return back to desired set point and lastly, PID controller was drop lightly than 85°C is 85.05°C and takes 735s to return back the desired input temperature. As a conclusion, STFPID-7 shows the better performance recovering from disturbance compare to the unstable PID controller. The performances for each controller were tabulate in table 6.

Table 6. The performance of STFPID-3, 5 and 7 and PID with disturbance injected

| Controller | Disturbance (°C) | Lowest drop point (°C) | Recovery duration (s) |
|------------|------------------|-------------------------|-----------------------|
| STFPID-3   | -5               | 85                      | 326                   |
| STFPID-5   | -5               | 85                      | 326                   |
| STFPID-7   | -5               | 85                      | 261                   |
| PID        | -5               | 85.05                   | 235                   |

4. Conclusion
The analysis of modelling and design the controller was successful done by using MATLAB/Simulink. ARX model of steam temperature was successfully modelled with best fit 98.42%. From the results, PID controller able to control the process system but it has weakness to change the parameters toward of step response. STFPID controller produce better performance compare the PID controller. The result shows, the higher number of membership function was improved the step response of this system such as produce the faster response and with lowest percent overshoot. In future work, the simulation is continued by implementing the STFPID controller in real application process.

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