Modified Relay Tuning PI with Error Switching: A Case Study on Steam Temperature Regulation

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Abstract

This study evaluates the performance between reaction curve Ziegler-Nichols tuning rules applied to FOPDT model and the open-loop relay feedback tuning method based on ultimate gain and period. Error and control signal switching were equipped to enhance the output response over a limited steam temperature response. The control performance was evaluated experimentally on a steam distillation process regulation. The proposed technique employing relay tuning together with error switching had produced an astounding closed-loop response even for a non-linear steam temperature control.

Keywords – ***steam temperature; PI control; Ziegler-Nichols tuning; relay feedback.***

1. Introduction

PID controller has been successfully applied in industries. However, optimal performance of the controller is really depends on the tuning method. Some prominent tuning methods are the Ziegler-Nichols, pole-placement and frequency domain specifications. The main issue in PID tuning is that, there was no general tuning method applicable for all types of applications.

Aidan[1], [2] had summarized more than twenty methods of PID tuning with their suitable applications and process types. Cominos and Munro [3] discussed on the most favorable PID tuning techniques with their suitable application. More studies being done to improvised or synthesized a new rule [4] to a specific process type such as an integrating process [5], integral plus time-delay process [6], and first-order plus dead-time [7]. Moreover, the fitness of Ziegler-Nichols rules are also depends on the relative time-delay of the process, see [8].

Generally, Ziegler-Nichols tuning method was synthesized based on the step response and frequency response methods. The first approach requires some information from the open-loop step response which is the gain, time lag and dead-time. The latter is based on the closed-loop response under proportional control. Here, the gain is increased until The closed-loop system becomes critically stable whereby the ultimate period and gain are acquired. This method is not easy to apply on a working plant because the system might be brought to unstable state. Anyway, these methods were very limited that led to an endless discussions and studies being conducted in order to improve it.

Alternatively, Astrom and Huggland proposed a more practical solution using a relay feedback test [9] where the automatic tuning was performed online by switching from automatic mode to tuning mode. Details on the implementation can be referred in [9–12].

This paper shared the idea of relay perturbation on the process in order to get the process gain and frequency. But, instead of implementing a closed-loop auto-tuned, this method gathered the information from the open-loop response. From these two parameters, the PID was then tuned using the classical Ziegler-Nichols rules. This simple approach unbelievably produced better results than a model-based tuning approach as discussed in [13] for metal chamber temperature control. However, in this application, the temperature response was quite linear and the dynamic response was fast. Regulating a steam temperature was more challenging.

Steam temperature control had been performed using various control techniques. Most literatures focused on the superheated steam temperature control but some had done a study on saturated steam temperature [12]. Nevertheless, regardless of its temperature range, the studies had pointed out the same non-trivial issues in steam temperature regulation which is normally comes from the nonlinearity, slow varying process dynamics, fast disturbance and unmodeled dynamics [14–17]. These characteristics made model-based tuning ineffective for steam temperature regulation.

This study supported the statement by comparing the output gathered from the proposed tuning method and compared it against the model-based Ziegler-Nichols PID. Experimental results will demonstrate this issue evidently.

2. Process Description and Modeling

Steam distillation is among the most popular method for essential oil extraction process. The proportion of different essential oils extracted by steam distillation is 93% and the remaining 7% is extracted by other methods such as hydro distillation [18]. This method applies hot steam to extract the essential oil from the raw materials. The mixture of oil and steam will be condensed and separated at their liquid form. In the majority of cases the oil is less dense than the water and so forms the top layer of the distillate and can be separated easily using proper method and instruments.

A pilot-scale steam distillation plant developed for this study consists of a stainless steel column of 26 cm inner diameter and a vertically mounted steel condenser to convert the steam into liquid form. Figure 1 shows the simplified schematic diagram of the plant. Two RTDs were installed; RTD1 was immersed in the water to monitor water temperature while RTD2 was installed 40cm from RTD1 to monitor the steam temperature inside the column. The distance of the sensor from its heat source will caused transport delay in steam temperature measurement.

During operation, steam will be generated by boiling the water inside the distillation column. In normal operation, the water volume is 10 liters. The water was heated up by a 1.5kW coil-type heater. It took about 3500s to boil the water. The open-loop response under normal operating condition is shown in Figure 2. Column temperature that represents the steam temperature started to rise gradually after 1500s when water temperature is around 70°C. The steam temperature increased exponentially until 80oC where the steam rate hiked to 100°C and saturates.

During closed-loop operation, the steam temperature will be measured by RTD2. RTD2 was installed over the raw material to monitor the temperature of steam that passed through the raw material instead of measuring the steam temperature that will enter the raw material bed. Continual exposure to excessive heat may degrade the quality of the essential oil as had been studied and reported in [19] for ginger extraction. This finding was supported by lots of literatures [20–24] from the area of botanical and chemical studies.

Signal conversion was necessary to convert the output from RTD (resistance) to voltage signal that was compatible with the acquisition card PCI 1711. The signal converter converts 0°C to 120°C to 1V to 5V. 1 volt offset was intentionally put to avoid misleading during measurement error. Control signal from the controller manipulated the heater power by providing a dc voltage from 0V to 5V to a continuous power controller.

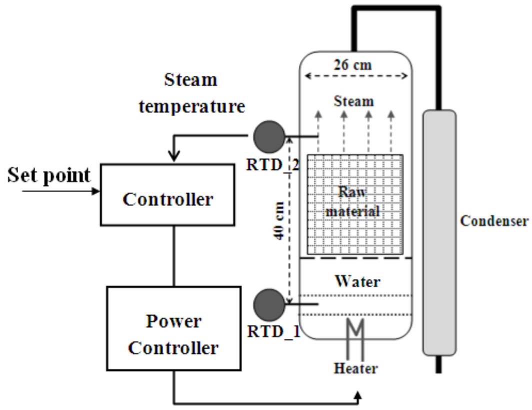

Fig.1 Schematic of a steam distillation process

A)

B) *FOPDT from open-loop response*

In process industry, first-order plus dead-time (FOPDT) is the most common model structure that was used to represent a process [7], [25], [26] because the parameters are easier to identify and understandable. Most PID control tuning techniques were derived based on FOPDT model acquired from the open-loop step test. From the response in figure 2, it can be observed that the steam temperature is not a linear variable over its full-range and obviously cannot be represented by the FOPDT model accurately. However, the response are linear within specific range i.e. between [30 50]°C, [50 70]°C and [70 100]°C.

This study was concerned to regulate the steam temperature at 85°C where the essential oil extraction took place. So, the operating range was limited to 80°C to 100°C only.

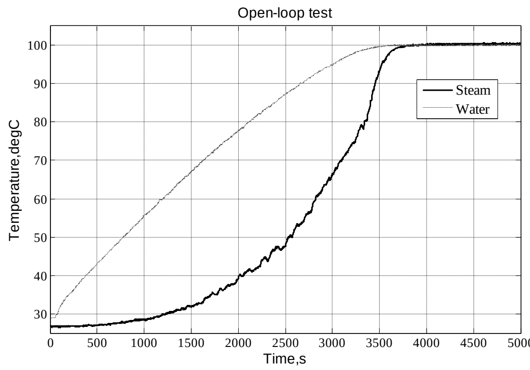

Fig.2 Open-loop response of steam and water temperature

General form of the FOPDT model is as follows:

$$\frac{Y(s)}{X(s)} = \frac{K_p e^{-\theta s}}{\tau s + 1} \qquad (1)$$

where

X(s) is the input

Y(s) is the output of the process

Kp is the process gain

τ is the time constant

θ is the dead-time

There were two methods available when estimating FOPDT model from the process reaction curve [27]. The first method required an inflection point to be determined to acquire an accurate model whereas the second method requires data at specific points which is much easier to be acquired. Using the second method of the process reaction curve will lead to the following equations:

$$Y(\theta+\tau) = \Delta Y(1-e^{-1}) = 0.632 * \Delta Y$$
$$Y\left(\theta+\frac{\tau}{3}\right) = \Delta Y\left(1-e^{\frac{-1}{3}}\right) = 0.283 * \Delta Y \qquad (2)$$

Thus, the values of time at which the output reaches 28.3% and 63.2% of its final value are used to calculate the model parameters according to equation 3.

$$t_{28\%} = \theta + \frac{\tau}{3}$$
$$t_{63\%} = \theta + \tau \qquad (3)$$
$$\tau = 1.5(t_{63\%} - t_{28\%})$$
$$\theta = t_{63\%} - \tau$$

This study applied the second method because it minimizes any doubt during inflection determination and hence gave more consistent result. The FOPDT model was given in equation 4. Model validation was done by comparing the output of the model and experiment when subjected to 5 volt input signal. The comparison produced RMSE = 0.3838^{o}C. Figure 4a shows the output from the model and experiment while figure 4b shows the error between both models.

$$G(s) = \frac{4.5}{160s+1}e^{-350s}, \qquad 80 \le T \le 100°C \qquad (4)$$

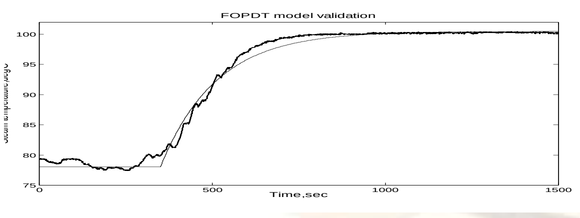

Fig. 4a Experimental output and model output validation

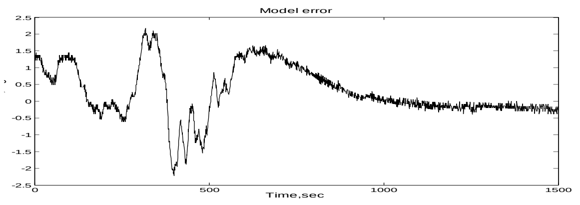

Fig. 4b Error between experimental and model output

3. PID CONTROLLER TUNING

This section explained on the PID tuning methods applied during this study. Table 1 summarizes the Ziegler-Nichols tuning rules based on process reaction curve parameter that is Kp = 4.5, τ = 160 and θ = 350. These rules make use of the parallel structure PID where Kc is the controller gain, Ti is the integral time constant, and Td is the derivative time constant. The equation for parallel form PID is given in equation 5. The calculated parameter was tabulated in Table 3.

$$G_c(s) = K_c\left[1+\frac{1}{T_i s}+T_d s\right] \qquad (5)$$

TABLE 1 ZIEGLER-NICHOLS FROM FOPDT[27]

	K_c	T_i	T_d
P	$\left(\frac{1}{K_p}\right)\left(\frac{\tau}{\theta}\right)$	-	-
PI	$\left(\frac{0.9}{K_p}\right)\left(\frac{\tau}{\theta}\right)$	3.3θ	-
PID	$\left(\frac{1.2}{K_p}\right)\left(\frac{\tau}{\theta}\right)$	2.0θ	0.5θ

The Ziegler-Nichols tuning PID from reaction curve method was compared with an open-loop relay tuning. The proposed method was based on an open-loop on-off switching around the operating point. In this study, temperature set point was at 85^{o}C. To minimize the effect of measurement error, hysteresis band of ±5^{o}C was introduced. Manual on-off switch was equipped in the system to turn the controller into fully on or off when steam temperature approaches 80^{o}C and 90^{o}C. Steam temperature was then oscillated between 80^{o}C to 90^{o}C. From the relay output, PID gain was calculated using Ziegler-Nichols rules based on frequency response analysis of the ultimate period and gain.

The process was started without a controller and the heater was controlled by a relay switch. The relay was turned ON whenever steam temperature reached 80^{o}C and turned OFF when steam temperature was at 90^{o}C. The relay operation was summarized by the following equation:

$$u(t) = \begin{cases} 5 & ,T \le 80°C \\ 0 & ,T \ge 90°C \end{cases} \qquad (6)$$

This process was repeated until a sustained oscillation was observed as in figure 5. Figure 5a shows the steam temperature response while figure 5b shows the relay switching. The critical gain, Ku and critical period, Pu could be found from these output and input signal. Ku was calculated using the following equation:

(7)

where
d = magnitude of relay (input)
a = magnitude of steam temperature (output)

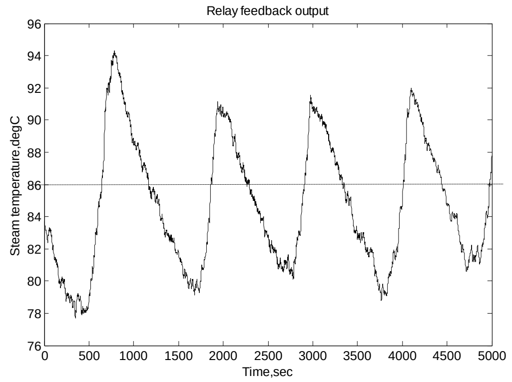

Fig. 5a Output from manual relay operation

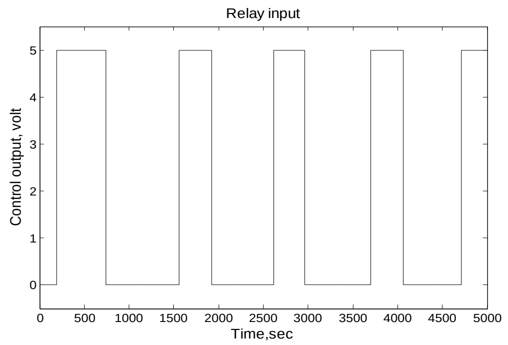

Fig. 5b Relay switching input signal

From the values of Pu and Ku, PID controller can be calculated using Ziegler-Nichols rules in table 2.

TABLE 2 **ZIEGLER-NICHOLS FROM FREQUENCY DOMAIN[27]**

	K_c	T_i	T_d
P	$0.5K_u$		
PI	$\frac{K_u}{2.2}$	$\frac{P_u}{1.2}$	
PID	$\frac{K_u}{1.7}$	$\frac{P_u}{2}$	$\frac{P_u}{8}$

This study implement a PI controller as the process can be estimated with a first-order system. The calculated PI parameters from both methods were tabulated in Table 3.

TABLE 3 TUNED PID PARAMETERS

Tuning method	K_c	T_i
Reaction curve	0.09	1155
Relay feedback	0.9	900

4. EXPERIMENTAL RESULTS

This section analyzed the output response regulated using PI controller but with different tuning method. The proposed method was using the information about Pu and Ku that was obtained from the open-loop relay switching. The method was easier to implement rather than the model-based Ziegler-Nichols tuning which requires a perfect model in order to perform well. This study compared the closed-loop response between these two methods.

The PI controller was developed using MATLAB/Simulink software. Since the PI was tuned between 80°C and 90°C, a control switch was set prior to the controller block to enable the PI control only after the steam temperature was greater than 80°C. Another switch was set before the controller to reset the error value when temperature was 80°C. By applying both switching, the controller gain will performed accordingly as it was tuned. The switching sequences were presented in equation 8 and 9 both for the error and control switching respectively.

$$e(t) = \begin{cases} 0 & ,T < 80°C \\ e(t) & ,T \geq 80°C \end{cases} \quad (8)$$

$$u(t) = \begin{cases} 5 & ,T < 80°C \\ u(t) & ,T \geq 80°C \end{cases} \quad (9)$$

Figure 6a shows the output response with PI controller tuned using reaction curve method. The resulting controller gain was smaller compared to the relay method and thus, producing a slower response. The ability of PI controller in regulating desired set point was evaluated with the presence of external disturbance. Steam temperature was disturbed by adding 1 liter of water inside the tank when t = 3500s.

Water temperature will drop which eventually reduced the steam temperature. From figure 6a, steam temperature was dropped to 78°C 500 s after the water temperature. The controller reacts by producing a higher control signal that increased the temperature to its desired value. Despite of the presence of integral form, the closed-loop response produced some offset during steady-state but the steam temperature might settled down at the desired set point beyond 7000s as can be observed from the output.

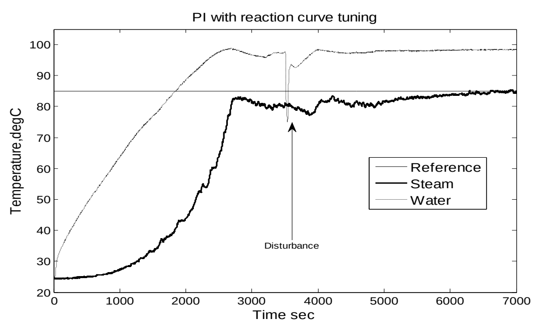

Fig. 6a Steam temperature with reaction curve tuning PI

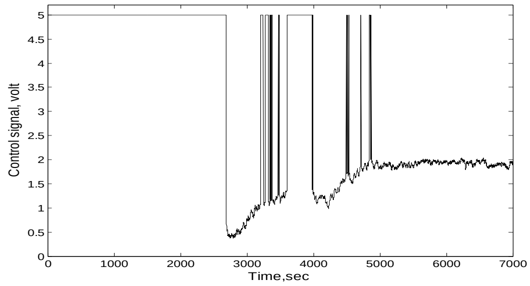

Fig. 6b PI control signal with reaction curve tuning

The same procedure was repeated for the PI controller tuned with the relay input. The output and control signal was given in figure 7a and 7b respectively. Generally, the relay tuning PI produced a faster and more accurate response. The output oscillated around the set point within ±2% marginal.

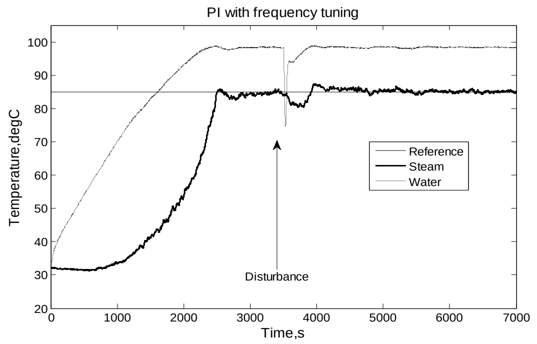

Fig. 7a Steam temperature with frequency tuning PI

The control signal was relatively better where it was smoother with no excessive turning on and off compared with the reaction curve tuning. Figure 7c shows the individual control action of P and I together with error signal when switching was activated. The advantage of error switching was that the error magnitude can be limited within 5°C only. This could minimize the integral wind-up that will increase the control signal until the error returned to negative magnitude. As a result, a smoother control signal was attained as shown in figure 7b.

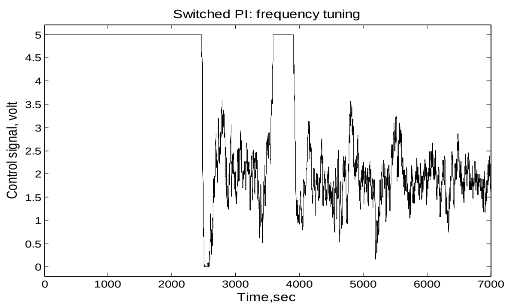

Fig. 7b PI control signal with frequency tuning

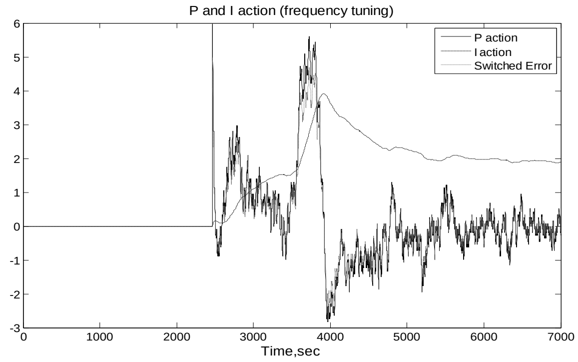

Fig. 7c P and I control signal with error switching

5. CONCLUSION

Modified tuning based on relay input and practical implementation of PI controller with error switching had been proposed and evaluated experimentally on a non-linear steam temperature regulation. The method was easy to implement but the performance was outstanding when compared with the classical PI with reaction curve tuning.

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