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The identification of open loop recording curve on heat exchanger to determine PID control parameters and eliminate overshot occurrence

***Abstract --**The changes in heat exchanger characteristics due to dirt sediment and the effect of corrosion on the conduction pipe can cause difficulty to control the system properly. To anticipate sudden changes in heat exchanger characteristics, this study then tried to identify the open loop recording curve on the heat exchanger in the form of a temperature curve and create a PID controller simulation program. The identification method used in this work was the C.L. Smith method. The simulation test results indicated that some changes in the process variables have occurred following the set point. In this case, the simulation often found some overshoot phenomena which would bring negative impact. In order to avoid the impact, the occurrence of overshoot must be reduced or eliminated.*

Streszczenie**. Zmiany w charakterystyce wymiennika ciepła spowodowane osadzaniem się brudu i wpływem korozji na rurę przewodzącą mogą powodować trudności w prawidłowym sterowaniu systemem. Aby przewidzieć nagłe zmiany w charakterystyce wymiennika ciepła, w ramach tego badania podjęto próbę zidentyfikowania krzywej rejestracji w pętli otwartej na wymienniku ciepła w postaci krzywej temperatury i stworzenia programu symulacyjnego regulatora PID. Metodą identyfikacji wykorzystaną w tej pracy była metoda C.L. Metoda Smitha. Wyniki testów symulacyjnych wykazały, że pewne zmiany w zmiennych procesowych wystąpiły po wartości zadanej. W tym przypadku symulacja często wykazywała pewne przeregulowania, które miałyby negatywny wpływ. Aby uniknąć uderzenia, należy ograniczyć lub wyeliminować występowanie przeregulowania.* (Identyfikacja krzywej rejestracji w otwartej pętli na wymienniku ciepła w celu określenia parametrów regulacji PID i wyeliminowania występowania przesterowania***)

Keywords: heat exchanger, temperature, PID controller, overshoot.
Słowa kluczowe: wymiennik ciepła, regulator PID, przeregulowanie

Introduction

Heat Exchanger is part of secondary process units in chemical manufacturing process. It can determine the quality of final product in the industry. Exchange the heat between two types of fluids having different temperatures is expected in this unit in order to provide a constant fluid temperature from the output. The type of controller that is widely used in industrial manufacturing process is the PID controller (Proportional, Integral, and Differential). This conventional controller has been considered stable and easy to operate. Generally, PID controller has three control methods, namely Proportional (P), integral (I), differential (D). In its operation, the three control parameters require good tuning in order to provide reliable and fast output responses.

To date, several methods have been introduced to tune the PID controller parameters including by conducting *trial and error* method manually. As the changes in process characteristics must be followed by re-tuning of the control parameters, performing controller tuning can be time-consuming and causing disruption in the running process. For this reason, we need a technique that is able to adapt to changes in process parameters and perform automatic re-tuning of controlling parameters. The trial and error method that is manually applied is risky because changes in process variables often occur suddenly leading to the need of constant supervision from the operator in the control room.

Therefore, this work tried to design and create software for making feasible simulation to identify the open loop curve in the form of a temperature curve on *the heat exchanger* [1, 2]. The open loop curve identified by the C.L Smith method is used to determine the relationship between time t_1 and t_2, so that the parameters will be obtained: time constant and delay time. Based on the results of the simulation design, the changes in process variables is similar or close to the *set-point* or target in accordance with the dynamic field.

After obtaining the values of the time constant parameter and the time delay, software then can be made for the simulation to determine the value of proportional strengthening K_p, time integral Ti, and time derivative T_d based on the Ziegler-Nichols method [3, 4]. Finally, the simulation design for the eliminating closed-loop curve overshoot can be achieved.

Research method

Figure 1 shows a *heat exchanger* configuration where the transfer function can be the ratio between the steam input pressure to the valve opening $P_s(t)/X(t)$, or the ratio between the output fluid temperature and the steam input $T_f(t)/P_s(t)$,, or the ratio between the output fluid temperature and steam input pressure $T_f(t)/T_s(t)$ [5].

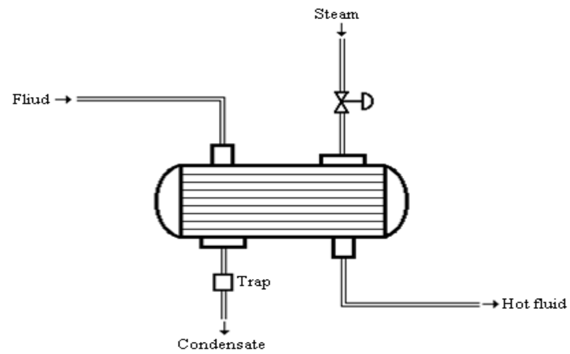

Fig 1. Heat exchanger configuration.

Analysing the transfer function of a process was done using the C.L Smith process that is expressed in the following transfer formula [6][7]

$$G_P(S) = \frac{K_S . e^{-tds}}{\tau s + 1} \quad (1)$$

where $G_p(s)$ is a transfer function of order -1 with time delay, Ks is the static gain of the process, t_d is the *deal time* of the process, and τ is the time constant of the process. In this analysis method, PV has an amplitude of 28.3% of the steady state point. When it is projected onto the time axis, t_1 can be obtained. Furthermore, the PV reaches an amplitude of 63.2% when it is projected onto the time axis, so t_2 will be obtained as shown in Figure 2.

C.L Smith's method determine the relationship between time t1, t2 with time constant and time delay td that can be stated as follows [6]

(2) $$t_1 = (t_d + \frac{1}{3}\tau)$$

(3) $$t_1 = (t_d + \tau)$$

While the static strengthening of the process can be determined by following equation:

(4) $$K_S = \frac{\Delta PV}{\Delta MP}$$

where ΔPV is the deviation of the amplitude of the process output signal (*process variable*), ΔMP is the deviation of the amplitude of the control signal (*manipulated variable*), and Δc_s is the change in the reference of price.

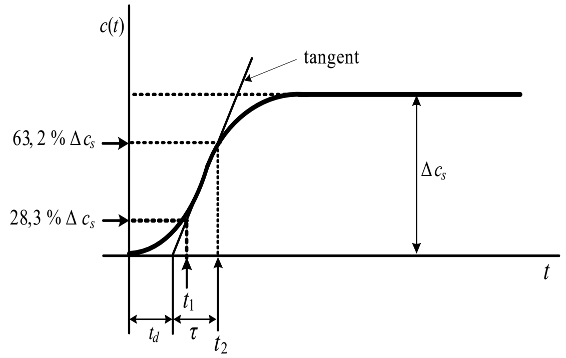

Fig 2. Analysis of the transition response curve of the process

The transfer function of the PID controller then is expressed as follows [8]

(5) $$G_c(s) = K_p(1 + \frac{1}{T_i s} + T_d s)$$

where K_p is the proportional amplifier, T_i is the integral time, and T_d is the derivative time. If $e(t)$ is the input signal to the PID controller, the output $u(t)$ of this controller is given by following function:

(6) $$u(t) = K_p\left[e(t) + \frac{1}{T_i}\int_0^t e(t)\,dt + T_d\frac{de(t)}{dt}\right]$$

To determine the value of proportional gain K_p, integral time T_i, and time derivative T_d the Ziegler-Nichols method was used. PID control tuning can be done by finding a mathematical model of the process that fully represents the dynamics of the process through experiments. The effort made in finding a mathematical model and determining the optimal process parameters experimentally in the problem is named identification process. Eventually, to analyze the performance of a complex process, a mathematical model approach is utilized by assuming the process as the first-order system as seen in Equation (1).

The value of the proportional strengthening of K_p, the integral time of T_i, and the derivative time of T_d are based on the Ziegler-Nichols method as shown in Table 1 [9][10].

Table 1. Ziegler-Nichols tuning based on on the response of the unit step of the system.

Controller Type	K_p	T_i	T_d
P	$\frac{1}{K_s}\left(\frac{t_0}{\tau}\right)^{-1}$	∞	0
PI	$\frac{0,9}{K_s}\left(\frac{t_0}{\tau}\right)^{-1}$	$3,33t_0$	0
PID	$\frac{1,2}{K_s}\left(\frac{t_0}{\tau}\right)^{-1}$	$2t_0$	$\frac{1}{2}t_0$

The response curve of a first-order system with a time delay that has an *overshoot* can be eliminated by setting the PI controller as expresses in the following equations [11][12]

(7) $$G(s)H(s) = K_p\left(1 + \frac{1}{T_i s}\right)\left(\frac{K_s}{\tau s + 1}e^{-t_d s}\right)$$

Where $s = j\omega$,

(8) $$G(j\omega)H(j\omega) = K_p\left(\frac{j\omega T_i + 1}{j\omega T_i}\right)\left(\frac{K_s}{j\omega\tau + 1}\right)e^{-j\omega t_d}$$

Selected $T_i = \tau,$ so that from Equation (8) we can get below formula

(9) $$G(j\omega)H(j\omega) = \frac{K_p.K_s}{j\omega\tau}e^{-j\omega t_d}$$

The magnitude of Equation (9) is

(10) $$|GH| = \frac{K_p.K_s}{\omega.\tau}$$

for $w = \omega_c$, then Equation (10) becomes

(11) $$|GH| = \frac{K_p.K_s}{\omega_c.\tau} \le 0{,}5$$

The angle of Equation (11) is

(12) $$\angle GH = -\frac{\pi}{2} - \omega.t_d$$

For $\omega = \omega_c,$ then Equation (12) becomes:

(13) $$\angle GH = -\frac{\pi}{2} - \omega_c.t_d$$

Equation (13) then becomes:

(14) $$-\frac{\pi}{2} - \omega_c.t_d = -\pi$$

Or

(15) $$\omega_c = \frac{\pi}{2.t_d}$$

So,

(16) $$K_p \le 0{,}5.\omega_c.\tau$$

(17) $$K_p \le 0{,}5.\frac{\pi}{2}.\frac{\tau}{t_d}.\frac{1}{K_s}$$

(18) $$K_p \le 0{,}8.\frac{\tau}{t_d}.\frac{1}{K_s}$$

For PI control

(19) $$K_p \le \frac{0{,}5}{K}$$

Or (20) $$K_p < 0{,}8 \cdot \frac{\tau}{t_d} \cdot \frac{1}{K_s}$$

Magnitude of $\left| G(j\omega)H(j\omega) \right|$

(21) $$\left| G(j\omega)H(j\omega) \right| = \frac{K_p . K_s \sqrt{(\omega T_i)^2 + 1}}{\omega T_i \sqrt{(\omega \tau)^2 + 1}}$$

The characteristic equation can then be stated as follows:

(22) $$1 + G(s)H(s) = 0$$

Or (23) $$1 + K_p \left(1 + \frac{1}{T_i s} \right) \left(\frac{K}{\tau_s + 1} \right) = 0$$

Or (24) $$(T_i s)(\tau s + 1) + K_p . K_s (T_i s + 1) = 0$$

Or (25) $$T_i \tau s^2 + T_i s (1 + K_p . K_s) + K_p . K_s = 0$$

with $GB = K_p.K_s$ and so that the system does not give oscillations, then from Equation (25) we get

(26) $$T_i^2 (1 + K_p . K_s)^2 - 4 T_i . \tau . K_p K_s \geq 0$$

Or(27) $$T_i \geq \frac{4 \tau \, GB}{(1 + GB)^2}$$

Figure 3 shows the relationship between GB and T_i at the boundary of the oscillating and non-oscillating system.

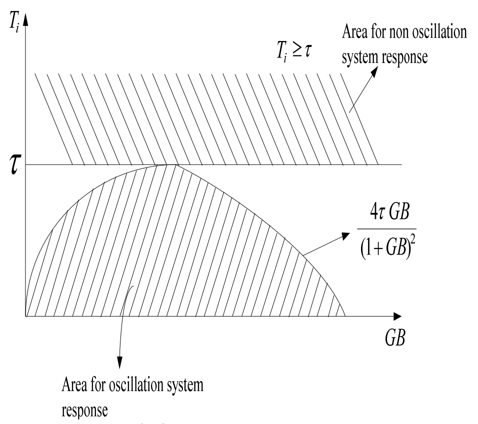

Fig 3. Relationship of GB to T_i system boundary oscillating and non-oscillating.

Heat Exchanger Open Loop Recording Curve

The open loop heat exchanger recording curve is shown in Figure 4.

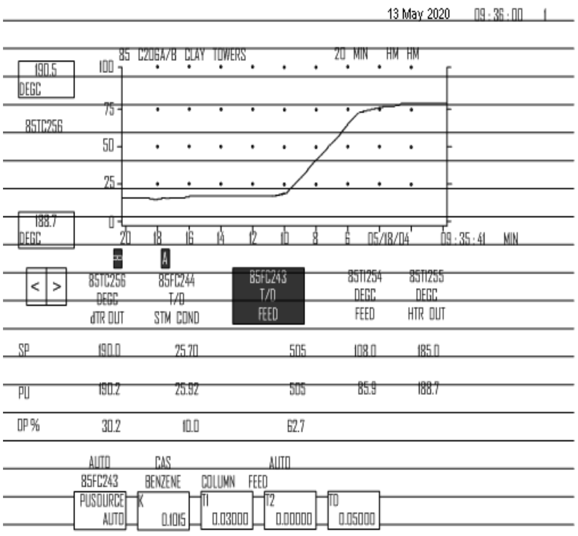

Fig 4. Curve of the open loop *heat exchanger* recording.

Results and analysis

Identification

Based in figure 4 that illustrates the open loop *heat exchanger* recording curve, further identification can be redrawn as seen in figure 5.

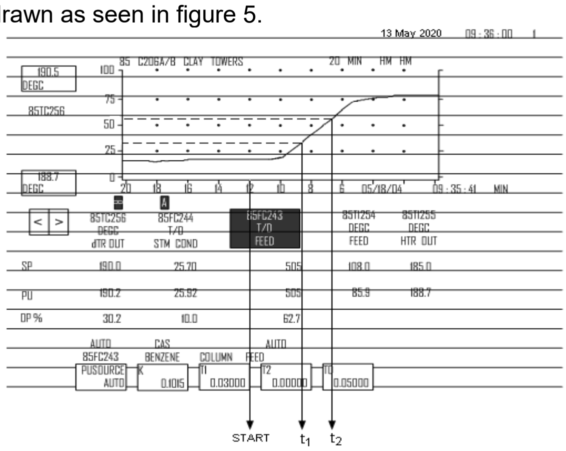

Fig 5. Identification of the open loop recordingcurve heat exchanger from Figure 4.

Identification Results

From Figure 5, the process parameter data for the controller can be obtained as follows:

$\Delta PV = 1{,}8^0C$; $\Delta MV = 1{,}3428^0C$; $K_s = \frac{\Delta PV}{\Delta MV} = 1{,}34$; t_1 = 2,9 minutes; t_2 = 5,7 minutes; τ = $\frac{3}{2}(t_2 - t_1) = 4{,}2$ minutes; $t_0 = t_2 - \tau$ = 1,5 minutes

From the data above, the process transfer function can be expresses as follows:

$$G_P(s) = \frac{1{,}34 \, e^{-1{,}5 s}}{4{,}2 s + 1}$$

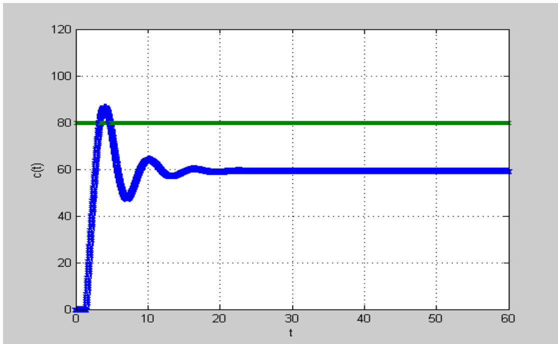

Fig 6. The results of the simulation program on a closed loop *heat exchanger* with P controller type.

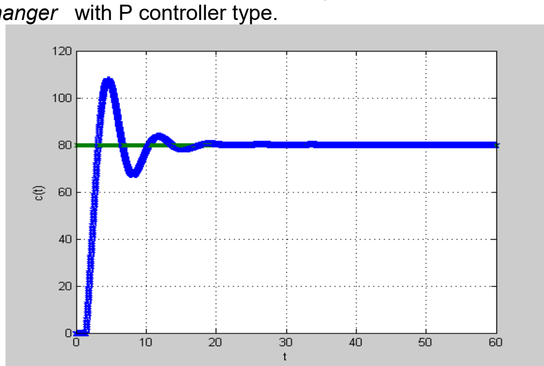

Fig 7. The results of the simulation program on a closed loop *heat exchanger* with PI controller type.

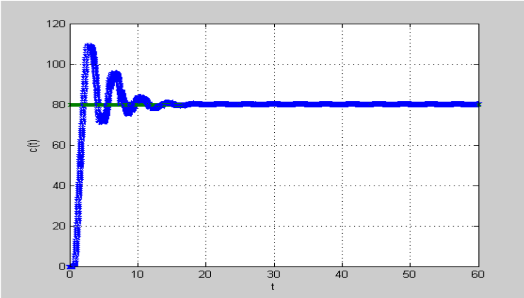

Fig 8. Results of the simulation program on a closed loop *heat exchanger* with PID controller type.

Simulation

Simulation program was conducting using MATLAB programming language. The product in the heat exchanger has a complete reaction at the desired temperature of 80^0C for 60 min, the control results with P, PI, and PID types then are obtained as shown in figures 6, 7, and 8.

Overshoot Elimination

There is a fairly large *overshoot* in figures 6 to 8 above. This *overshoot* can be eliminated by determining the value of K_p, T_i, and for T_d = 0. The value of K_p, T_i, can be found using Equations (19) to (2-27). According to Equations (19) to (27), it is necessary to evaluate the value of the static amplifier or K, and τ, from the data for the price of K = 1.34 and τ = 4.2 min. So the value of K_p can be obtained as follows:

$$K_p \le \frac{0{,}5}{K}$$

$$K_p \le \frac{0{,}5}{1{,}34}$$

$$K_p \le 0{,}373$$

For this K_p, price K_p = 0.3 is taken. For the price of T_i, it can be further examined as follows:

$$T_i \ge \frac{4\tau . K_p . K}{(1 + K_p . K)^2}$$

By entering the prices above,

$$T_i \ge \frac{4 \ . \ 4{,}2 \ . \ 0{,}3 \ . \ 1{,}34}{(1 \ + \ 0{,}3 \ . \ 1{,}34)^2}$$

$$T_i \ge 3{,}436$$

Or $\quad 3{,}436 \le T_i$

T_i price can be taken T_i = 3.5 minutes.

In the simulation, the value of K_p = 0.3, T_i = 3.5 min, and T_d = 0, the results then are as shown in Figure 9

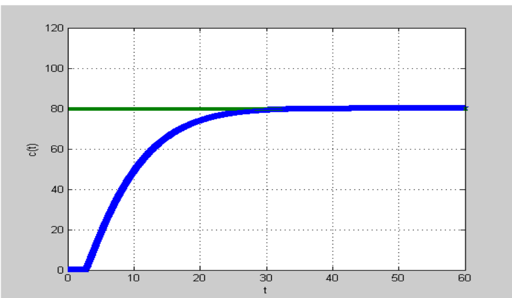

Fig 9. Response curve without *overshoot*.

The combination of figures 7 and 9 then produced the particular pattern as depicted in figure 10.

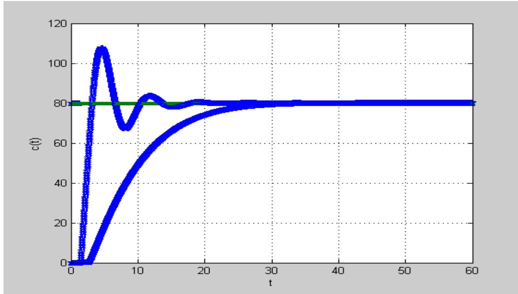

Fig 10. Combined Figures 7 and 9.

Analysis

Based on the closed-loop response curve displayed in figure 6, the variable process for the long time cannot reach the target temperature *(set point) of* 80^0C. It can be seen that, for the long time, the variable process temperature is ± 600^0C. For the closed loop response curve in Figure 7, the variable process for the long lead time is close to or equal to the target temperature *(set point)* of 80^0C. However, there was an *overshoot* (initial spike) at t_p = 4.60 min. The amount of *overshoot* can be calculated as follows

$$M_p = \left(\frac{107{,}52 - 80}{80} \right) x100 \ \% = 34{,}4 \approx 34\%$$

For the closed loop response curve (figure 8), the variable process for the long lead time is close to or equal to the target temperature *(set point)* of 80^0C. However, for the long time leading to the variable process, it can be seen that *overdamped* oscillations occur. There is also a large *overshoot* at t_p = 3.02 min. The amount of *overshoot* that occurs is stated as follows

$$M_p = \left(\frac{137{,}75 - 80}{80} \right) x100 \ \% = 72{,}19 \approx 72\%$$

Conclusion

The results of the closed-loop response curve in the variable process for the long time cannot reach the target temperature *(set point)* of 80^0C. It just achieved variable process temperature of ± 60^0C instead. Moreover, there was an overshoot (initial spike) at t_p = 4.60 min. The amount of overshoot was around 34%. Furthermore, the variable process for the long lead time was close to or equal to the target temperature (*set point)* by 80^0C. However, for the long time leading to the variable process, it can be seen that (overdamped) oscillations occurred along with a large *overshoot* at t_p = 3.02 min. In this case, the occurrence of *overshoot* was 72%. Regarding the results of the closed loop response curve, it can be assumed that it is relatively good with the PI controller type. It can also be implemented by process control engineers to eliminate *overshoot* only closed loop response curve with PI controller type for reducing *overshoot* chances and (overdamped) oscillation rate.

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