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A program design to form an oscillation curve and reduction with PID control on a heat exchanger

Abstract--- *A Heat Exchanger is a secondary process unit that is widely needed in the chemical process industry. This equipment is used to exchange heat between two types of fluids that have different temperatures. The existence of several physical events that change the characteristics of the process causes the stability of the system to be disturbed that necessitates to control the changes in the process parameters. PID controllers are actually conventional controllers which, due to their relatively good condition and easy operation, are still widely used. Many methods have been introduced to analyze PID control parameters, including the Rungge-Kutta method. However, the controlling operators in an industrial process, in order to get good control performance in every industrial process in the event of overshoot or oscillation, adjust the control parameters manually through the trial and error method. For this reason, we need a technique that is able to adapt to changes in process parameters that occur, and at the same time perform automatic re-tuning of controlling parameters. This paper describes a program designed to form an oscillation and reduction curve with a PID controller on a heat exchanger. The design of this program must at least be in accordance with the dynamics of the actual events in the field. the results of the oscillation curve reduction program design which are quite good are the one with the 'PI' controller type as compared to those with the 'P' and 'PID' controller types. The results of the one with the control type 'P' are not good because the process variable (process temperature) is not close to the set. o be used for operator training in industrial processes in the event of disturbances in the form of oscillations..*

Streszczenie. *Wymiennik ciepła jest drugorzędną jednostką procesową, która jest powszechnie potrzebna w przemyśle chemicznym. To urządzenie służy do wymiany ciepła między dwoma rodzajami płynów, które mają różne temperatury. Istnienie kilku zdarzeń fizycznych zmieniających charakterystykę procesu powoduje zaburzenie stabilności systemu, co wymusza kontrolowanie zmian parametrów procesu. Regulatory PID to właściwie regulatory konwencjonalne, które ze względu na stosunkowo dobry stan techniczny i łatwą obsługę nadal znajdują szerokie zastosowanie. Wprowadzono wiele metod analizy parametrów regulacji PID, w tym metodę Rungge-Kutty. Jednak operatorzy kontrolujący w procesie przemysłowym, w celu uzyskania dobrej wydajności sterowania w każdym procesie przemysłowym w przypadku przeregulowania lub oscylacji, dostosowują parametry sterowania ręcznie metodą prób i błędów. Z tego powodu potrzebujemy techniki, która jest w stanie dostosować się do zachodzących zmian parametrów procesu, a jednocześnie wykonać automatyczne przestrojenie parametrów sterujących. W artykule opisano program przeznaczony do tworzenia krzywej oscylacji i redukcji z regulatorem PID na wymienniku ciepła. Projekt tego programu musi być przynajmniej zgodny z dynamiką rzeczywistych wydarzeń w terenie. wyniki projektu programu redukcji krzywej oscylacji, które są dość dobre, to te z regulatorem typu „PI" w porównaniu z tymi z regulatorami typu „P" i „PID". Wyniki tego ze sterowaniem typu „P" nie są dobre, ponieważ zmienna procesowa (temperatura procesu) nie jest zbliżona do zadanej. o być używany do szkolenia operatorów w procesach przemysłowych w przypadku zakłóceń w postaci oscylacji.* (***Projekt programu do tworzenia krzywej oscylacji i redukcji z regulacją PID na wymienniku ciepła***)

Keywords. -Heat Exchanger, PID Control, Oscillation, Reduction.
Słowa kluczowe: wymiennik ciepła, sterownik PID, oscylacje

Introduction

Heat Exchanger is a secondary process unit that is widely needed in the chemical process industry [1]. This equipment greatly determines the quality of the final product in an industry. This equipment is used to exchange heat between two types of fluids that have different temperatures [2]. The existence of several physical events that change the characteristics of the process causes the stability of the system to be disturbed, so it is necessary to control the changes in the process parameters. So far, the type of controller that has been widely used in the field of industrial control is the PID controller (Proportional, Integral, and Differential) [3]. PID controllers are actually conventional controllers which are still widely used due to their relatively good condition and easy operation. The PID controller provides three kinds of control methods, namely: Proportional (P), Integral (I), Differential (D). In their operation, the three control parameters require good tuning in order to provide good and fast output responses [4] [5].

Many methods have been introduced to analyze PID control parameters, including the Rungge-Kutta method. However, controlling operators in an industrial process often adjust the control parameters manually through the trial and error method in order to get good control performance in every industrial process in the event of overshoot or oscillation. Every change in process characteristics must be accompanied by re-tuning of the control parameters [6] [7]. The job of performing controller re-tuning is a time-consuming job and greatly disrupts the running process. For this reason, we need a technique that is able to adapt to changes in process parameters that occur, and at the same time perform automatic re-tuning of controller parameters. This paper discusses a program designed to form an oscillation and reduction curve with a PID controller on a heat exchanger. The design of this program must at least be in accordance with the dynamics of the actual events in the field. The results of this program design are expected to be used for operator training in industrial processes in the event of disturbances in the form of oscillations.

Research Methods

The heat exchanger process system is as shown in Figure 1 below [8] [9] [10].

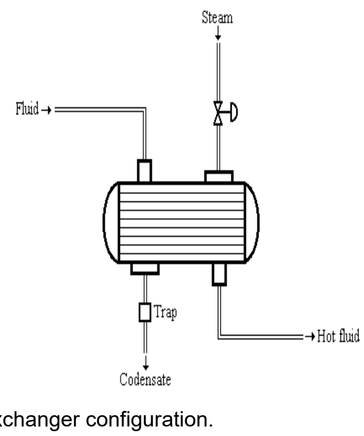


Fig 1. Heat exchanger configuration.

Figure 1 shows a configuration of a heat exchanger using steam as the heating medium. The transfer function of the heat exchanger is 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 $T_f(t)/T_s(t)$.

In order to obtain the transfer function in this discussion, the ratio between the output fluid temperature and the steam input pressure $T_f(t)/T_s(t)$ is determined, assuming that under steady conditions there is no axial conduction propagation, there is no back mixing, and other variables such as pressure and fluid flow are considered constant. Likewise, to limit the higher order equations, it is assumed that there is no pipe wall resistance and capacity in the condensate film in the conducting pipes.

The energy balance equation for the heat exchange between the heated fluid and the inner pipe is as follows:

(1) $$M_f.c_f\left(\frac{\partial T_f(t)}{\partial t}\right)+F(t)c_f\left(\frac{\partial T_f(t)}{\partial x}\right)=h_1.A_1\left(T_d(t)-T_f(t)\right)$$

in which M_f is the mass of the heated fluid per *foot* in lb/ft unit, c_f is the heat coefficient of the fluid in Btu/lb^{o}F, $T_f(t)$ is the temperature of the heated fluid in ^{o}F unit, $F(t)$ is the flow of the heated fluid in lb/sec unit, h_1 is the coefficient of heat propagation of the inner pipe in Btu/sec.ft^2.^{o}F units, A_1 is the area of heat transfer on the inner pipe wall per foot in units of ft^2/ft.

If the heated fluid is water, then $F(t) = v(t)$. M_f, in which $v(t)$ is the fluid flow velocity in the pipe (ft/sec), so Equation (2) becomes

(2) $$M_f.c_f\left(\frac{\partial T_f(t)}{\partial t}\right)+v(t)M_f.c_f\left(\frac{\partial T_f(t)}{\partial x}\right)=h_1.A_1\left(T_d(t)-T_f(t)\right)$$

with $\frac{M_f.c_f}{h_1.A_1}=\tau_1$, which is the time constant of heat propagation between the fluid and the pipe wall, therefore Equation (3) becomes

(3) $$\tau_1\frac{\partial T_f(t)}{\partial t}+v(t).\tau_1\frac{\partial T_f(t)}{\partial x}=T_d(t)-T_f(t)$$
$$T_d(t)=\tau_1\frac{\partial T_f(t)}{\partial t}+v(t).\tau_1\frac{\partial T_f(t)}{\partial x}+T_f(t)$$

Then review the energy balance equation between the conduction pipe wall and the heating medium as follows:

(4) $$M_d.c_d\left(\frac{\partial T_d(t)}{\partial t}\right)=h_2.A_2\left(T_s(t)-T_d(t)\right)-h_1.A_1\left(T_d(t)-T_f(t)\right)$$

in which $T_s(t)$ is the steam input temperature in units of ^{o}F, $T_d(t)$ is the temperature of the conduction pipe wall in units of ^{o}F, $M_d.c_d$ is the heat capacity of the pipe wall in units of Btu/^{o}F.ft, while h_2 is the coefficient of heat propagation in the pipe outside in units of Btu/sec.ft^2.^{o}F, and A_2 is the area of heat transfer on the outside of the pipe per foot in units of ft^2/ft.

Because $\frac{M_d.c_d}{h_2.A_2}=\tau_2$ is the time constant of heat propagation between the pipe wall and the heating medium (steam), while $\frac{M_d.c_d}{h_1.A_1}=\tau_{12}$ is the total heat propagation time constant between the fluid and steam, then Equation (4) becomes

(5) $$\tau_2\frac{\partial T_d(t)}{\partial t}=\left(T_s(t)-T_d(t)\right)-\frac{\tau_2}{\tau_{12}}\left(T_d(t)-T_f(t)\right)$$

or

(6) $$\tau_2\frac{\partial T_d(t)}{\partial t}=T_s(t)+\frac{\tau_1}{\tau_{12}}T_f(t)-T_d(t)\left(1+\frac{\tau_2}{\tau_{12}}\right)$$

If the value of $T_d(t)$ from the Equation (3) is substituted into the Equation (5 or 6), one will get

(7) $$\tau_2\frac{\partial T_d(t)}{\partial t}=T_s(t)+\frac{\tau_1}{\tau_{12}}T_f(t)-\left(1+\frac{\tau_2}{\tau_{12}}\right)\left\{\tau_1\frac{\partial T_f(t)}{\partial t}+v(t)\tau_1\frac{\partial T_f(t)}{\partial x}+T_f(t)\right\}$$

(8) $$\tau_2\frac{\partial T_d(t)}{\partial t}=T_s(t)+T_f(t)\left\{\frac{\tau_1}{\tau_{12}}-\left(1+\frac{\tau_2}{\tau_{12}}\right)\right\}-\left(1+\frac{\tau_2}{\tau_{12}}\right)\left\{\tau_1\frac{\partial T_f(t)}{\partial t}+v(t)\tau_1\frac{\partial T_f(t)}{\partial x}\right\}$$

(9) $$\tau_2\frac{\partial T_d(t)}{\partial t}+\left(1+\frac{\tau_2}{\tau_{12}}\right)\left\{\tau_1\frac{\partial T_f(t)}{\partial t}+v(t)\tau_1\frac{\partial T_f(t)}{\partial x}\right\}=T_s(t)+T_f(t)\left\{\frac{\tau_1}{\tau_{12}}-\left(1+\frac{\tau_2}{\tau_{12}}\right)\right\}$$

(10) $$\tau_2\frac{\partial T_d(t)}{\partial t}+\left(1+\frac{\tau_2}{\tau_{12}}\right)\left\{\tau_1\frac{\partial T_f(t)}{\partial t}+v(t)\tau_1\frac{\partial T_f(t)}{\partial x}\right\}=T_s(t)-T_f(t)$$

In fact, the conduction pipe wall temperature $T_d(t)$ is a process variable that is difficult to measure, therefore $\frac{\partial T_d(t)}{\partial t}$ in the Equation (6 or 7 or 8 or 9 or 10) must be removed, by changing the Equation (3) into a differential equation of a function of time, as follows

(11) $$\frac{\partial T_d(t)}{\partial t}=\frac{\partial}{\partial t}\left\{\tau_1\frac{\partial T_f(t)}{\partial t}+v(t)\tau_1\frac{\partial T_f(t)}{\partial x}+T_f(t)\right\}$$

Then by entering the value of $\frac{\partial Td(t)}{\partial t}$ from the Equation (11) into the Equation (7 until 10), one will get

(12) $$\frac{\partial^2 T_f(t)}{\partial t^2}+v(t).\tau_1\tau_2\frac{\partial^2 T_f(t)}{\partial t\partial x}+\tau_2\frac{\partial T_f(t)}{\partial t}+\tau_1\frac{\partial T_f(t)}{\partial t}+v(t).\tau_1\frac{\partial T_f(t)}{\partial x}$$
$$+\frac{\tau_1\tau_2}{\tau_{12}}\frac{\partial T_f(t)}{\partial t}+v(t)\frac{\tau_1\tau_2}{\tau_{12}}\frac{\partial T_f(t)}{\partial x}=T_s(t)-T_f(t)$$

Or

(13) $$\tau_1\tau_2\frac{\partial^2 T_f(t)}{\partial t^2}+v(t).\tau_1\tau_2\frac{\partial^2 T_f(t)/dt}{\partial t.\partial x/dt}+\tau_2\frac{\partial T_f(t)}{\partial t}+\tau_1\frac{\partial T_f(t)}{\partial t}$$
$$+v(t).\tau_1\frac{\partial T_f(t)/dt}{\partial x/dt}+\frac{\tau_1\tau_2}{\tau_{12}}\frac{\partial T_f(t)}{\partial t}+v(t)\frac{\tau_1\tau_2}{\tau_{12}}\frac{\partial T_f(t)/dt}{\partial x/dt}=T_s(t)-T_f(t)$$

By considering other factors as constant factors, it is assumed that $\partial t = dt$, and the velocity of fluid flow in the pipe $v(t) = \partial x/dt$, then Equation (12 or 13) becomes

(14) $$2\tau_1\tau_2\frac{\partial 2T_f(t)}{\partial 2}+2\tau_1\frac{\partial T_f(t)}{\partial t}+\tau_2\frac{\partial T_f(t)}{\partial t}+2\frac{\tau_1\tau_2}{\tau_{12}}\frac{\partial T_f(t)}{\partial t}+T_f(t)=Ts(t)$$

The Laplace transform of each part of the Equation (14) is

(15) $$\text{L}\left[2\tau_1\tau_2\frac{\partial 2T_f(t)}{\partial t2}\right]=2\tau_1\tau_2\left[s2T_f(s)-sT_f(0)-\dot{T}_f(0)\right]$$
$$\text{L}\left[2\tau_1\frac{\partial T_f(t)}{\partial t}\right]=2\tau_1\left[sT_f(s)-T_f(0)\right]$$
$$\text{L}\left[\tau_2\frac{\partial T_f(t)}{\partial t}\right]=\tau_2\left[sT_f(s)-T_f(0)\right]$$

$$\mathcal{L}\left[2\frac{\tau_1\tau_2}{\tau_{12}}\frac{\partial T_f(t)}{\partial t}\right] = 2\frac{\tau_1\tau_2}{\tau_{12}}\left[sT_f(s) - T_f(0)\right]$$

$$\mathcal{L}\left[T_f(t)\right] = T_f(s)$$

$$\mathcal{L}\left[T_s(t)\right] = T_s(s)$$

Assuming all initial conditions are zero, so that $T_f(s) = 0$, $\dot{T}f(0) = 0$, then the Laplace transform of the Equation (15) is as follows

$$2\tau_1\tau_2 s^2 T_f(s) + 2\tau_1 s T_f(s) + \tau_2 s T_f(s) + 2\frac{\tau_1\tau_2}{\tau_{12}} s T_f(s) + T_f(s) = T_s(s) \qquad (16)$$

or

$$T_f(s)\left[2\tau_1\tau_2 s^2 + 2\tau_1 s + \tau_2 s + 2\frac{\tau_1\tau_2}{\tau_{12}} s + 1\right] = T_s(s) \qquad (17)$$

So the transfer function of the heat exchanger is as follows:

$$\frac{T_f(s)}{T_s(s)} = \frac{1}{2\tau_1\tau_2 s^2 + \left(2\tau_1 + \tau_2 + \frac{2\tau_1\tau_2}{\tau_{12}}\right)s + 1} \qquad (18)$$

The Equation (18) above is a second-order transfer function with processing time constants τ_1 and τ_2, in which $\tau_{12} = \tau_1 + \tau_2$.

Proportional Plus Integral Plus Derivative (PID) Controller

The combination of proportional control action, integral control action, and derivative control action is called proportional plus integral plus derivative control action. The proportional plus integral plus derivative transfer function in the Laplace transform is as follows [4]

$$\frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \qquad (19)$$

Figure 2(a) shows a block diagram of this controller. If the error generating signal $e(t)$ is a slope function as shown in Figure 2(b), then the controller output is as shown in Figure 2(c).

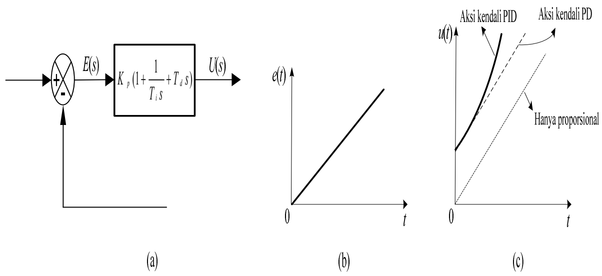


Figure 2. (a) Proportional plus integral plus derivative control block diagram , (b) Input slope function, (c) Control output

Tuning of PID Controller

In determining the value of proportional gain K_p, integral time T_i, and time derivative T_d is based on the Ziegler-Nichols method. Determining the parameters of the PID control is also called tuning. The tuning of the PID control can be done by looking for a mathematical model of the process that fully represents the dynamics of the process [11].

There are two ways that can be taken to obtain the model, namely:

1. Theoretically, through mathematical derivation based on the laws of physics.
2. Experimentally.

Usually in the first way, namely a review based on the laws of physics has not been able to provide an accurate model, because there are several process parameters that must be determined experimentally. Therefore, people prefer experimentally to look for process models.

The effort made in finding a mathematical model and determining the optimal process parameters experimentally in the problem at hand is called identification. To facilitate the analysis of the performance of a fairly complex process, a mathematical model approach is held by assuming the process is a first-order system as follows [8]

$$G_p(s) = \frac{K_s . e^{-tds}}{\tau s + 1} \qquad (20)$$

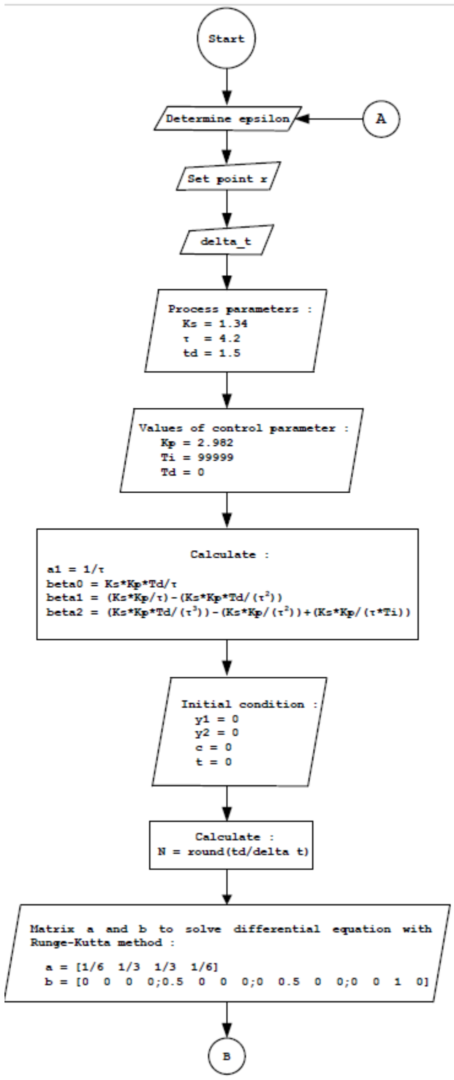
To determine the value of the proportional strengthening of K_p, the integral time of T_i, and the derivative time of T_d are based on the Ziegler-Nichols method as shown in Table 1 below [4].

able 1. Ziegler-Nichols tuning based 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	$\frac{1,2}{K_s}\left(\frac{t_0}{\tau}\right)^{-1}$	$2t_0$	$\frac{1}{2}t_0$

Program to form an oscillation curve

The program to form the oscillation curve in the heat exchanger is like the flow chart [12] []13] [14] [15] in Figure 3 below.



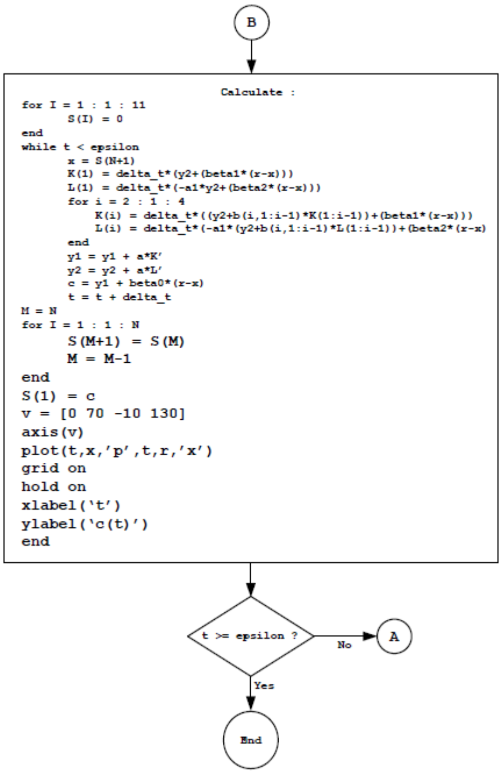


Fig 3. Program to form oscillation curve in heat exchanger

PID Controller tuning to reduce oscillation curve

Critical gain Kpu and Tosc period determined from measurement or calculation (see Figure 4).

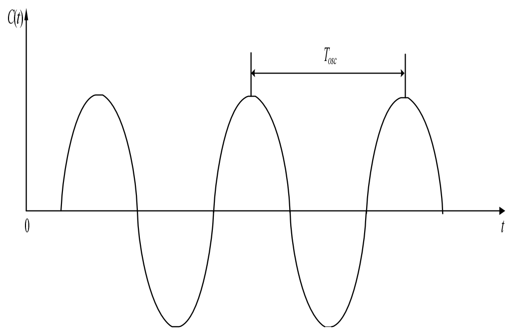


Fig 4. Continuous oscillation of the Tosc period.

Zigler and Nichols suggested tuning the parameter values of K_p, T_i, and T_d based on the equations shown in Table 2 [12].

able 2. Ziegler-Nichols tuning rules are based on Kpu gain and the critical period

Controller Type	K_p	T_i	T_d
P	$0{,}5K_{pu}$	∞	0
PI	$0{,}45K_{pu}$	$\frac{1}{1.2}T_{osc}$	0
PID	$0{,}6K_{pu}$	$0{,}5\,T_{osc}$	$0{,}125\,T_{osc}$

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Program to reduce oscillation curve in heat exchanger [14] [15] [16] as flow chart of Figure 5, The program is written in the language of MATLAB Version 6.5.

Resukts and analysis

Results.

The results of a program to produce a continuous oscillation curve with the values: epsilon = 70.01, r = 70, delta_t = 0.2, and K_{pu} = 2,982 as shown in Figure 6 below.

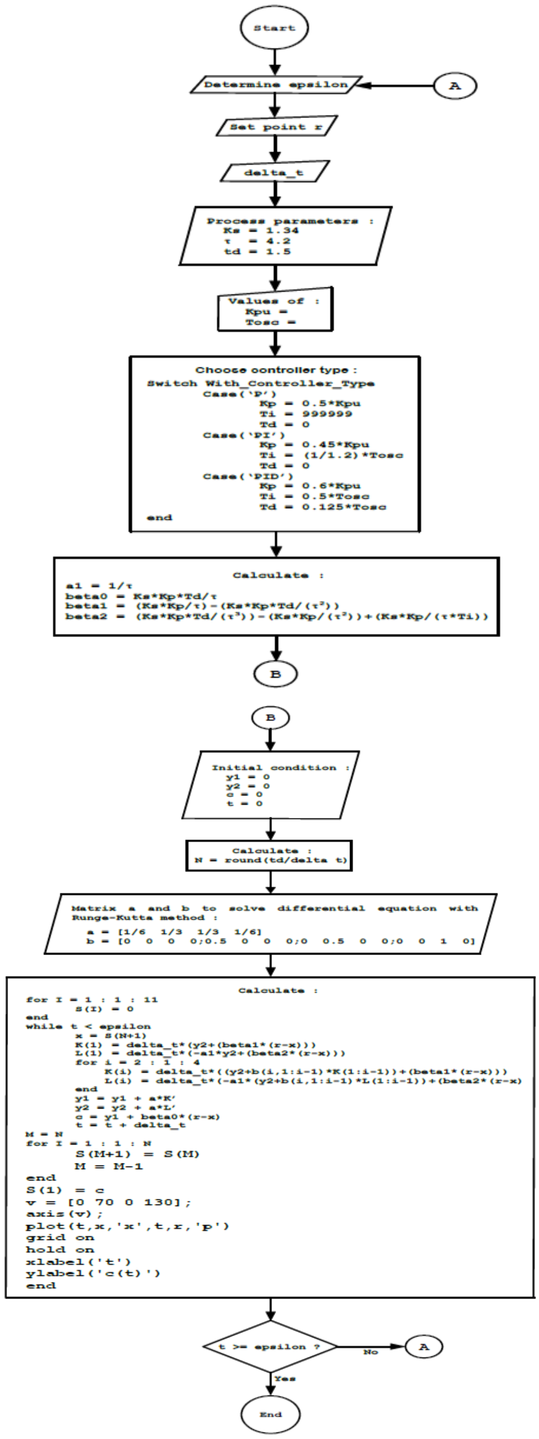

Fig 5. Program to reduce oscillation curve in heat exchanger

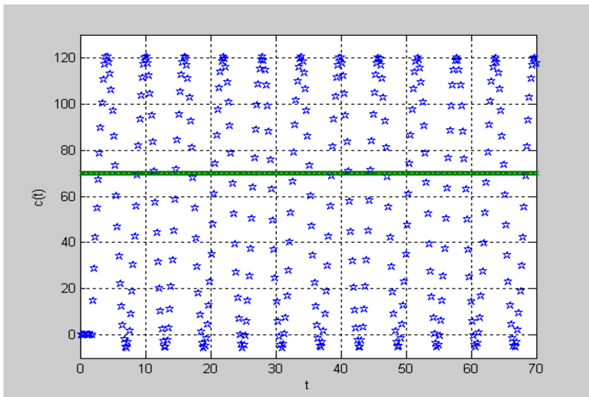

Fig 6. Results of a continuous oscillation response curve program.

Reduction of the continuous oscillation response curve in Figure 6 above with the values: epsilon = 70.01, r = 70, delta_t = 0.2, K_{pu} = 2,982, Tosc = 6 minutes, and the control types selected are 'P', 'PI', and ' PID'. The results of the 'P' controller type are as shown in Figure 7, those of the 'PI' controller type are as shown in Figure 8, and those of the 'PID' controller type are as shown in Figure 9.

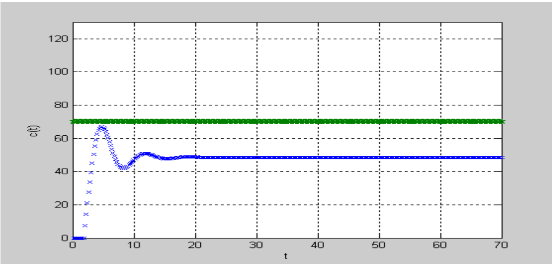

Fig 7. Reduction of continuous oscillation response curve of Figure 6 for the 'P' controller type.

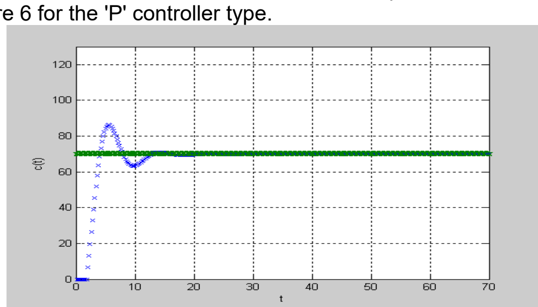

Fig 8. Reduction of continuous oscillation response curve of Figure 6 for the 'PI' controller type.

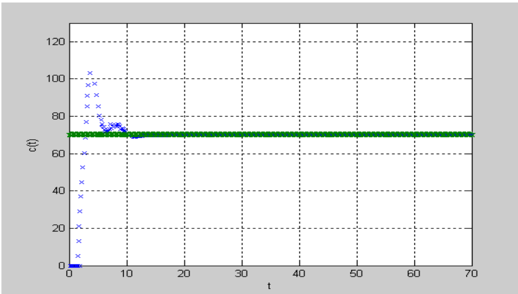

Fig 9. Reduction of continuous oscillation response curve of Figure 6 for the 'PID' controller type.

Analysis

In designing a program to produce a continuous oscillating curve, very important values need to be determined first are epsilon, r (set point), Δt. It is also necessary to know the values of the process parameters: static gain (Ks), tau (τ), and time delay (td). Then, set the values of the control parameters: Kp, Ti, Td. Next, arrange the programming language code to solve the problem that will be used. The program to produce a continuous oscillation curve in this paper uses the numerical solution of the Rungge-Kutta differential equation. The usage of the solution of the Rungge-Kutta numerical differential equation produces quite perfect results for a continuous oscillation curve.

Reduction of continuous oscillation response curve in arranging programming language code is not much different from arranging program structure to produce continuous oscillation curve. It is just that one needs to know the K_{pu} data from the company and the Tosc data. In this paper the value of Tosc = 6 minutes. The results of the simulation program reveal that at t = 2.40 minutes, the value of c(t) = 120.52^{o}C and at t = 8.40 minutes, the value of c(t) = 120.18^{o}C. So the value of Tosc = (8.40-2.40) minutes = 6 minutes. And to run the program, select the controller type such as: 'P' or 'PI' or 'PID'. The results of the continuous oscillation response curve reduction reveal that a fairly good picture is the one with the 'PI' controller type as shown in Figure 8. Figure 7 shows that the one with the 'P' controller type produces the results that are not good because the variable process (process temperature) does not approach the set point or the variable process is below the set points. And Figure 9 also shows that the one with the 'PID' type of controller produces the results which are not good because the process variable contains a large enough overshoot.

Conclusion

The results of the continuous oscillation curve program design are quite perfect as shown in Figure 6. And the results of the oscillation curve reduction program design which are quite good are the one with the 'PI' controller type as compared to those with the 'P' and 'PID' controller types. The results of the one with the control type 'P' are not good because the process variable (process temperature) is not close to the set point or the process variable is below the set point. While the one with the 'PID' type of controller produces the results which are not good either because the process variable contains a large enough overshoot.

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