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A Review on Temperature Process Control: Case Study on Boiler

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Abstract

Process control is an important aspect area to be studied as many industries are dealing with it. During a lab course in Mechatronics Engineering at Assumption University, Thailand, a temperature process control is introduced and a basic study is made. This study covers kettle and thyristor power module including a plant, thermocouple and thermistor as temperature sensors, and Bosch Rexroth Programmable Logic Controller (PLC) as a controller. This review article will be beneficial to the reader to understand the link between a mathematical model and an actual system model. To control the temperature of the boiler, a three-mode control (0%-50%-100%), and a proportional-integral (PI) control are used to vary the output responses. The three-mode control can use digital output from the PLC, while the PI control needs to use analog output from the PLC. A simulation model with MATLAB®/Simulink® is studied before the actual experiment. Students can apply the temperature process control concept to others process controls such as position control, speed control, pressure control, flow control, level control, etc.

Keywords: *Three-mode control, proportional-integral control, system transfer function.*

1. Introduction

Process control is very useful in industries applications. To provide a practical description of process control and to be able to control it efficiency, it is essential to understand the block diagram and mathematical model of the system. A mathematical block diagram will allow the scientist to choose appropriate parameters for the controller.

Initially, we will review the classical control theory block diagram, which is normally used in process control applications. Each block diagram is explained, so that the reader can follow and understand the main concept of a process control system.

When we understand the process control system thoroughly, we can extend the knowledge further into industrial applications. Proportional, integral, and derivative (PID) control is a popular control system that is being widely used. Kiam *et al*. (2005) proposed a software method in tuning PID. He claimed that with “plug and play” method, PID variants can be adjusted easily. Mohammad (2007) used a pulse-width-modulation (PWM) output to control the temperature with PLC; with this method, the analog module can be excluded from the experiment and thus the cost is reduced. In our paper, the reader will understand temperature process control using proportional and integral (PI) control with a PLC unit. The reason we are not using a derivative term is because water itself acts as a damping parameter in the system.

We use temperature control as a case study. This report reviews a mathematical model used to represent a complete system. Section 2 highlights the process control system including a plant, sensors and controllers. Section 3 discusses different control methods: three-mode and proportional-integral (PI) controls. The simulation study is reviewed in Section 4. The Conclusion of the paper is explained in Section 5.

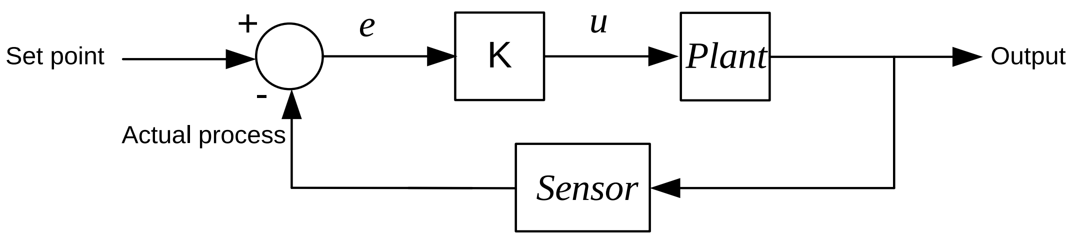


Fig. 1. The control system block diagram.

The further study on other control techniques, such as Fuzzy Logic Control (FLC), is allocated as a future work.

2. Process Control System

A process control system is used to regulate the value of any process variable, such as temperature in our case study (Jacob 1989). In this section, initially we will review the concept of a control block diagram. Then the contents of each block will be briefly explained. Finally, the modeling of the boiler system will be presented.

2.1 The Control System

The block diagram of the control system consisting of the components listed below is shown in Fig. 1 and the temperature control system is illustrated in Fig. 2:

- Plant: Thyristor Power Module (TPM) and kettle;
- Sensor: Thermocouple, thermistor and amplifier circuit;
- Controller: IndraLogicL20 PLC system.

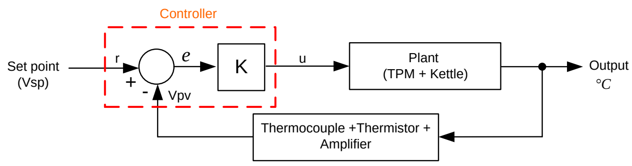
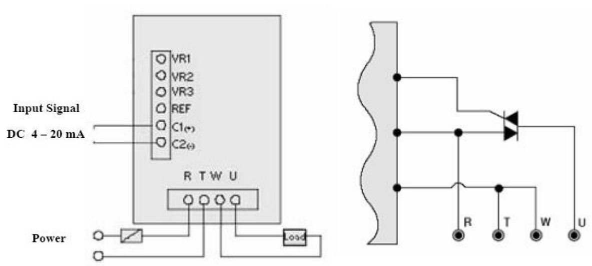


Fig. 2. The temperature control system block diagram.

2.1.1 Plant

The plant in this system includes a thyristor power module (TPM) by Hanyoung (2001) and a kettle. Figure 3 shows the TPM which is used in this case study. TPM takes an input from 4-20 mA and represents 0°-180° firing angles (α). The output of TPM, with firing angles set at 4°, 20°, 40°, 56°, and 92°, is shown in Fig. 4, respectively.

(a)



(b)

Fig. 3. (a) Thyristor Power Module: TPR2; and (b) Wiring diagram.

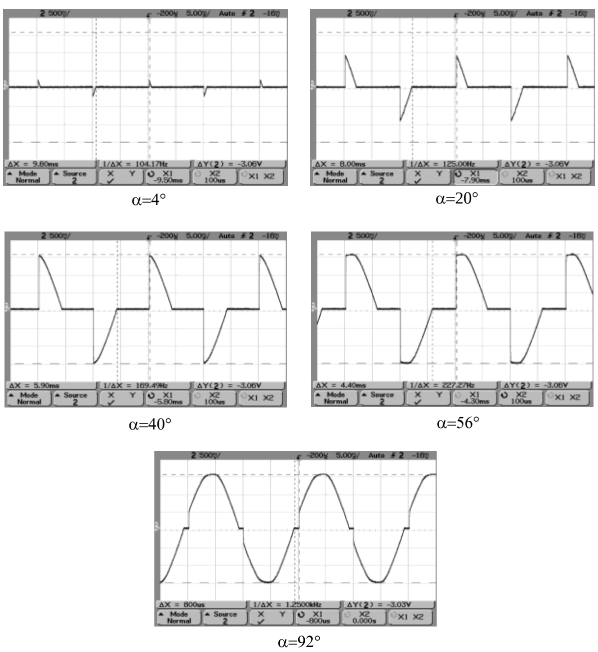


Fig. 4. Output voltage of TPM (Variation of firing angles).

2.1.2 Sensor

Thermocouple type *K* (Chromel-alumel) is chosen as one of the sensors in this study. A thermocouple is a voltage-generating sensor; an electromotive force (emf) is produced that is proportional to the temperature. This effect can be described by an emf which has been established in the circuit that is causing the current to flow.

Thermocouples are widely used in the industries and therefore chosen as sensors. A thermocouple has a wide range of temperature measurements. Normally, thermocouple tables are prepared for a particular junction temperature. For a thermocouple type *K* with 0°C reference: $V_0(100°C)$ = 4.096 mV and $V_0(25°C)$ = 1.005 mV. Therefore, with 25°C reference: $V_{25}(100°C)$ = 3.091 mV. A practical problem with the use of a thermocouple is the reference junction. To solve this problem, a thermistor is used to offset the room temperature as the reference temperature. A thermistor NTC TTC03 resistance at 25°C is added, and the sensor block diagram is shown in Fig. 5. Therefore, for this laboratory setting, 100°C corresponds to 3.091 mV if the room temperature is 25°C.

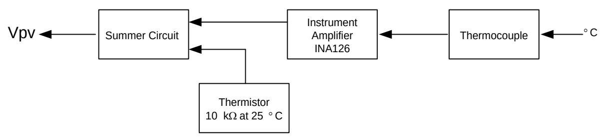


Fig. 5. Sensor block diagram.

The thermocouple value is too small for further manipulation and needs to be amplified. INA126 instrument amplifier by TI (2005) is used as shown in Fig. 6(a). Hence, to have 5 V maximum output from the sensor, a resistor gain is calculated as:

$$V_{out} = V_{thermocouple}G,$$

$$G = \frac{5\,\text{V}}{3.091\,\text{mV}} = 1{,}617.6 \approx 1{,}618,$$

and since

$$G = 5 + \frac{80k}{R_G}, \qquad (1)$$

$$\Rightarrow R_G \approx 50\ \Omega.$$

Usually, an instrumentation amplifier has very high impedance, therefore, 10 KΩ resistor is needed to be connected at the non-inverting pin as shown in Fig. 6(b).

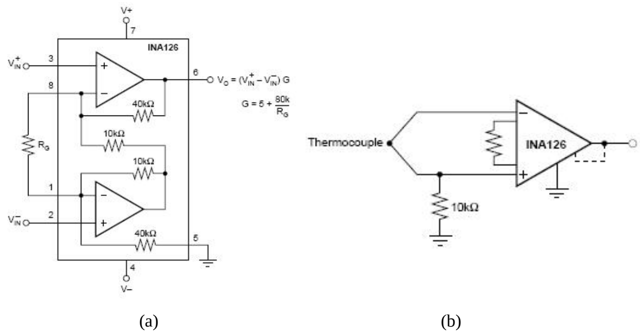


Fig. 6. (a) INA126 Instrument amplifier; and (b) 10 KΩ to be connected to a non-inverting pin.

2.1.3 Controller

PLC IndraControl L20 by Bosch Rexroth (2002, 2005) is used as a main controller in this case study.

Fig. 7. PLC IndraControl L20 unit.

Figure 7 shows the PLC unit, which includes the onboard and inline modules listed below:

- ***Onboard***
  - Digital inputs: 8 inputs, 24V DC;
  - Digital outputs: 8 outputs, 24V DC, 500 mA;
  - Ethernet: RJ45, female connector, 8-pin;
  - RS232: D-Sub male connector, 9-pin.

- ***Inline***
  - Digital inputs (R-IB IL 24 DI 16): 16 inputs, 24V DC;

- Analog inputs (R-IB IL AI 2/SF): 2 inputs, 0-20mA, 4-20mA, ±20 mA, 0-10V, ±10V;
- Digital outputs (R-IB IL 24 D0 16): 16 outputs, 24V DC, 500mA;
- Analog outputs (R-IB IL AO 2/U/BP): 2 outputs, 0-10V, ±10V.

2.2 System Transfer Function

The system responses, such as transient and steady state output, can be previewed from the transfer function. Katsuhiko (1997) has clearly defined the transfer function parameters, such as DC gain (K_{DC}) and time constant (τ). These parameters can be determined using the step response function from MATLAB®. The step response of our plant (TPM + kettle) is shown in Fig. 8.

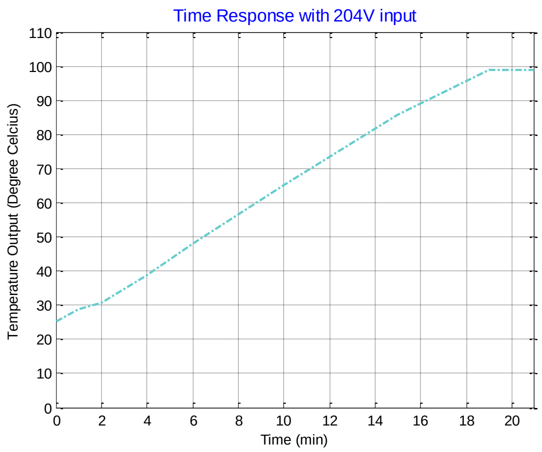


Fig. 8. Plant's response.

The response of the plant can be written as:

$$T_{^\circ C} = K_{DC}(1 - e^{-\frac{t}{\tau}}). \qquad (2)$$

DC gain (K_{DC}) and time constant (τ) can be found from the step response, as follows:

$$\ln T_1 - \ln K_{DC} - \ln(1 - e^{-\frac{t_1}{\tau}}), \text{ and}$$

$$\ln T_2 - \ln K_{DC} - \ln(1 - e^{-\frac{t_2}{\tau}}). \qquad (3)$$

Hanselman and Littlefield (2005) have defined the numerical analysis toolbox; K_{DC} = 108.171 and τ = 555 s are determined by the toolbox. From Eq. (1), the transfer function can be obtained by taking Laplace transform as:

$$T(s) = \frac{1}{s}\frac{K_{DC}}{(\tau s + 1)}. \qquad (4)$$

$U(s) = \frac{204}{s}$, thereafter the system transfer function becomes:

$$G_{Plant}(s) = \frac{T(s)}{U(s)} = \frac{0.530}{(555s + 1)}. \qquad (5)$$

Hence, the sensor transfer function is defined as:

$$G_{Sensors}(s) = \frac{V_{PV}}{^\circ C} = \frac{5}{100} = 0.05. \qquad (6)$$

3. Control Methods

In this section, we review control methods that are applied to control the desired temperature of the boiler. This paper focuses on two control methods: three-mode control and proportional-integral (PI) control. Curtis (2000) has demonstrated these two control methods to be applied to process control. Output of the controller is the indirectly controlled firing angle (α) from the Thyristor Power Module (TPM).

3.1 Three-mode Control

The most elementary controller is the two-mode (0%-100%) control. We add an intermediate point (50%) to reduce both the overshoot and undershoot that occur in the said two-mode control. The three-mode control is given as:

$$u_{ThreeModes} = \begin{cases} 100 & \text{if } e < e_{MAX} \\ 50 & \text{if } e_{MIN} < e < e_{MAX} \\ 0 & \text{if } e > e_{MIN} \end{cases}, \qquad (7)$$

where e_{MAX} and e_{MIN} are the maximum error and minimum error, respectively, which are set as per the user's requirement.

3.2 Proportional-Integral (PI) Control

The proportional-integral control is a combination of continuous control actions P and I that are commonly used in process control.

A proportional (*P*) control gives a smooth, linear relationship, between the error (*e*) and the output of the controller (u_P). The *P*-control is expressed by:

$$u_P = K_P \times e + p_0, \qquad (8)$$

where K_P is proportional gain and p_0 is the controller output when the error = 0%. The *P*-control gives a permanent residue error when a change in load occurs.

The integral control can adapt to the change in loads, and can eliminate the residue error that is caused by *P*-control. This action is provided by summing the error over time, multiplying that sum by a gain, and adding the result to the control output. The *I*-control is represented by:

$$u_I = K_I \int_0^t edt + p(0), \qquad (9)$$

where K_I is the integral gain and $p(0)$ is the controller output when the integral action starts (initial value).

The proportional-integral (PI) control is a result of the combination of the proportional mode and the integral mode. This mode provides a proportional output, while the integral mode eliminates the inherent offset error. The PI control is found from a combination of Eqs. (8) and (9) as

$$u_{PI} = K_P \times e + K_I \int_0^t edt + p(0)\,. \qquad (10)$$

Next, we will discuss the PI control algorithm when applied to the boiler system.

4. Simulation Study

The plant model is simulated with MATLAB®/Simulink®. Figure 9 shows the simulation block diagram. Figure 10(a)-(b) shows the three-mode control and PI control block sets, respectively.

The set points: 45°C and 65°C were chosen as desired set points to verify the effectiveness of the control methods. Figure 11 shows the simulated output response of the three-mode control. The output shows the chattering responses between the set point and actual temperature. However, three-mode control has a good rise time and the desired temperature is controlled. The PI control could perfectly control in both set points. The responses of PI control are evaluated in Fig. 12.

The simulation model has shown a good comparison between the three-mode control and PI control. Next, we will carry out the actual experiment.

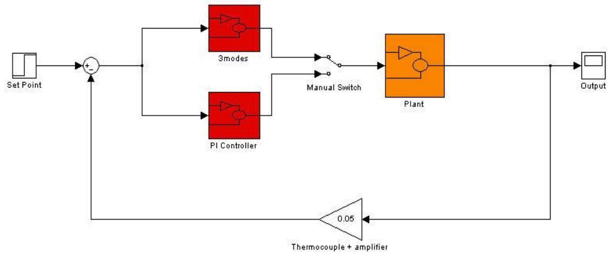
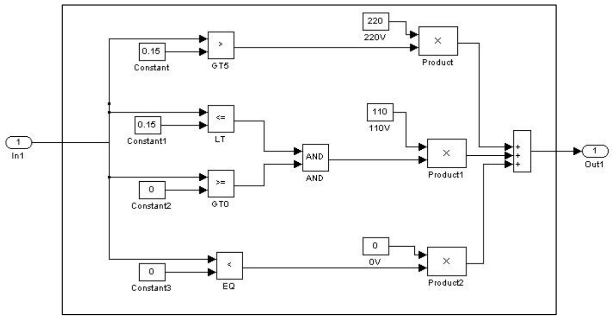
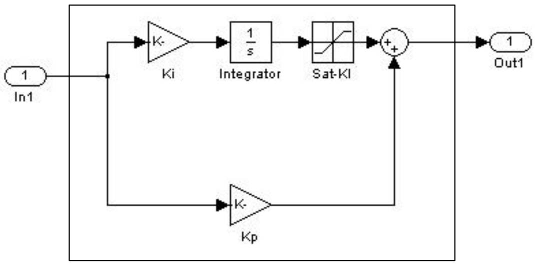


Fig. 9. Simulation block diagram.



(a)



(b)

Fig. 10. (a) Three-mode control; and (b) Proportional-integral control.

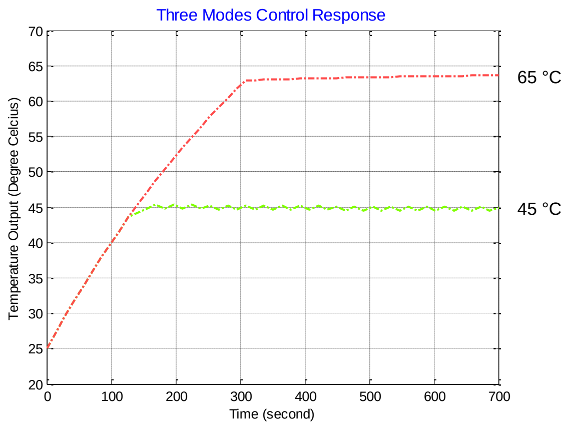


Fig. 11. Three-mode control response with 45°C and 65°C set points.

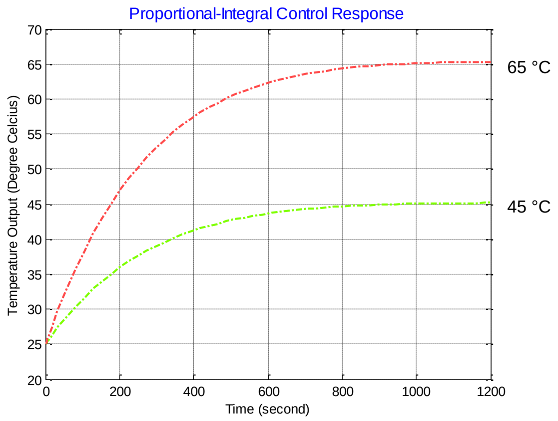


Fig. 12. Proportional-Integral control response with 45°C and 65°C set points.

5. Experimental Study

In this section, we review the actual experiment of the temperature process control. A complete block diagram of the temperature process control is shown in Fig. 12. Figure 13 shows a picture of the experimental set up.

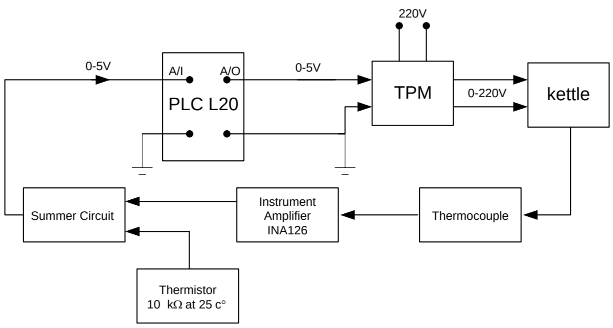


Fig. 12. Complete block diagram of the experiment.

Fig. 13. An experimental set up.

The set points 45°C and 65°C (as used in the simulation study) are used in the experiment. The three-mode control and PI control written in structure text (ST) are applied to the control algorithm. With three-mode control, chattering is not obvious as water acts as a natural damp to the system's temperature. However, the desired set points can be achieved as shown in Figure 14. With PI control, overshoot has occurred in the first cycle. With this control method, the desired temperature can be perfectly achieved after settling time of about 2,500 seconds. Figure 15 shows the output response of the PI control.

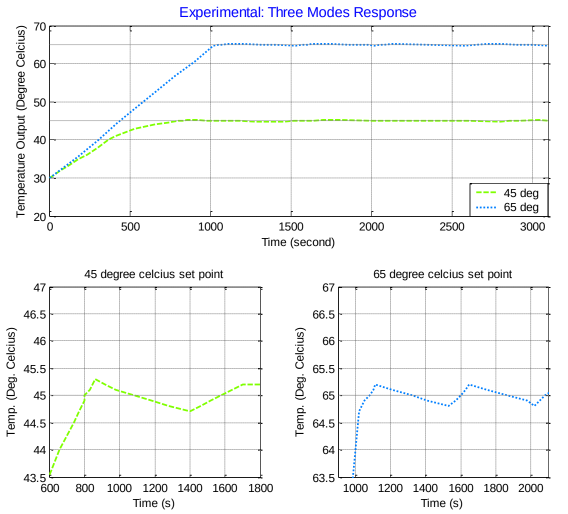


Fig. 14. Output response for three-mode control.

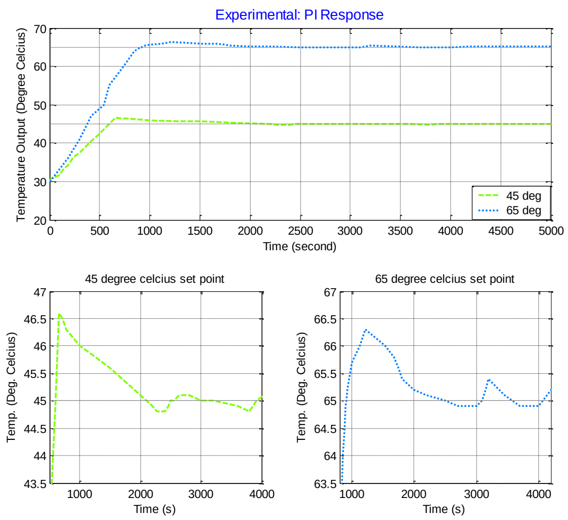


Fig. 15. Output response for PI control.

In the experiment, both control methods show excellent results. The three-mode control can control average desired temperatures, while the PI control can control the desired temperature exactly. The PI control needs to wait for the temperature to settle down (2,500 seconds settling time). However, which control methods to use will depends on the user's application. With a price to pay, the PI control needs an analog output module, while a digital output module is sufficient for the three-mode control.

6. Concluding Remarks

A process control is normally carried out in the industries in the form of temperature, pressure, speed, position, etc. This article summarized the temperature process control as one of the Mechatronics Laboratory II experiments. This process control model is considered suitable for Assumption University's laboratory experiments.

The system was first modeled mathematically and then simulated in MATLAB® using Simulink® block sets. Later the actual system was set up with industrial standard equipments, such as PLC, Thyristor Power Module and thermocouple. Two control methods: three-mode and proportional-integral (PI) were discussed and applied as control algorithms. Both controllers perfectly control the desired set points. The three-mode control is usually used when the average temperature is to be controlled. If a specific temperature is required, PI is a better control method. Students had to analyze the advantages and disadvantages of the two controllers and are expected to apply this knowledge in other circumstances.

Our goal is to provide guidelines for students to read and prepare themselves for the experiment. Consequently, after completing the experiment, the students will have a comprehensive knowledge of the industrial process control. The students are expected to apply this knowledge once they graduate from the University and start their professional career.

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