Development of PID-based furnace temperature control system for zirconium calcination

Enrico Willmanda Febriardy, Sutanto, Adi Abimanyu
Department of Nuclear Technophysics, Polytechnic Institute of Nuclear Technology, National Nuclear Energy Agency of Indonesia, Babarsari street PO BOX 6101/YKBB, Yogyakarta 55281, Indonesia
enricowillmanda99@gmail.com

Abstract. The calcinator furnace in PSTA-BATAN is currently installed with ON-OFF temperature controller to maintaining temperature changes in calcination process. Calcination is a process of heating a substance at high temperature in stages but still below its melting point to remove its impurities. The ON-OFF temperature controller using a relay as the power switching for AC voltages applied on furnace electric heat element when the temperature exceeds or below the set point temperature. The contactor movement in relay will cause a sudden surge of voltage and currents which could lead to the thermal shock or unstable heating rates and unstable holding time. In this paper, the ON-OFF method was developed into Proportional Integral Derivative (PID)-based which has simple structure and robust performance for phase angle controlling in AC voltages applied on furnace electric heat element to controlling the temperature in multi stages by using Arduino Nano as the microcontroller.

1. Introduction
Nuclear fuel cladding is one of the essential parts in a chain reaction which is used for fuel rods coating so that the fuel rods does not absorb neutrons while the reaction is in progress. Zirconium is one of the elements commonly used for the nuclear fuel cladding due to the its properties such as corrosion resistant, high strength, high hardness, low level of neutron absorption, radiation damaging resistant, and easy in treatment. Zirconium naturally founded in the form of Zircon sand with high impurities content which could lead to the higher level of neutron absorption so that the removal of impurities content is required by purifying and reaction process at high temperature in stages which called as calcination process. Calcination is the process of heating an object at high temperatures in stages but still below its melting point to remove its impurities through the evaporation process [1]. Calcination process intends to removing or decomposing all substances that are not needed such as volatile substances and H2O, and to forming the desired oxide compounds. In the Zirconium calcination process, crystalline water molecules can be removed at 150°C -200°C for 10-16 hours, whereas to remove the remaining ammonium hydroxide and polyvinyl alcohol (PVA) is carried out at 200°C -800°C for 2-24 hours [2]. All stages of the calcination process are taking place in a calcinator furnace. Therefore Center for Science and Accelerator Technology –National Nuclear Energy Agency of Indonesia (PSTA-BATAN) developed a calcinator furnace that was used for the purification of Zircononium as nuclear fuel cladding material.
The calcinator furnace in PSTA-BATAN is currently installed with a single-stage ON-OFF temperature controller to maintaing the temperature changes at one reference temperature or set point temperature. This control system using a relay as the power switching for AC voltages applied on furnace electric heat element when the temperature exceeds or below the set point temperature. The contactor movement in relay will cause a sudden surge of voltages and currents which could lead to crack on calcination product due to the thermal shock or unstable heating rates and unstable holding time at temperature changes in furnace. This thermal shock could be avoided by reducing the heat rates or ramping the heat stages or combining both [2]. In this paper, the single-stage ON-OFF controller was developed into the multi-stages Proportional-integral-derivative (PID) controllers which have been widely used in the industry due to the facts that they have a simple structure and robust performance for phase angle controlling in applied AC voltages on furnace electric heat element so that it is possible to maintaining the temperature changes, heating rates, and holding times at each stages.

2. Material and Method
2.1. System Modelling
To determining the control parameters and designing the control system based on the electric power conversion in furnace electric heat element, it is required to obtaining the system model of furnace which is expressed mathematically as first-order model. The empirical transfer function is as follows [3]:

\[
G(s) = \frac{Ke^{-sT_d}}{1 + sT_c}
\]  

(1)

In this paper, the system model obtained by experimenting and collecting datas from two variables as input (voltage) and output (temperature). Fig.2 shown the block digram of furnace modelling.
Figure 2. Block diagram of furnace modelling

This system modelling intends to find out the correlation between voltage and temperature so that plant response towards the input during voltage changing could be analyzed to designing and determining PID parameters. The experiment to obtaining the model parameters done by heating the furnace until reach it is steady state temperature with 220 AC voltage supply which resulted datas represent the correlation between time versus temperature as shown in the Fig.3.

![Figure 3. Experimental datas result](image)

By using MATLAB software, datas could be performed in form of curves and results transfer function from curve fitting function as shown in Fig.4.

![Figure 4. Curve fitting on MATLAB](image)

Therefore the transfer function is as follows:

\[
G(s) = \frac{4.5e^{-700s}}{1 + 1400s}
\]
2.2. System Hardware Design

2.2.1. Furnace
Furnace is a device used for heating purpose. They are mainly used in the industries to melt metals like aluminum, copper, gold etc. and also used to mold the materials. They used to extract materials from ores [4]. This is implemented in Zirconium calcination process which is intended for impurities removal or purification. In this paper, the furnace used in PSTA-BATAN as the calcinator furnace is Nabertherm L512/B170.

2.2.2. Arduino Nano
Arduino Nano R3 is a minimum board system based on ATmega328P microcontroller. Arduino Nano R3 has 14 digital inputs / outputs (6 should be used for PWM output), 6 analog inputs, 16 MHz crystal oscillator, USB connection, power jack, ICSP header and button reset. In this paper, Arduino Nano is used as the microcontroller which function to processing inputs and outputs in temperature control system and sending trigger signal in form of adjustable pulse width at one signal period to determine the firing angle for TRIAC.

2.2.3. Temperature Sensor
In this paper, K-type thermocouple used as the temperature sensor for temperature measuring in system which will be compared to the desired temperature. When the thermocouple senses temperature, sensor element (measuring junction) which consists of two metal conductor will produces a voltage difference or electromotive force (emf), then the emf produced will be compared to a specific conversion scale to unit of temperature. K-type thermocouple is widely used for high temperature measurement at -200°C until +1200°C range.

2.2.4. Zero Crossing Detector
Zero crossing detector is a circuit that is used to detect whether the phase of AC voltage is in zero voltage position and serves to start triggering and how much the phase angle will be fired on TRIAC.

2.2.5. Optocoupler
Optocoupler is a TRIAC driver that using optical isolation. This driver bridges the trigger signal coming from the controller which generally has a low voltage and current level with a load part that has a relatively high voltage and current.

2.2.6. Buttons
This hardware design uses four buttons for temperature control setting such as time setting, set point setting, and number of stage setting.

2.3. System PID Tuning
The process of determining the PID controller parameters Kp, Ti, and Td to achieve high and consistent performance specifications is known as controller tuning [5]. In this paper, system PID Tuning is intended to obtaining the optimal PID parameters in the form of Kp, Ki, and Kd using Ziegler-Nichols method 2. The Ziegler-Nichols tuning method is based on the determination of process inherent characteristics such as the process gain, process time constant and process dead time [6]. The design of PID control is based on oscillation curves to obtaining the variation of the gain in the system so that the tuning is done in a simulation using the toolbox simulink of MATLAB. The simulation structure diagram of the system is shown in Fig.5.
System PID tuning is done by giving a gain to the system with a certain set point until the system results an oscillation curves as the Fig.6.

From the oscillation curves, it can be obtained $K_{cr} = 200$ and $P_{cr} = 50$ second. By using Ziegler-Nichols method 2, the value of $K_{cr}$ and $P_{cr}$ could be determined based on the rules as the Table below:

**Table 1.** Ziegler-Nichols method 2 tuning rules are based on critical gain and critical periods

| Controller Type | Kp     | Ti      | Td       |
|-----------------|--------|---------|----------|
| P               | $0,5 \ K_{cr}$ | $\infty$ | 0        |
| PI              | $0,45 \ K_{cr}$ | $\frac{1}{12} \ P_{cr}$ | 0        |
| PID             | $0,6 \ K_{cr}$ | 0.5 $P_{cr}$ | 0.125 $P_{cr}$ |
2.4 System Software Design
The system software design is programmed in Arduino IDE software. After no running errors, the ino file compiled and generated by the software will be implemented onto the Arduino Nano to carry out the temperature control system operation. The system flowchart is shown in Fig.7.

![System Flowchart](image)

**Figure 7**. System Flowchart

2.5 System Development
After the hardware and software are designed, the temperature control system is installed by developing the ON-OFF controller installation onto the PID-based controller installation as shown in Fig.8.
In this development installation started with time and set point setting by pressing the push buttons on hardware. The temperature sensor which is installed in furnace heat chamber will reading the actual temperature and transmitting to Arduino Nano to be compared with set point temperature given. The difference between actual temperature and set point will be the error signal for control system and results PID calculation for TRIAC firing angle every zero voltage position detected by zero crossing detector. TRIAC firing angle value is obtained from the deviation between one half wave period from 220 AC voltage which is equals to 10000 microseconds and PID value which is sum of Kp, Ki, and Kd. Figs.9 and 10 shown the hardware design and implementation of this research.

![Figure 8. Developed system installation](image)

3. Result and Discussion

3.1. PID Tuning Simulation Testing

From the PID tuning that have been simulated in simulink toolbox, the critical gain and critical periods will be determining the value of PID parameter as the initial Kp, Ki, and Kd in temperature control system software. The equation to obtaining PID parameters and transfer function is as follows [7]:

\[ \text{PID parameters and transfer function} \]
Based on the equation, it is obtained $K_p = 120$, $K_i = 8$, and $K_d = 750$. Those $K_p$, $K_i$, and $K_d$ value will generating a system response as Fig.11.

Figure 11. Tuned system responses with $K_p = 120$, $K_i = 8$, and $K_d = 750$

From the system responses graph analysis, it is obtained that system responses has 25.362% overshoot; 357 seconds of rise time; 54 seconds of settling time; and 0.0003% steady state error. For optimum performance of control systems, the steady state errors and overshoot must be eliminated to enable stability of the close loop systems which are basically controlled by PID. Therefore the value of $K_p$, $K_i$, and $K_d$ is tuned until generating an optimum system response which is shown in Fig.12.
The optimization of PID parameters results $K_p = 135$, $K_i = 10$, and $K_d = 10$. From the system responses graph analysis, it is obtained that system response has 1.55% overshoot; 8.25 seconds of rise time; 20 seconds of settling time; dan 0.003% steady state error. These $K_p$, $K_i$, and $K_d$ value is used as initial PID parameter in system software that feed to the plant.

### 3.2. Temperature Control System Testing

The testing is done by heating the furnace in 2 stages gradually starts from room temperature 25°C based on the calcination process stage but it takes shorter times than the actual process. Stage 1 is crystalline water molecules removal process that carried out at 200°C for 30 minutes and stage 2 is is ammonium hydroxide and polyvinyl alcohol (PVA) removal process that carried out at 300°C for 60 minutes. The result of testing which represented the correlation between time and temperature is shown in Fig.13.

![System responses graph](image)

**Figure 12.** Tuned system responses with $K_p = 135$, $K_i = 3$, and $K_d = 10$

The system responses graph shows 2 heating process in form of ramp stages. From the two heating process it can be analyzed that at stage 1 resulted a system response with 575 seconds of rise time; 0%
overshoot; 603 seconds of settling time; 0.75% steady state error; and 5,725°C/minutes heating rates. Whereas at stage 2 resulted a system response with 309 seconds of rise time; 0% overshoot; 357 seconds of settling time; 0.25% steady state error; and 1,69°C/minutes heating rates. This results show that the control system is run well at 2 stages of gradual temperature controlling which has no overshoot, small steady state error, faster rise time and settling time.

4. Conclusion
In this paper, PID controller is designed using Ziegler-Nichols method 2 tuning algorithms by using MATLAB simulink toolbox to control the temperature of calcinator furnace which mathematically expressed as \( G(s) = (4.5e^\frac{-700s}{s})/(1 + 1400s) \). The system PID tuning in simulation and optimization results \( K_p = 135; K_i = 3; \) and \( K_d = 10 \) that feed to the plant and results the temperature control system responses. The system responses generated based on calcination process at stage 1 (set point = 200°C) has 575 seconds of rise time; 0% overshoot; 603 seconds of settling time; 0.75% steady state error; and 5,725°C/minutes heating rates. Whereas at stage 2 (set point = 300°C) resulted a system response with 309 seconds of rise time; 0% overshoot; 357 seconds of settling time; 0.25% steady state error; and 1,69°C/minutes heating rates.

5. Acknowledgment
The authors would like to deliver a great thank to Mr. Triyono from PSTA-BATAN for assistance to operate and develop the calcinator furnace in this research. His invaluable technical expertise was beneficial for the first author during the research.

6. Reference
[1] Suyanti and Purwani V 2016 Calcium Cerium Concentrate Into Cerium Oxide Proc. Conf. on Research and Nuclear Devices of Center Science and Accelerator Technology (Surakarta: Indonesia) ISSN 1410-8178, p 125
[2] Wahyuningsih F, Sediawan W, Ariyanto T, and Widiyati S 2016 Ceria Zirconia Calcination Kinetics from External Gelation Process. J.Rek.Pros (Gadjah Mada University: Indonesia) Vol. 10 No.1, pp. 16-22
[3] Xie X, Long Z 2015 Fuzzy PID Temperature Control System Design Based on Single Chip Microcomputer iJOE – Volume 11, Issue 8, pp. 29-33
[4] U. Rajkanna, K. Guna Sekaran, D. Manivannan and A. Umamakeswari, 2012. Design and Development of Temperature Control System in Induction Furnace using LPC2148 and XBee. Journal of Artificial Intelligence, 5: 193-199.
[5] Bagis A 2007 Determination of the PID Controller Parameters by Modified Genetic Algorithm for Improved Performance Journal of Information Science and Engineering 23, pp. 1469-1480
[6] Kumar R, Singla Sunil, Vikram 2013 A Comparative Analysis of different Methods for the tuning of PID Controller International Journal of Electronics Communications and Electrical Engineering Volume 3 Issue 2
[7] Vaishnav S, Khan Z 2010 Performance of tuned PID controller and a new hybrid fuzzy PD + I controller World Journal of Modelling and Simulation Vol. 6 No. 2, pp.141-149