Optimization of high temperature furnace system as one of the spray pyrolysis subsystems based on R type thermocouples and PID control

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Abstract One method that can produce nanoparticle material is the spray pyrolysis method, but the use of a spray system requires a high temperature heating or pyrolysis system therefore a furnace is needed which can reach high temperatures. The built furnace has a vertical elongated turbular type with dimensions measuring 60 cm x 50 cm x 150 cm. For this furnace used nickell type windings which are loosely shaped, and given type R thermocouples that are able to measure up to 1600 oC, using a PID control system. The design scheme of the furnace is divided into 3 blocks, with heaters arranged in series to obtain the best efficiency when using electric power. The results obtained are that the furnace is able to reach a maximum temperature of 1000 oC with high accuracy in all three blocks, but the achievement time of the maximum temperature in each block is only the best block 2 compared to other blocks, this is due to the heat induction arising from blocks 1 and 2.

1. Introduction
Methods of synthesis of nanostructured particles are widely developed by researchers to create the desired nanomaterial. One of the methods under development is the spray method. Spray is a small droplet generation derived from a liquid phase medium. The most common methods used in the synthesis of nanostructure particle solids are spray drying and spray pyrolysis. The method is initiated from a solution of metal nitrate or other atomized solutions[1], [2]. Then, after passing through the heating system, solid particles will be formed according to the desired temperature. The spray method has many advantages, including; the resulting particles are spherical (round shaped)[3], the diameter distribution is uniform and can be controlled from micrometer to submicrometer;
In the spray pyrolysis method, a heater or furnace reactor is required to assist the synthesis of the particles to be formed[4], where built the furnace is a high-temperature furnace tube designed for the processing of materials in the form of particles and films by aerosol decomposition (spray pyrolysis). This furnace is the main and most important system of the spray pyrolysis method because in this system the process of forming the particles of the synthesized material takes place. Therefore, there is a need for special research and design of a high-temperature furnace tube[5], especially the electrical control system using the PID system[6], which gives the result of a more stable and efficient temperature control compared to the conventional control. Research on the spray pyrolysis method has been conducted in the electronics and instrumentation laboratory of the Department of Physics, ITS Surabaya.

1.1 Spray Pyrolysis Method
Aerosols are colloidal systems of solid or liquid particles dispersed in gases. Aerosols are considered solid or liquid particles in gases, where the particle size ranges from a molecular dimension measuring
100 micrometers. There are various technologies in exploiting aerosol to produce powder or thin film, one of which is the method of spray pyrolysis.

![Figure 1. The overall design of spray pyrolysis.](image)

The spray pyrolysis method is similar to spray drying in the way it works as shown in Figure 1. The spray method is initiated by an atomizer/spraying solution in droplets into a heating reactor or other energy sources that can heat the droplets until a particle is formed. The particle resulted from the spray pyrolysis method does not only produce powder, but also can be used to make thin layer (film).

1.2 Furnace and Thermocouple

Furnace is a type of kitchen heater that is often used in engineering. In the present research, it very important role in the process of heating treatment of a material [5]. Based on its heat-generating method, a furnace is divided into two types: the combustion type furnace (using fuel to generate heat) and the electric type furnace (using electrically heated elements). The combustion type consists of several sub-types in terms of the fuel used, some of which includes oil, coal, or gas. The combustion type is considered less effective than the electric one because the key of the efficiency of a furnace lies in the perfection of the fuel combustion. The combustion type produces more air pollution than the electric furnace [6]. The electric furnace has a working principle of heating the material that has been incorporated into the furnace heating chamber. When the heating element is supplied with a voltage source, the heating element gets heated and then the heat will propagate toward the radiated material. The heating element is a device that converts electrical energy into thermal energy through the Joule Heating process [7]. The working principle of the heating element itself is the electric current that flows on elements that have a certain resistance.

In thermodynamic science, temperature is a measure of the tendency of forms or systems to release energy spontaneously. There are several different temperature units, but the Kelvin (K) is set as the base unit of temperature in the International System of Units. Thermocouples can measure the temperature within a high range and have relatively small measurement error limits. They consist of two types of conductor wires in which both ends of the wires are tied into one. A potential difference will occur when the tip of the two wires is heated, with a value around 1-70 μV/°C[7], depending on the type of the thermocouple. As Thomas Johann Seebeck claims, a very small current will flow through a conductor circuit that has a temperature difference, this is called the thermoelectric effect.

![Figure 2. Seebeck Effect](image)
For small temperature changes, the Seebeck voltage changes linearly to the temperature:

\[ \Delta e_{AB} = a \cdot \Delta T \]  

then: \( \Delta e_{AB} \) = EMF voltage read  
\( \alpha \) = Seebeck coefficient  
\( \Delta T \) = temperature measured

1.3 PID Control System

Feedback on the system is a characteristic of the PID control that is used to determine the accuracy of the instrumentation system. The PID control system consists of three components, namely Proportional Control (P), Integral Control (I), and Differential Control (D). Proportional control serves to control the response quickly to achieve a steady state. The integral control plays a role in muffling the overshoot when it reaches a steady state. Derivative control plays a role in making the system more stab[8], [9]. The general equation of PID control can be mathematically written as follow:

\[ f(t) = K_p e(t) + K_i \int_0^t e(t) \, dt + K_d \frac{de(t)}{dt} \]  

then,

\[ K_i = \frac{K_p}{T_i} ; K_d = K_p \times T_d \]  

Substitute equation (3) into equation (2), so that:

\[ f(t) = K_p e(t) + \frac{K_p}{T_i} \int_0^t e(t) \, dt + K_p T_d \frac{de(t)}{dt} \]

By using Laplace transform, the transfer function of PID control will be obtained as follow:

\[ G(s) = \frac{K_p + \frac{K_i}{s} + K_d s}{s} \]

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**Figure 3. Block PID control diagram**

In the design of the PID control system in Figure 3, it is to be noted that the setting of parameters P, I, and D for the response of the output signal from the system to the given input (setpoint) can be achieved as desired. Trial or error method is often used in designing PID control systems because the parameters Kp, Ki, and Kd are not independent. Trial & error method is needed to get good control action[10], [11]. It is applied by alternately combining P, I, and D until the desired Kp, Ki, and Kd values are achieved and the errors and overshoots are minimized.
2. Experimental Methods

2.1 Furnace Design and fabrication
The design of the high-temperature furnace consists of four main parts: digital controller (PID control system), solid state relay, heating elements mounted on the furnace, and transducer walls (thermocouple temperature sensors).

![Block diagram of high-temperature furnace control system](image)

![Design of the furnace](image)

**Figure 4.** Block diagram of high-temperature furnace control system, and Design of the furnace

The furnace built in this project is an electric one consisting of 3 blocks, as shown in Figure 4. Each block has the same width, length, and height. The design of the furnace has the following dimensions,

| Dimension of furnace | Length (cm) | Width (cm) | Height (cm) |
|---------------------|-------------|------------|-------------|
| **Exterior Dimensions** | 60          | 50         | 150         |
| **Interior Dimensions** | 33          | 23         | 144         |

2.2 Selection of PID Control System
The design of the control system was created by testing the P, PI, and PID control systems to get the best result that is suitable to the furnace control system. In this research, Ziegler-Nichols method with closed loop system was used. In the application of this method, originally integrative parameters are set in infinite values and derivative parameters are set to zero (Ti = ∞, Td = 0). Further proportional parameters are then setup by raising the value gradually until it reaches a value that results in system oscillation with fixed amplitude (sustained oscillation). The value of the proportional parameters when the system reaches the sustained oscillation condition is called the ultimate gain or Kcr. The period of sustained oscillation is called the ultimate period or Pcr. The formula to determine PID parameters based on this method is shown in Table 2 below.

| Table 2. Parameter Equations of PID Control System |
|---------------------|-------|-------|-------|
| Control System     | Kp    | Ti    | Td    |
| P                  | 0.5 Kcr | ∞     | 0     |
| PI                 | 0.45 Kcr | (1/1.2)Pcr | 0     |
| PID                | 0.6 Kcr | 0.5 Pcr | 1.25 Pcr |

3. Result and Discussion
Almost all of the three control systems tested are the same in terms of rise time. But, there are some differences in terms of system overshoot and time to achieve stability or settling time. The P control system has a larger overshoot and the system tends to be unstable. As for the PI control system, it has almost the same overshoot as the P control system, and the PI control system also looks unstable. Both
the P control system and the PI control system require a long period of time to achieve stability. This is different from the PID control system, whose overshoot is smaller. In addition, the system requires a relatively faster time to achieve stability than the P and PI control systems. So, it can be said that the PID control system in block 1 has a better response than other control systems as shown in Figure 5.

**Figure 5.** Graph selection of block 1, 2 & 3 furnace control system

**Figure 6.** Graph of furnace temperature increase at 500, 700, 1000 °C
From the graph above (Figure 5), it can be seen that the system in block 1 tends to respond more fast than those in block 2 and block 3. The fastest system response is evidenced by the fast rise time in block 1 among others. However, the faster system will create some drawbacks in the overshoot rate of block 1. When compared to block 1, block 2 has a slightly slower response, as evidenced by its rise time which tends to be slower than that of block 1. In block 2, the overshoot response also tends to be smaller. Meanwhile, as seen in the graph above, block 3 is the system that has the slowest response. However, the slow response is not observed at all set temperatures. At temperatures below 300°C, the system is fairly normal. However, at temperatures above 300°C the system undergoes a slowing response. Hence, the rise time in block 3 becomes slow. However, when compared to blocks 1 and 2, block 3 has the least system overshoot.

4. Conclusion
Results of data processing from furnace testing, it can be concluded that, the research has successfully designed and manufactured a spray pyrolysis furnace by using the R type thermocouple as temperature sensor, where heating furnace can reach a temperature of 1000°C. The PID control system is considered most appropriate in controlling the temperature of the furnace at a set point or a certain temperature. Of the three furnace blocks, block 2 has the best system response compared to blocks 1 and 3. On the other hand, block 3 has a slow system response due to several factors.

5. Acknowledgement
The authors would like to thank Department of Physics and LPPM ITS. This research is funded by LPPM ITS. Subject to Contract Research Number: 1413/PKS/ITS/2018.

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