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Automatic Temperature Control System of the Neutralization Unit in Granular Ammonium Nitrate Production

Jabborov Alisher Oltiboyevich, Islamova Farida Kamiljanovna
Tashkent Institute of Chemical Technology

Annotation: This article presents the modeling of an automatic temperature control system in the neutralization stage of granular ammonium nitrate production. The process object was analyzed using mathematical and computer models, and a PID-based control system was developed in MATLAB/Simulink. The impact of various controller parameters on system performance was studied, and optimal control settings were identified. The results demonstrated that temperature regulation can be achieved quickly, stably, and efficiently. This plays a crucial role in ensuring safety and quality in the production process. The findings can also be applied to other industrial processes requiring precise control.

Key words: Ammonium nitrate, neutralization process, automatic control, temperature regulation, PID controller, MATLAB/Simulink, mathematical modeling, industrial automation, dynamic systems, optimal control, time constant, gain coefficient, simulation, technological process, control system.

Introduction

In modern chemical industry, automation of production processes plays a crucial role in improving product quality, reducing energy and raw material consumption, and ensuring safety. Especially in technological stages involving high temperatures and rapid reactions, it is essential to maintain accurate and reliable control with minimal human intervention. One such stage is the neutralization process in the production of granular ammonium nitrate, where ammonia reacts with acidic components to form a stable product at a specific temperature. Any deviation in temperature can lead to a decline in product quality, uneven reaction progress, or even hazardous conditions. Therefore, continuous monitoring and optimal regulation of temperature in the neutralization unit are critical [1]. This study aims to design an automatic temperature control system through mathematical and computer modeling, followed by the synthesis of a control algorithm using a PID controller. The mnemonic PID refers to the first letters of the names of the individual terms that makeup the standard three-term controller [2]. Developing such a system contributes to making the production process more stable, efficient, and safe.

Methodology

In this study, a mathematical model, computer simulation, and PID-based control system were developed to automatically regulate the temperature during the neutralization process in granular ammonium nitrate production. The methodology consists of several key stages, each of which contributes to ensuring accurate and efficient control of the system.

Analysis of the Object and Identification of Parameters

Within the scope of this study, the **neutralization unit** was selected as the **main control object** of the automatic control system. In the production of granular ammonium nitrate, this unit plays a crucial role in **ensuring the stability of the reaction environment**. In particular, maintaining the **temperature within the specified range** — between 15°C and 19°C — is a key factor that directly influences product quality [3]. Therefore, temperature was identified as the primary controlled parameter.

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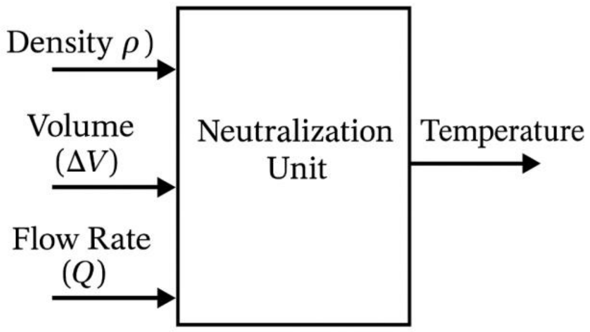

Figure 1

Figure 1 presents a **block diagram** illustrating the operational principle of the neutralization unit, showing the interconnection of the main input and output parameters of the system. As depicted in the diagram, the unit receives three essential **input parameters**:

- **Density (ρ):** the physical density of the product, which directly affects **heat exchange** and **flow inertia**.
- **Volume (ΔV):** the effective working volume of the neutralization unit, determining the **residence time** of the product inside the reactor.
- **Flow Rate (Q):** the **inlet or outlet velocity** of the product, which plays a vital role in managing **reaction intensity and dynamics**.

These three input parameters collectively determine the **output parameter** — the **temperature** of the product [4]. Based on these physical factors, a mathematical model of the system is developed, which then serves as the foundation for formulating the **transfer function** and designing an **optimal PID control strategy**.

Determination of the Transfer Function of the Control Object

In the process of modeling an automatic control system, the first step involves identifying the mathematical representation of the control object based on its physical and technological characteristics. In this study, the control object is modeled as a **first-order inertial system**, which typically responds gradually but consistently to changes in the input signal.

Determining the Gain Coefficient

The first parameter to be identified is the gain coefficient (also known as the static gain), which defines the quantitative relationship between a variation in the input parameter and the resulting change in the output parameter. It can be calculated using the following formula [4]:

$$K_{ob} = \frac{\Delta t}{\Delta G}$$

Where:

K_{ob} – gain coefficient of the object (dimensionless),

Δt – change in the output parameter (e.g., temperature),

ΔG – change in the input parameter (e.g., ammonia flow rate).

In this study:

$$K_{ob} = \frac{2}{2} = 1$$

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This indicates that a unit change in the input parameter results in an equivalent unit change in the output, meaning the system has a gain of 1.

Determining the Time Constant

The second important parameter is the **time constant** (TTT), which represents the speed at which the system responds to a change in the input signal. It is calculated using the following formula [6]:

$$T = \frac{\Delta V \cdot \rho}{\Delta G_x}$$

Where:

- T – time constant of the object (in seconds),
- ΔV – effective volume of the neutralization unit (m³),
- ρ – product density (kg/m³),
- ΔG_x – product flow rate (m³/s).

Substituting the given values:

$$T = \frac{0.7 \cdot 950}{2} = 332.5 \text{ seconds}$$

This result indicates that the system takes approximately 332 seconds to fully respond to a change in the input.

Deriving the Transfer Function

To model the object within the automatic control system, the **transfer function** is established. A transfer function mathematically expresses the relationship between input and output signals in the Laplace domain. For a first-order inertial system, the general form of the transfer function is [7]:

$$W_{ob}(s) = \frac{K}{T_s + 1}$$

Substituting the previously determined values:

$$W_{ob}(s) = \frac{1}{332s + 1}$$

This transfer function accurately describes the dynamic behavior of the control object. It will be used to build a simulation model in the Simulink environment, which in turn serves as the foundation for selecting appropriate PID controller parameters, analyzing the system's transient response, and developing an optimal control strategy.

Developing a Computer Model of the Control Object and Obtaining the Step Response Graph

To thoroughly analyze the dynamic behavior of the control object and evaluate the effectiveness of the automatic control system, a computer model of the object is developed based on the previously determined transfer function. One of the most widely used environments for this purpose is the **Simulink package within the MATLAB software**, which enables visual modeling of systems, construction of block diagram-based system structures, and simulation of their behavior.

Within the scope of this study, the following transfer function of the object was used as the basis:

$$W_{ob}(s) = \frac{1}{332s + 1}$$

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A corresponding model was constructed in the Simulink environment based on this transfer function (Figure 2).

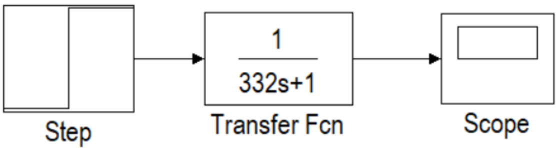

Figure 2.

An experiment is conducted in the Simulink environment to observe and analyze the object's step response curve (Figure 3).

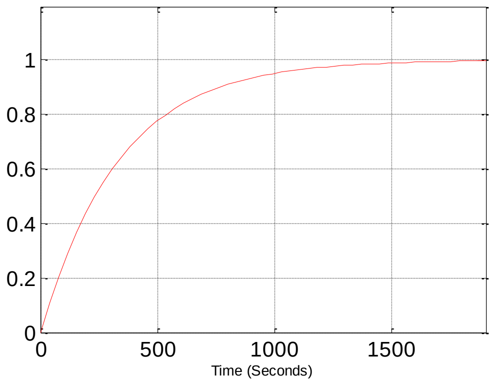

Figure 3.

Formation of the Automatic Control System

Based on the modeling of the object and the determination of its transfer function, the next step involves the formation of the automatic control system. At this stage, the most appropriate control algorithm is developed for the control object, and a suitable controller is selected accordingly.

Since the object exhibits inertial characteristics in its dynamic behavior, a PID controller (Proportional–Integral–Derivative) is selected for effective control. PID controllers are widely used in practice due to their high efficiency in improving system responsiveness, minimizing overshoot, and ensuring overall stability.

Thus, after a thorough analysis of the object's behavior, the PID controller was selected as the most appropriate control method. During simulation, different combinations of controller parameters (K_p, K_i, K_d) are applied, and the system's step response is analyzed to determine the **optimal control configuration.** This approach is grounded in control theory and ensures high accuracy and effectiveness in practical applications.

$$\mu(t) = K_p \cdot x(t) + \frac{1}{T_i}\int_0^t x(t)dt + K_d \frac{dx(t)}{dt} = K_p \cdot x(t) + K_i \int_0^t x(t)dt + K_d \frac{dx(t)}{dt}$$

The structural diagram of the automatic temperature control system is as follows: Figure 4.

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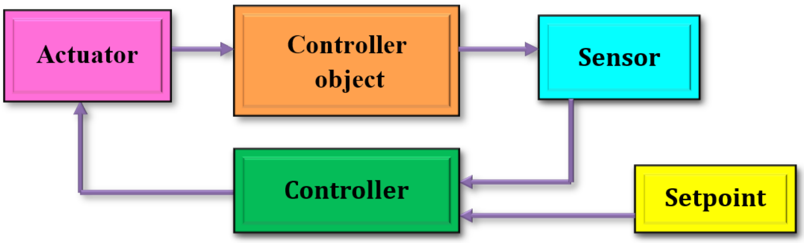

Figure 4.

The block diagram of the automatic temperature control system based on the MATLAB software is shown below (Figure 5):

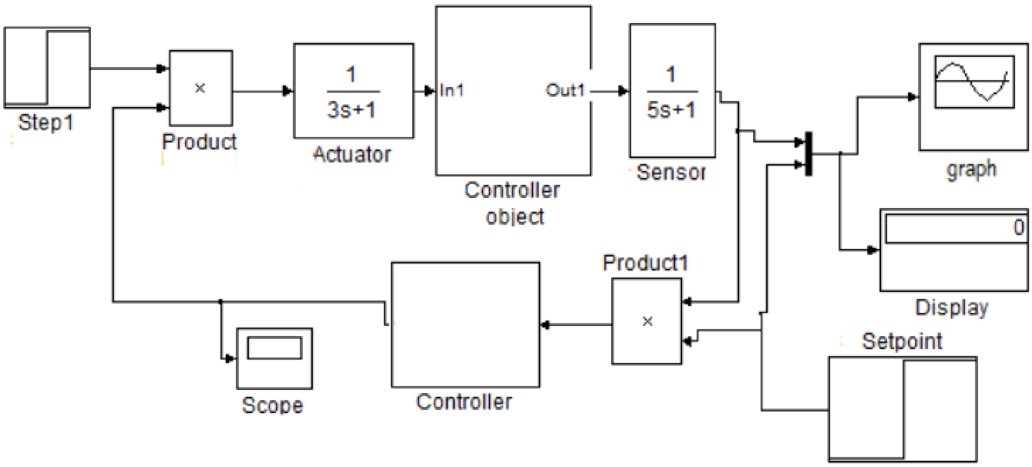

Figure 5.

The procedure for synthesizing the optimal control system, selecting the controller, and determining the optimal tuning parameters of the controller (K_p, K_i, K_d) is based on the results of the computer model provided below (Figure 6).

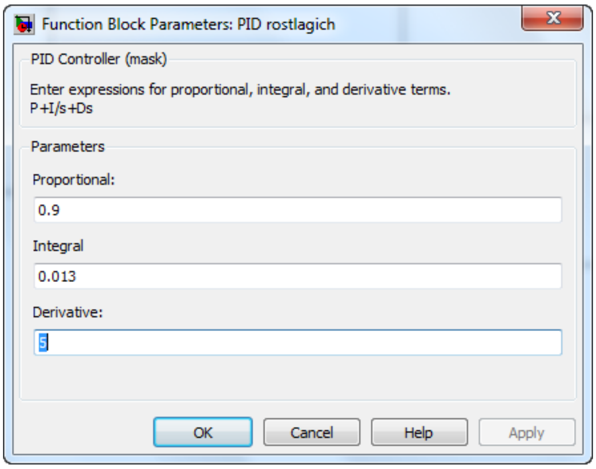

Figure 6.

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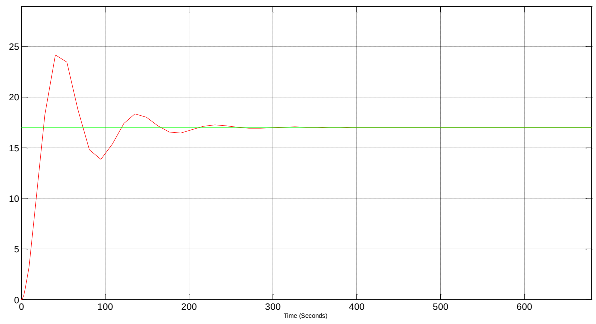
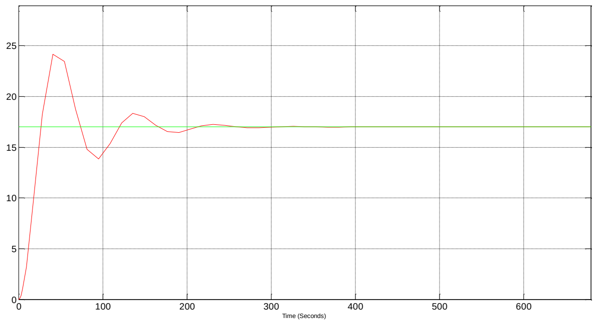
Results

Determining the Optimal Parameters of the Automatic Control System.

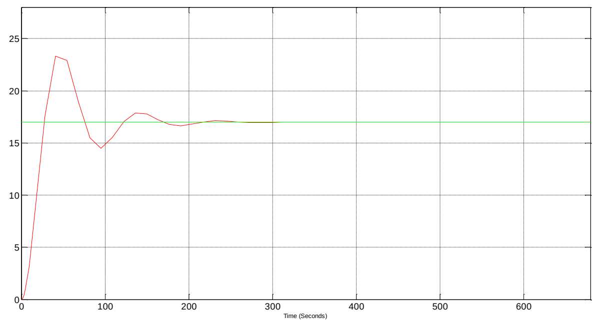
Once the computer model is developed, the values of the gain coefficient and time constant are entered, and the corresponding step response curves are generated on the screen. Among the resulting response curves, the most optimal control configuration is selected.



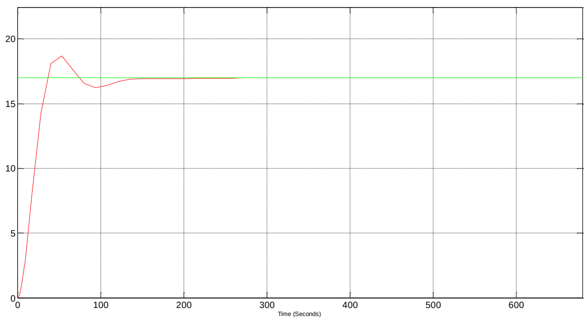
The proportional gain coefficient is $K_p = 0.2$, the integral gain coefficient is $K_i = 0.1$, and the derivative gain coefficient is $K_d = 10$.
Figure 7.



The proportional gain coefficient is$K_p = 0.4$, the integral gain coefficient is $K_i = 0.009$, and the derivative gain coefficient is $K_d = 7$.
Figure 8.



The proportional gain coefficient is $K_p = 1.2$, the integral gain coefficient is $K_i = 0.02$, and the derivative gain coefficient is $K_d = 4.5$.
Figure 9.



The proportional gain coefficient is $K_p = 1$, the integral gain coefficient is $K_i = 0.01$, and the derivative gain coefficient is $K_d = 5$.
Figure 10.

In **figure 7**, when the proportional gain coefficient was set to $K_p = 0.2$, the integral gain coefficient to $K_i = 0.1$, and the derivative gain coefficient to $K_d = 10$, the settling time was 320 seconds. During this period, deviations from the setpoint were observed in the step response graph.

In **figure 8**, with $K_p = 0.4$, $K_i = 0.009$, and $K_d = 7$, the settling time was 300 seconds. Deviations from the target value were still observed during the settling process.

In **figure 9**, when $K_p = 1.2$, $K_i = 0.02$, and $K_d = 4.5$, the system settled in 390 seconds. As in previous cases, the step response deviated from the reference value during the transition.

In **figure 10**, with $K_p = 1$, $K_i = 0.01$, and $K_d = 5$, the settling time was reduced to 140 seconds. Compared to the previous configurations, the response time decreased significantly, and the deviation from the setpoint during the settling phase was minimal.

Therefore, the optimal control parameters are determined to be $K_p = 1$, $K_i = 0.01$, and $K_d = 5$.

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Conclusion

Within the framework of this scientific study, an automatic temperature control system was developed and analyzed for the neutralization stage of granular ammonium nitrate production. Based on the physical and technological characteristics of the process object, it was modeled as a first-order inertial system. Consequently, the gain coefficient and time constant were determined, and the transfer function of the object was derived.

Using the established transfer function, a computer model of the system was constructed in the MATLAB/Simulink environment. Through simulation, the system's transient response was evaluated, enabling the optimization of the automatic control strategy. A PID (Proportional–Integral–Derivative) controller—recognized for its high reliability and efficiency—was implemented. Various combinations of controller parameters (Kp, Ki, Kd) were tested, and the configuration with $K_p = 1$, $K_i = 0.01$, and $K_d = 5$. was identified as optimal. Under these settings, the system achieved a settling time of 140 seconds with minimal deviation in temperature.

The results of the study indicate that the proposed control approach, based on mathematical modeling and computer simulation, can be effectively applied not only to the neutralization stage but also to other industrial technological processes. This methodology plays a significant practical role in ensuring product quality and enhancing operational safety in industrial environments.

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