DERIVATIVE PROPORTIONAL INTEGRAL CONTROLLER FOR GLYCERIN HEATING PROCESS

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FOR GLYCERIN HEATING PROCESS

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DEDICATION

This thesis is dedicated to my supervisors, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my family, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Temperature control is crucial because a glycerin heating process depends significantly on the heat requirement. An uncontrolled increase in temperature above the operating temperature and excessive prolonged heating can jeopardize the final glycerine's oxidative stability. A glycerine heating process requires an efficient and simple control system to provide a temperature that is gradually increasing without showing significant overshoot and could settle in a reasonable time. Conventional Proportional Integral Derivative (PID) controllers have significant disadvantages in controlling temperature. They contribute to an increase in extreme temperature and a longer settling time to reach the desired temperature. Therefore, the study aims to build an improved temperature control system that can produce fast control signals without overshooting the process. The study focuses on designing the heating process and temperature control system loop using the Derivative Proportional Integral (DPI) controller structure. The heating system operation uses the principle that the crude glycerine is heated using heat transferred from the electrical heater mounted outside the tank. The study covers the development of process input and output relationships based on the experimental step input tests. The DPI controller is designed using the proposed Nelder-Mead optimization algorithm method based on the Integral Absolute Error (ITAE) performance criteria calculated using Simpson's one-third rule. The DPI is a proposed controller which consists of the Proportional and Derivative control actions that operate on process variables rather than error signals and generate fast control signals to drive the process. The analysis was performed by comparing the achievement of the control system criteria and its robustness to input changes with conventional Ziegler-Nichols PID and the newer PID controllers. The results showed that the optimal parameters were successfully achieved using the proposed optimization algorithm. The DPI controller performs well in tracking the input changes with no overshoot in temperature and achieves the fastest settling time of 3867.2 seconds. The developed glycerine heating process system has a great potential for commercialization of the end-product.

ABSTRAK

Pengendalian suhu sangat penting kerana proses pemanasan gliserin sangat bergantung pada keperluan haba. Peningkatan suhu yang tidak terkawal di atas suhu operasi dan pemanasan berpanjangan yang berlebihan dapat menggugat kestabilan oksidatif gliserin akhir. Proses pemanasan gliserin memerlukan sistem kawalan yang cekap dan mudah untuk memberikan suhu yang secara beransur-ansur meningkat tanpa menunjukkan perubahan mendadak dan berupaya kekal dalam masa yang munasabah. Pengawal *Proportional Integral Derivative (PID)* konvensional mempunyai kelemahan yang signifikan dalam mengawal suhu. Ia menyumbang kepada peningkatan suhu keterlaluan dan masa penyelesaian yang lebih lama untuk proses mencapai suhu yang dikehendaki. Oleh itu, kajian ini bertujuan untuk membina sistem kawalan suhu yang lebih baik yang dapat menghasilkan isyarat kawalan yang cepat tanpa menggugat kestabilan suhu proses tersebut. Kajian ini memfokuskan pada reka bentuk proses pemanasan dan gelung sistem kawalan suhu menggunakan struktur pengawal *Derivative Proportional Integral (DPI)*. Operasi sistem pemanasan menggunakan prinsip bahawa gliserin dipanaskan menggunakan haba yang dipindahkan dari pemanas elektrik yang dipasang di luar tangki. Kajian ini merangkumi pembangunan hubungkait masukan dan keluaran proses berdasarkan ujian input langkah secara eksperimental. Pengawal DPI dirancang menggunakan kaedah algoritma pengoptimuman *Nelder-Mead* yang dicadangkan berdasarkan kriteria prestasi *Integral Absolute Error (ITAE)* yang dikira menggunakan peraturan sepertiga *Simpson*. DPI adalah pengawal cadangan yang terdiri daripada tindakan kawalan *Proportional* dan *Derivative* yang beroperasi pada pemboleh ubah proses dan menghasilkan sejumlah isyarat kawalan untuk menggerakkan proses. Analisis dilakukan dengan membandingkan pencapaian kriteria sistem kawalan dan ketahanan terhadap perubahan input dengan *PID Ziegler-Nichols* konvensional dan pengawal terbaru. Hasil kajian menunjukkan bahawa parameter optimum berjaya dicapai dengan menggunakan algoritma pengoptimuman yang dicadangkan. Pengawal DPI menunjukkan prestasi yang bagus dalam mengesan perubahan input tanpa peningkatan suhu secara mendadak dan mencapai masa penyelesaian terpantas 3867.2 saat. Sistem proses pemanasan gliserin yang dikembangkan mempunyai potensi yang besar untuk pengkomersialan produk akhir.

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LIST OF ABBREVIATIONS

PID	-	Proportional Integral Derivative
PI	-	Proportional Integral
DPI	-	Derivative Proportional - Integral
FFA	-	Free Fatty Acid
FOPDT	-	First-Order plus Dead Time
ITAE	-	Integral Time Absolute Error
ISE	-	Integral Square Error
IAE	-	Integral Absolute Error
SSE	-	Sum of Square Error
RMSE	-	Root Mean Square Error
GA	-	Genetic Algorithm
PSO	-	Particle Swarm Optimization
NM	-	Nelder – Mead
SISO	-	Single Input Single Output
MIMO	-	Multiple Input Multiple Output
DAQ	-	Data Acquisition
MONG	-	Matter Organic Non-Glycerol

LIST OF SYMBOLS

σ	-	Reflection Line
β	-	Expansion Line
γ	-	Contraction Line
δ	-	Shrink Line
h	-	Width
n	-	Interval
τ	-	Time constant

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CHAPTER 1

INTRODUCTION AND THESIS OVERVIEW

1.1 Overview

The background of the research study is explained in Section 1.1 of the chapter. In Section 1.2 of the chapter, the description of an issue that needs to be addressed is followed. The significant contribution of the research study is set out in Section 1.3 of the chapter. Section 1.4 outlines the research study's objectives, and Section 1.5 outlines the scope and limitations of the research study.

1.2 Research Background

The glycerine purification process removes excessive free fatty acid (FFA) content and contaminants in crude oil (Cowan, 1976) (Aiken, 2006) (List, 2010) (Wan Isahak, et al., 2016) (Habaki, Hayashi, Sinthupinyo, & Egashira, 2019). The process is vital for the production of pure glycerine used as the main ingredient in many of the end-products produced by the pharmaceutical and food industries (Ardi, Aroua, & Awanis Hashim, 2015) (Jungermann & Sonntag, 2018) (Wan Azelee, et al., 2019).

On the industrial scale, purification is carried out in the distillation column system using high-temperature steam, which is transferred to the internal column packing for the separation of the crude from its components based on the differences in volatilities (Abdul Raman, Hooi W., & Buthiyappan, 2019) (Sotelo, et al., 2019) (Tan, Aziz, & Aroua, 2013) (Yong, Ooi, Dzulkefly, Wan Yunus, & Abu Hassan, 2011).

The standard process for glycerin purification involves three main stages, namely mixing, heating, and filtering (Xiao, Xiao, & Varma, 2013). The mixing process involves mainly applying activated carbon as an absorbent agent to the process so that the undesirable compounds are absorbed and removed via filtration (Farid, et al., 2021). In general, the mixing process can be performed either with or without the heat generated. The mixing process that is carried out using the heat generated is known as the heating process. The heating process is simply that of maintaining the operating temperature for a sufficient time to allow the absorption to take place to the maximum extent possible.

Heating is a vital stage of purification, where the purity of glycerine depends significantly on the optimum operating temperature (Rich, 1964) (Rich, Some Fundamental Aspects of Bleaching, 1970) (Chakrabarty, 2003) (Kim & Choe, 2005) (Mićić, et al., 2019). The operating temperature should be maintained as low as possible but should high enough to obtain the desired process output (Aiken, 2006). For instance, when the heating process is experiencing extreme temperature changes, the changes should dissipate quickly to avoid oxidation instability. Therefore, the temperature control system plays a crucial role in increasing efficiency and ensuring the process output meets the desired specifications. In this case, the most crucial part of the entire control system is the correct controller and control structure to ensure optimum system performance.

1.3 Problem Statement

Maintaining and controlling temperatures for a typical heating process is inherently difficult due to various factors such as process thermal response and slow dynamic response due to process scale (Marlin, 2000). Finding an appropriate temperature control structure for the glycerin heating process usually involves comparing the control performance of different control structures.

The conventional Proportional + Integral + Derivative (PID) controller structure is most widely used in the industry (Atherton & Majhi, 1999) (Dorf &

Bishop, 2011) (Deshmukh & Kadu, 2016). In this structure, the control output is made up of the Proportional, Integral, and Derivative control modes which each mode reacts differently to the error signals. However, there are certain drawbacks associated with the controller. The disadvantage includes that the controller keeps adjusting the power input to the heating elements, contributing a higher maximum overshoot and exhibiting a longer response time in the output response. The high percentage overshoot in the output response indicates the process experiencing excessive temperature changes and considerable time to reach the desired temperature (Atherton & Majhi, 1999).

Besides, there are several problems in the typical process plant to achieve optimal control. The problems include the variations in process parameters, variable conditions, interactions between parameters, and uncertainty in the model. In general, plant design and construction often emphasize chemistry, cost, and safety rather than control. Therefore, the best temperature control approach will generally be ineffective if the glycerin heating process is not thoroughly understood and does not correctly implement the regulatory controls.

The relationship between the control output and the process variables plays an important role in designing and tuning the controller (Deshpande & Kadu, 2016). The actual heating process dynamics are usually modeled using either first-order or higher-order systems, depending mostly on the system design. Therefore, the approximation behavioral dynamics of the glycerin heating process are best determined by understanding how a control output responds to the process changes. In this case, process plant design plays a key role in producing the desired process dynamic behavior that is easy to compute and offers robust temperature control.

The existing distillation column system has some disadvantages, such as high energy input requirements for steam generation, which involve high capital and maintenance costs. The system is inefficient in terms of power consumption. The process usually operates without considering the amount of heat required for the process, and without the controller maintaining the steam temperature (Rodrigues, Bordado, & Santos, 2017). Besides, the distillation operation will take at least 3 hours to complete the process and sometimes longer for a single process, followed by deterioration problems that may affect significant glycerine losses (Sotelo, et al., 2019). Furthermore, the distillation control system's characteristics are nonlinear, complex models, and coupling effects between parameters (Anbarasan, Suji Prasad, Meenakumari, & Balakrishnan, 2013).

Based on the factors mentioned above, the glycerin heating process requires an efficient and easy to deliver process plant, and a simple temperature control system to operate. Therefore, there is a continuing need for research into improving the percentage overshoot and settling time of the glycerine heating process. There is also a need for an improved process model to represent the glycerine heating process for various purposes, including the temperature control system's design.

1.4 Significance of the Research

A developed small-scale glycerine heating process system using a closed jacket-controlled tank controlled using DPI controller contributes to a system easily implemented by a non-expert with a fast process duration. The heater installed at the outer diameter of the closed jacket-controlled tank determines the uniqueness of the system. The arrangement minimizes the heater's malfunction and, as a result, contributes to the long service life of the heater, resulting in minimal system maintenance costs. The system can also hold the tank's temperature within a specific band around the set-point, without oscillation. The developed glycerin heating process system has excellent potential for the commercialization of end-product.

Since many studies on the purification process are more focused on chemical-based, the present study's findings are considered new in the glycerin instrumentation and control system field. Although the input step test is a well-known and established method, the developed glycerin heating process model differs from any related publications in equipment and instrumentation systems. The developed process model offers simplicity but holds the essential process dynamics without finding the complex physics involved. Regardless of the type of input, the time constant is the same, but the process gain depends on the relation between the controller output and the process variable.

Another significance is that the glycerin heating process system ran efficiently without exhibiting drastic temperature changes in the control loop and settled in a reasonable settling time. The DPI controller keeps the system operations running within the operating temperature, which the temperature is gradually increasing without showing significant overshoot and settle in a reasonable time. Furthermore, the system is easily operated by non-experts, whereby the optimal parameters for the controller are automatically calculated by just inputting the initial guess of the controller parameters.

Although the Nelder-Mead algorithm optimization technique is well-known and well-established, the algorithm's implementation differs from any related publications in the aspects of the input-output relationship, constraints, and objective function. The technique is considered new to the DPI controller and the glycerin heating process system as a whole.

1.5 Research Objectives

The main objective is to test the hypothesis that the proposed DPI controller structure can maintain the glycerine heating process system within the operating temperature by steadily increasing the temperature without demonstrating an oscillating response and a sudden temperature rise. Three objectives are set as follows to achieve the goal of the study:

(a) To construct an efficient glycerin heating process plant using industry-standard equipment and instrumentation.

(b) To formulate the First Order plus Dead Time (FOPDT) model representing the glycerine heating process dynamic.

(c) To design a DPI controller that maintain the temperature of the glycerine heating process.

1.6 Scope of the Research

The study focused primarily on the temperature control system development for the glycerine heating process. The development includes designing small-scale hardware systems for the process based on the information gathered from the literature. The hardware system component considers the transducer and actuator, the interface between the process plant and the control unit, and the input and output signal used for system operation.

The study also focuses on developing a process model for the glycerine heating process. The model is developed and validated through experimental and simulation works. The dynamic process behaviour from the developed hardware system is judged under the standard step input test application. The step input used is in the form of an industry-standard IEC60059 electrical current signal of 4 to 20 mA. The main process parameters under consideration are the process gain, a time constant, and delay time, which then approximates the FOPDT model. The validation process includes comparing the approximated model to experimental data. The Microsoft Excel and MATLAB R2017a Simulink software environment are used as a simulation tool throughout the research analysis work.

In this study, the DPI controller with the three control actions, i.e. Derivative, Proportional and Integral, is designed to deliver the control output at a desired operating temperature of 85°C. The controller parameters adjustment only involves the three controller gains using Direct Search Nelder-Mead Optimization algorithm. The DPI controller evaluation is scoped to the transient response characteristic analysis, specifically the rise time, percentage overshoot, and settling time. Apart from that, the controller robustness performance is checked at an operating temperature of 40ºC and 85ºC for input change tracking analysis. Detailed analysis concerning the pole and zero, and steady-state criteria is outside the scope of this study. The control performance analysis is a simulation using MATLAB R2017a Simulink software environment. The Ziegler-Nichols tuning method, conventional PID, and Integral-Proportional Derivative (I-PD) controller are used to verify the overall DPI control performance.

However, the glycerin final product quality and type of sample is not considered in the study. Despite this limitation, the study's findings are important because techniques related to the instrumentation and control for the purification process has not been discussed scientifically in the literature.

1.7 Thesis Outline

This thesis consists of six chapters. The content of each chapter is briefed in the following paragraphs.

Chapter 1 presents the introduction and the research study overview. The research study background is explained in Section 1.1.1 of the chapter. In Section 1.2 of the chapter, the description of an issue that needs to be addressed is followed. The research study significance is set out in Section 1.3 of the chapter. Section 1.4 outlines the research objectives, and Section 1.5 outlines the research scope and limitations.

Chapter 2 discusses a review of relevant literature for this study. The review covers the glycerin purification process system presented in Section 2.2. In Section 2.3, the heating process model is reviewed. A literature review on the controller for the temperature control system is presented in Section 2.4. A summary of the chapter is presented in Section 2.5.

Chapter 3 sets out a description of the research methodology used for conducting the research study. The chapter begins with Section 3.2, explaining the process flow in completing the research study. The development of the glycerine heating process system is briefly explained in Section 3.3. It followed with a brief methodology on the process model determination in Section 3.4. Section 3.5 presents the DPI controller design methodology. The system performance evaluations carried out in this research study are presented in Section 3.6 of the chapter. A summary of the chapter is presented in the last section of the chapter.

Chapter 4 comprises six sections. The chapter begins with Section 4.2, which details the methodology on the glycerine heating process's hardware development. Section 4.3 describes the prototype of the glycerine heating system. Details methodology of the glycerine heating process modeling is explained in Section 4.4. The results are set out in Section 4.5 of the chapter. The overall analysis is presented in Section 4.6 and follows a summary of the chapter in Section 4.7.

Chapter 5 details the design process and the performance analysis of the proposed controller. The chapter begins with Section 5.2, which describes the design and implementation of the PID controller for the glycerine purification process system. It is followed by Section 5.3, which describes the results. System performance analysis is presented in Section 5.4, and Section 5.5 summarizes the content of the chapter.

Chapter 6 outlined the conclusions and the recommendation for future research work. The chapter begins with Section 6.2, which shows the achievement of the study. This section is divided into three subsections that explain each achievement accordingly. Section 6.3 describes the recommended research work that can be carried out in the future. A summary of the chapter is presented in the last section of the chapter.

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