UNIVERSITI TEKNOLOGI MARA

MODELING AND CONTROL OF STEAM DISTILLATION IN ESSENTIAL OIL EXTRACTION SYSTEM USING FUZZY MODEL REFERENCE LEARNING CONTROL (FMRLC)

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CHAPTER ONE
INTRODUCTION

1.1 RESEARCH OVERVIEW

Malaysia, like many other developing countries, possesses abundant aromatic plant resources. Thus, the extraction of aromatic plant essential oils offers an economic opportunity. Essential oil is one of a plant's primary metabolites, and this valuable product is in great demand in many industries and for numerous applications such as aromatic and fragrance products [1], food and flavorings [2], cosmetics [3], insect repellents and pesticides [4], medicine, and so forth. Moreover, public awareness of natural products has increased, and essential oils provide an alternative to synthetic chemicals and drugs.

The consumer demand for essential oil products greatly depends on oil concentration and purity. Furthermore, for industrial standards, essential oil production must be maximized while maintaining reasonable quality, which can be achieved through the advancement of extraction technology. Hence, many research efforts involving the distillation process, from advanced to conventional schemes, have aimed to establish and improve techniques for enhancing the quality and production volumes of essential oil. Based on common practice, the steam distillation technique is still preferred and applied in many industrial and research areas due to several factors such as system cost, cleanliness, productivity, and operational cost [5], and its reliability for the mass production of essential oil [6, 7].

In this research, a pilot-scale steam distillation system with temperature monitoring and control module was employed. Steam temperature was chosen as the controlled variable that significantly influences essential oil yield and quality [8, 9]. A model of steam temperature was derived and represented by first-order autoregressive exogenous (ARX) function. Thus, fuzzy model reference learning control (FMRLC) was implemented in the system to improve system performance and increase plant flexibility while tracking the desired, predetermined temperature profile that suits the raw material to be processed. The integration of an advanced control system can improve energy efficiency. The elements of learning and adaptability in an FMRLC enable automatic control of the system and ensure the system is stable.

1.2 PROBLEM STATEMENT

The essential oil from plant materials contains fragile aromatic molecules that can easily be destroyed or modified by changes caused during the extraction process. Even a subtle difference in extraction process conditions can have a significant effect on oil quality. In conventional steam distillation method, high temperatures or extended heat were exposed to botanical plants that can cause thermal degradation in the extracted oil [3, 10-13]. Consequently, the quality of the chemical composition properties of the oil decreases, affecting the aromatic profiles and color of the oil. Numerous researchers made continuous efforts to improve the existing extraction methods and to overcome any shortcomings of the present techniques. Similarly, the drawbacks of conventional extraction techniques motivated the author to embed technological advancements in the respective processes to solve the identifiable problems. Some other drawbacks that have been highlighted in the steam distillation process include the system operating in saturated temperatures [5], and long extraction periods [14, 15], with the common steam distillation process taking from 3 to 8 hours [16-18] depending on the quantity and particle size of the raw materials. In addition, there is no selectivity [10] in steam distillation.

Nevertheless, steam distillation holds several advantages, such as having lower development and operational costs compared to other extraction methods [19], being appropriate for most essential oil extraction [20], and having potential for commercialization [21] due to its reliability in mass oil production. Furthermore, the advantages of steam distillation compared to other distillation methods were mentioned in several previous studies. According to Ozel et al. [22], the relative chemical composition of volatile compounds obtained by steam distillation and superheated water extraction (SWE) were proven to be similar. In fact, steam distillation itself can produce more oil compared to superheated water extraction. Additionally, Scalia et al. [3] revealed that the qualitative profile of essential oils obtained by supercritical fluid extraction (SFE) was comparable with those produced by steam distillation. Indeed, Ammann et al. [21] concluded that, for the chosen study, steam distillation was the most effective technique compared to SFE and SWE. In comparison to supercritical carbon dioxide extraction methods, steam distillation produced a greater yield, and the quality of oil extracted by both methods was similar [9]. The advantages and disadvantages of the steam distillation process highlighted above notwithstanding, in practice, whether in industrial or agricultural activities, the steam distillation method is still preferred. Therefore, the trade-offs regarding the drawbacks of the system remain worthwhile. In this study, the shortcomings identified in the steam distillation system provide areas for improvement. By focusing on research opportunities, these shortcomings can be resolved hypothetically by proposing an advanced temperature controller integrated in steam distillation systems. This also provides a user-defined function that enhances selectivity or options for the system operator. Further, the implementation of an advanced controller is expected to improve system efficiency, which implies shortening the duration of extraction and consequently lowering energy consumption.

1.3 RESEARCH OBJECTIVES

The purpose of this research was to develop an FMRLC for steam temperature regulation in a pilot-plant steam distillation process for the extraction of essential oil. In meeting this aim, the researcher

i. Performed a system identification of process characteristics based on its steady-state and dynamic behavior to obtain a model of steam temperature
ii. Designed an FMRLC to regulate steam temperature in a steam distillation plant based on model reference. The output response followed the model reference, with time constant 220 s with no overshoot. The performance of the FMRLC was compared with that of a model reference adaptive controller (MRAC), fuzzy PID controller, and PID controller.
iii. Compared and analyzed the quality and quantity of kaffir lime (limau purut) essential oil for different steam-temperature control conditions.

1.4 THESIS SCOPE AND LIMITATION

The research begins with the application of a pilot-scale steam distillation essential oil extraction system with a 20-liter capacity. Taking into account the importance of temperature, which has the most significant effect on oil quality and production, steam temperature was selected to be a controlled variable for the proposed system. The voltage applied to the power controller was chosen as a manipulated variable that corresponded to the change of temperature response. The extraction process was executed under atmospheric pressure conditions. For the purpose of steam-temperature modeling, a pseudorandom binary sequence (PRBS) signal was used as perturbation signal to trigger the dynamics of steam temperature inside the distillation column. An autoregressive exogenous (ARX) structure was used to represent the system. To determine the steam temperature model, a study of several experimental data sets was performed and the best model was selected.

A proposed controller, fuzzy model reference learning controller (FMRLC) was designed and implemented in the system. The function of the controller was based on

1) Maintaining the distillation column temperature as closely as possible to its desired reference profile regardless of unwanted temperature changes, uncertainties, or the presence of large time delays. The time constant of the desired reference was set at 220 s with no overshoot.
2) Minimizing distillation duration and avoiding large temperature overshoot
3) Allowing process temperature tracking at the appropriate heating profile of the extracted material that provides the desired quantity and quality of essential oil compounds

The implementation of an adaptive controller may improve the efficiency of the system and the above-mentioned performance. Initially, MRAC and fuzzy PID were studied. Fuzzy PID and MRAC based on Lyapunov's and the MIT-rule structures were designed, and their performance was evaluated in terms of squared error and the efficiency of their efforts. Moreover, the fuzzy rule-base in fuzzy PID controllers was considered in designing the FMRLC. The performance of all the controllers mentioned was compared in simulated and real-time conditions. The robustness of each controller also was tested based on tracking the performance of model reference function and set point change. The proposed steam distillation process was performed using real extraction of kaffir lime peel oil. The amount of oil produced was measured and oil composition quality was assessed using gas chromatography for different controlled temperatures.