Improvement on Step Response in Steam Distillation Process through of Fuzzy Based Controller Integrated PID Anti-Windup

Haslizamri Md Shariff, Mohd Hezri Fazalul Rahiman*, Mazidah Tajjudin, Mohd Hezri Marzaki, Mohd Hafiz A. Jalil and Ku Siti Syahidah Ku Mohd Noh

***Abstract*- The Proportional-Integral-Derivative (PID) controller is widely used in control systems due to its ease of development, tuning, efficiency, and reliable. However, it has a significant drawback known as the wind-up phenomenon, which occurs when the integrator action does not account for input saturation. This can lead to high overshoot and longer settling times, as the controller struggles to unwind the control input signal. Additionally, PID controllers often struggle to manage the nonlinear dynamics of Small-scale Steam Distillation Systems. This paper aims to develop a Fuzzy-based controller with an integrated anti wind-up strategy to improve system response. The Fuzzy controller is chosen due to its ability in regulate the nonlinear dynamics of the system. The anti wind-up strategy helps reduce overshoot and improve settling time, ensuring better temperature regulation. Simulation results demonstrate that the proposed Fuzzy-based controller integrated anti wind-up significantly outperforms the conventional PID controller. The Fuzzy integrated anti wind-up controller achieves an overshoot of less than 1%, while the PID controller exceeds 16%. Furthermore, the Fuzzy integrated anti wind-up controller has a settling time of under 4000 seconds, compared to over 7700 seconds for the PID controller.**

***Index Terms*—Proportional-Integral-Derivatives integrated Anti-Windup (PIDAW), Hybrid Fuzzy-PID (HFPID), Hybrid Fuzzy-PID Anti-Windup (HF-PIDAW).**

I. INTRODUCTION

Since the 1930s, PID controllers have been widely used in industrial processes because they are easy to tune, efficient, and reliable [1]–[6]. According to [7], hundreds of tuning methods have been developed over the years to improve PID performance. However, no single method has been officially proven to be the best. A major drawback of classical PID controllers is integral windup, which happens due to input saturation—a common nonlinear behavior in control systems.

This occurs when the controller's output exceeds the actuator's limits, often during large disturbances or set-point changes. When this happens, the integral part of the PID keeps accumulating error even though the actuator can't respond anymore, causing the control signal to grow excessively.

As a result, the system may experience large overshoots, longer settling times, or even instability [8]–[11]. This issue is worsened when the controller incapable unwind the excessive signal once the actuator comes back within its operating range. Essentially, the feedback loop becomes ineffective, and the controller continues to respond incorrectly.

Input saturation and wind-up are common problems in nonlinear systems, and must be carefully considered when designing PID controllers to ensure stable and efficient closed-loop performance [8], [12], [13]. In steam distillation process, the PID controller are commonly utilized in order to regulate the whole process [14]–[18]. However, only a few number of research of development of PID controller are focus and consider the windup phenomenon problem in steam distillation system [19]–[21]. Until today, the engineers and practitioners only focusing to regulate the process of steam of distillation column only without consider encountered wind-up phenomena [10], [21].

The classical PID controller has limitations, particularly in handling the windup phenomenon, which occurs due to system nonlinearities caused by control input constraints [10]. This issue is linked to the integral action of the PID, which keeps accumulating error even when the actuator has reached its limits. As a result, the controller generates signals that exceed the actuator's operating range, leading to integral windup [22], [23]. This breaks the feedback loop and degrades system performance, causing problems like high overshoot, steady-state error, and instability [10], [24], [25]. To address this, a PID controller with Anti Wind-up (PIDAW) has been developed. While it reduces wind-up effects, it may still fall short in minimizing overshoot and settling time. Therefore, fuzzy-based controllers, such as Hybrid Fuzzy-PID (HF-PID) and Hybrid Fuzzy-PID with Anti-Windup (HF-PIDAW), have been introduced. Comparative studies show that HF-PIDAW

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performs better than HF-PID, especially in reducing overshoot and settling time.

This paper proposes using the HF-PIDAW controller, tuned with the Integral Square Error (ISE) method, to overcome windup issues. The anti wind-up mechanism integrated into the controller helps reduce the negative effects of input nonlinearities and improves closed-loop system performance [26].

II. Using the Template PID and PID Anti-Windup Structure

The PID is the feedback controller that consist of three elements (as shown in Figure 1) knowns as Proportional action, *P*, Integral action, *I* and Derivative action, *D*. The PID structure is shown in Equation (1)

$$u(t) = K_p e(t) + \int_0^t K_i\, e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

Where the *Kp*, *Ki* and *Kd* are the proportional gain, integral gain and derivative gain respectively. Those gains is able to express as in Equation (2), (3) and (4)

$$K_p = K_p \quad (2)$$

$$K_i = \frac{K_p}{T_i} \quad (3)$$

$$K_d = K_p T_d \quad (4)$$

Where the T_i and T_d indicates the integral time constant and derivative time constant.

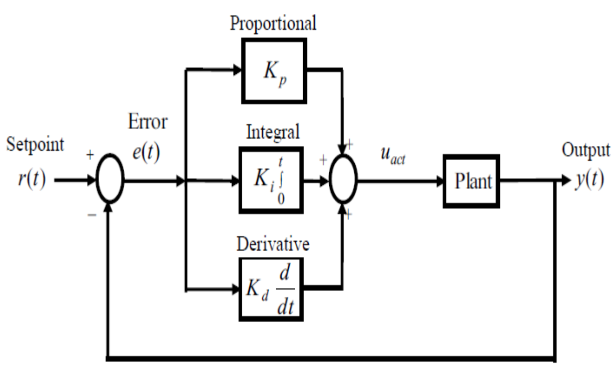

Fig. 1. Basic PID Controller Block Diagram

The PID controller is able to control a system response at a desired set point so that there is no error between output signal and desired set point. The PID parameter's have their own function where the proportional gain gives output which is proportional to current error, *e(t)*. It compares between reference signal versus output value and; resulting error is multiplied with proportional constant to obtain the output signal. Due to limitation of proportional gain, the integral action is needed to improve the steady state error. The integral action will improve the steady state error so that the output is close to desired set point. Meanwhile, derivative action is to improve the system response by anticipating future behavior of the error.

The PID is well-known and engineers still applied the controller in production floor due to easy to operate and design. Unfortunately, the PID has some limitation especially once a system is nonlinear in dynamic behavior. In addition, the limitation of actuator in order to regulate integral action at saturate region.

In this research, the basic PID structure will be integrated with additional feedback (as shown in Figure 2); known as anti wind-up function. The functionality of additional feedback which developed in PID structure is to determine the discrepancy value produced of saturated control signal and unsaturated/actual control signal, u_{act}.

The wind-up problem start to attack system dynamic once actual control input penetrate beyond the saturated region. The improvement is done by anti wind-up integrated with PID controller which; an error between saturated signal and actual signal will be notified to new integrator via $1/T_a$ gain to recompute the new integral action value.

The T_a value will continuously compute until the value of T_a form an actual control signal and system dynamic stand at desire set point.

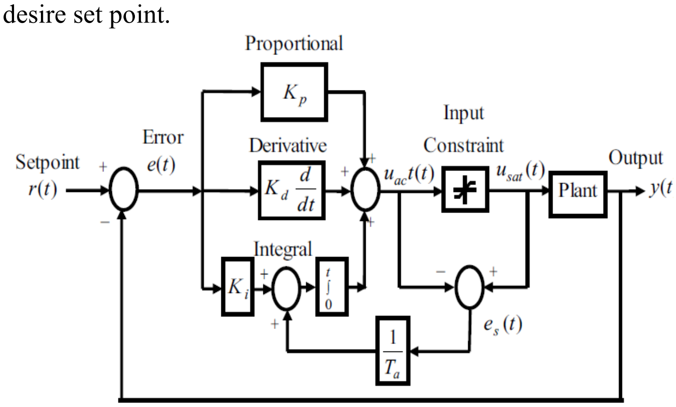

Fig. 2. PID Integrated Anti-Windup (PIDAW) Contoller Block Diagram.

To ensure the controller has high performance; the selection of Tracking Time Constant, T_a value is important [45]. The T_a value highly effect on new integrator feedback to reset faster or not and, this phenomenon indirectly effect on overall controller performance [46]. In [47] has suggested the range selection of Tracking Time Constant, T_a value as in Equation (5)

$$T_i \geq T_a \geq T_d \quad (5)$$

So, referring to the Equation (5), determination of T_a values as in Equation (6), (7) and (8)

$$T_a = T_d \quad (6)$$

$$T_a = T_i \quad (7)$$

$$T_a = \sqrt{T_i T_d} \quad (8)$$

The advantage of selection T_d value as smallest value which is $T_a = T_d$; will contribute the fastest reset time to the integrator [29]. The values of new T_a will be applied as new integrator feedback for PID Integrated Anti Wind-up strategies. The compensator will be developed using Tracking Time Constant values based on Equation (6), (7) and (8). Each compensator will be evaluated using transient response and performance indexes to determine the best controller.

II. HFPID and HFPIDAW Structure

Today, conventional PID controller integrated with fuzzy logic is widely applied to enhance the robustness of the classical structure of PID. The integration of PID and fuzzy logic controllers, the PID gain were automatically tuned from the output of fuzzy error information. The basic configuration of the fuzzy system as described in Figure 3.

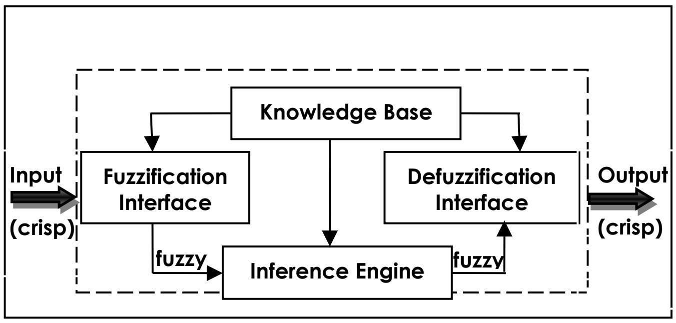

Fig. 3. Configuration of Fuzzy System

The function of fuzzy logic controller is supervise the PID algorithm in attempting to be tuned within the range. All the gains tuned following a set of fuzzy rules in order to achieve the optimum performance. In this study, the CHR tuning rule as a reference to build the range of PID parameters. And, the designing of Membership Function (MF) and fuzzy rules were built based on experimental experience and knowledge which is depend on the plant to be regulated.

A. Parameters of Hybrid Fuzzy-PID Controller

The Mamdani inference system is applied in order to develop the HFPID and, two approaches have involved which were five and seven (Membership Function (MF). The 5MF and 7MF have couple of input variables whice are error, *e(t)* and derivative of error, de/dt. The three elements of *Kp, Ki* and *Kd* parameters are act as the output variable of the HFPID control that then will be fed to each of the PID controller parameter.

Figure 4 illustrates the use of trapezoidal and triangular membership functions (MFs), which were chosen for all linguistic variables in designing the 5MF and 7MF fuzzy systems. One of the main challenges in designing a fuzzy system is selecting the right MFs, as they form the core of the controller. The proper arrangement and shape of MFs greatly affect the system's performance. Currently, there is no universal or best method for determining the ideal MF shapes—they are usually chosen based on the specific problem domain. However, triangular and trapezoidal MFs are the most commonly used, especially in applications involving fuzzy logic controllers, as shown in Figure 4. Triangular MFs are often preferred due to their simplicity and low computational cost.

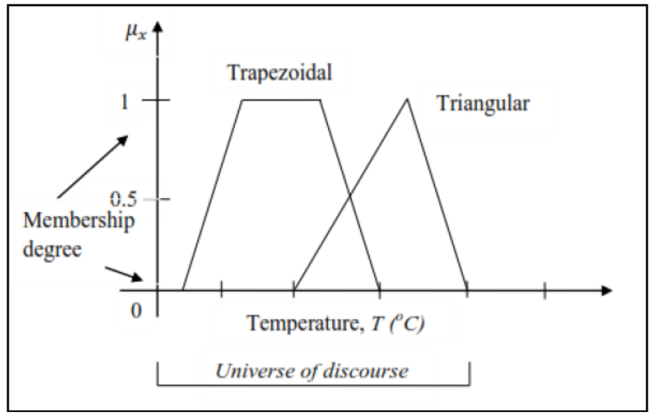

Fig. 4. Shape of Triangular and Trapezoidal MF

TABLE I. Fuzzy Rules Mapping

Derivative of Error	Error: NB	NS	ZE	PS	PB
NB	NB	NB	NM	NS	ZE
NS	NB	NS	NS	ZE	PM
ZE	NM	NS	ZE	PS	PB
PS	NS	ZE	PS	PS	PB
PB	ZE	PM	PB	PB	PB

The fuzzy rules are developed by mapping the behavior of the system to be controlled. Each rule consists of two inputs (antecedents) and one output (consequence), based on an input-output relationship. A total of 49 if-then rules were created, as summarized in Table I. In this study, the PID parameters K_p. K_i, K_d are defined within the ranges [*Kp min Kp max*], [*Ki min Ki max*] and [*Kd min Kd max*] respectively. These ranges were determined through PID control simulations to ensure effective and feasible rule bases with high interference efficiency. The parameter values can be normalized within the interval [0,1][0, 1][0,1] as shown in Equations (9), (10), and (11).

$$K'p = \frac{K_p - K_{pmin}}{K_{pmax} - K_{pmin}} \quad (9)$$

$$K'i = \frac{K_i - K_{imin}}{K_{imax} - K_{imin}} \quad (10)$$

$$K'd = \frac{K_d - K_{dmin}}{K_{dmax} - K_{dmin}} \quad (11)$$

II. The Simulation Of Steam Distillation Process

MATLAB 2018 was used to develop a simulation model of the steam distillation process. The system's transfer function was derived from the process reaction curve, which was obtained from the actual operation of a small-scale steam distillation setup. This curve reflects the system's dynamic behavior and provides three key parameters: gain (*k*), dead time (θ), and time constant (τ).

The steam distillation experiment was carried out at the Distributed Control System (DCS) Laboratory, Faculty of

Electrical Engineering, UiTM Shah Alam. The small-scale steam distillation plant, was designed to extract essential oils using steam distillation. The setup includes several components: a 30 cm diameter stainless steel distillation tank, a water-cooled copper condenser, two resistive temperature detectors (RTDs) for measuring steam and water temperatures, a control panel, and a data acquisition unit. The stainless steel distillation column has a maximum capacity of 25 liters. During oil extraction, raw materials are placed inside this column.

TABLE II. TRACKING TIME CONSTANT, T_a VALUE

Controller Name	Tracking Time Contant, *Ta* Value
PIDAW-Td	374
PIDAW-TiTd	488
PIDAW-Ti	638

The simulation study begins with testing both the PID and PIDAW controllers, focusing on step response, setpoint tracking, and load disturbance performance. The PIDAW controller is evaluated with various values of the tracking time constant, T_a, to identify the optimal value that yields the best performance for each tuning.

Next, a comparative study is conducted using advanced intelligent controllers, specifically fuzzy-based controllers, including HF-PID and HF-PIDAW. The HF-PIDAW controller is also tested with different T_a values to determine the most effective tracking time constant for optimal performance.

TABLE III. HFPIDAW CONTROLLER TRACKING TIME CONSTANT, T_a VALUE AND MF

Controller Name	Tracking Time Constant, T_a	T_a Value	Membership Function (MF)
HF-PIDAW - T_i-5MF	T_i	638	5
HF-PIDAW- $\sqrt{T_i T_d}$ - 5MF	$\sqrt{T_i T_d}$	488	
HF-PIDAW- -T_d-5MF	T_d	374	
HF-PIDAW- T_i-7MF	T_i	638	7
HF-PIDAW- $\sqrt{T_i T_d}$ - 7MF	$\sqrt{T_i T_d}$	488	
HF-PIDAW- T_d-7MF	T_d	374	

In this research, the development of PIDAW will be divided to three difference parameters of Tracking Time Constant, T_a. The PIDAW were tested with three differences of Tracking Time Constants, T_a values as in Table II.

While, HFPIDAW controllers are developed based on difference values of Tracking Time Constant, *Ta* where all given name with suffix depend on *Ta* and MF applied for that controller. The name of the controllers is listed in Table III.

III. SIMULATION RESULTS OF PID AND PIDAW CONTROLLERS

Figure 5 illustrates the step response of PIDAW-ISE-. T_dThe analysis of the responses is as provided in Table IV. Based on the percentage of overshoot, the smallest overshoot is contributed by PIDAW-ISE-T_d. This percentages overshoot is 0.63% lower as compared with PIDAW-ISE-$\sqrt{T_i T_d}$ and 1.47% smaller overshoot as compared with PIDAW-ISE-T_i. Unfortunately, the PID-ISE contribute the highest overshoot as compared to other PIDAW-ISE controllers with 26.72%. In term of rise time, the PIDAW-ISE-T_d PIDAW-ISE-T_i and PIDAW-ISE-$\sqrt{T_i T_d}$ have the fastest rising time with 1405 seconds as compared to PID-ISE controller.

The result for settling time, *Ts* indicate that the PIDAW-ISE-T_d provides the fastest settling time and only tooks 7773 seconds to reach its settling time. It is 11 s faster as compared with PIDAW-ISE-$\sqrt{T_i T_d}$ and 41 s faster than PIDAW-ISE-T_i controller. Unfortunately, the PID-ISE is required 12684 s to reach the settling time which is more than 4000 s slower than PIDAW-ISE controllers. In term of steady state analysis, the result show that PIDAW-ISE- $T_d$provides the smallest IAE, ITAE and ISE index and PID-ISE contribute the highest of IAE, ITAE and ISE index as compared to other controllers. The root cause of higher overshoot and longer settling time of PID-ISE compared to others PIDAW-ISE due to PID-ISE is unintegrated with anti-windup strategy which the controller unrealized that the integral part reach the saturation point and continuously integrate an error.

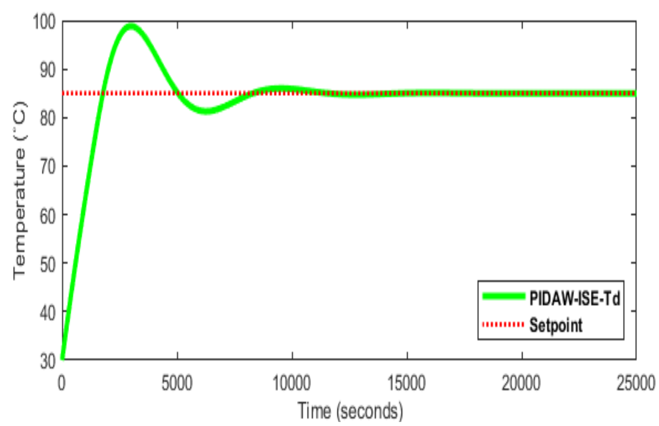

Fig. 5. Output for PIDAW-ISE-T_dControllers in Step Test Simulation.

TABLE IV. SIMULATION RESPONSE ANALYSIS OF PID-ISE AND PIDAW-ISE CONTROLLERS WITH DIFFERENT TRACKING TIME CONSTANT, T_a

Controller Time, (seconds)	%OS	Rise Time, Tr (seconds)	Settling, Ts
PID-ISE	26.7211	2353	12684
PIDAW-ISE-T_i	17.7318	1405*	7814
PIDAW-ISE-$\sqrt{T_iT_d}$	16.8949	1405*	7784
PIDAW-ISE-T_d #	16.2615*	1405*	7773*

Note: # indicate for the best controller / * indicate the best performance by category.

IV. SIMULATION RESULTS FOR HFPID AND HFPIDAW CONTROLLERS

The step response on steam distillation process are applied to evaluate the controller performance based on the percentage of overshoot, rise time, settling time and matrices index as the numerical data are tabulated in Table V. And, Figure 6 illustrates the step response of HF-PIDAW-ISE-T_d-5MF. The HF-PID are developed by using two set of Membership Function (MF) which are 5MF and 7MF. Then, the modified version of HF-PID which enhancement with anti-windup strategy is also presented. The Table V shows the HF-PIDAW-ISE-$\sqrt{T_iT_d}$ -7MF recorded the lowest percentage of overshoot with 0.04% followed by the HF-PIDAW-ISE-T_i-5MF, HF-PIDAW-ISE-$\sqrt{T_iT_d}$ -5MF, HF-PIDAW-ISE-T_i-7MF, HF-PIDAW-ISE-T_d-5MF, HF-PIDAW-ISE-T_d-7MF, HF-PID-ISE-7MF and lastly HF-PID-ISE -5MF.

In term of rise time, HF-PID-ISE-5MF revealed the fastest rise time with 2261 seconds followed by the HF-PID-ISE-7MF, HF-PIDAW-ISE-T_d-5MF, HF-PIDAW-ISE-T_d-7MF, HF-PIDAW-ISE-T_i-5MF, HF-PIDAW-ISE-$\sqrt{T_iT_d}$ -5MF, HF-PIDAW-ISE-T_i-7MF, and lastly HF-PIDAW-ISE--7MF. $\sqrt{T_iT_d}$ The settling time criteria shown that HF-PIDAW-T_dISE--7MF recorded the fastest settling time with 3887 seconds and followed by HF-PIDAW-IST_dE--5MF, HF-PIDAW-ISE--T_i5MF, HF-PIDAW-ISE$\sqrt{T_iT_d}$ --5MF, HF-PIDAW-ISE-T_i-7MF, HF-PIDAW-ISE$\sqrt{T_iT_d}$ --7MF, HF-PID-ISE-7MF and lastly HF-PID-ISE-5MF.

After carefully putting into consideration the factor mentioned above, the HF-PIDAW-IST_dE--5MF controller has better transient response compared to all HF-PID and HF-PIDAW control variance. Although the HF-PIDAW-IST_dE--5MF is not selected the preferred performance in any category, the %OS is still lower which less than 1%, and second lower of rise time and settling time among the controllers.

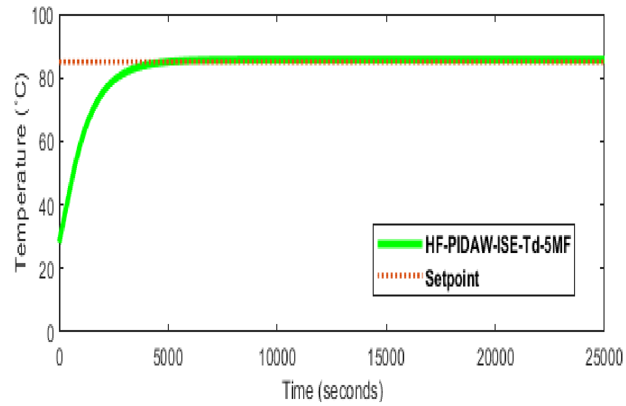

Fig. 6. Output for HF-PIDAW-ISE-T_d-5MF Controllers in Step Test Simulation.

TABLE V. SIMULATION RESPONSE ANALYSIS OF HF-PID VERSUS HF-PIDAW CONTROLLER

Controller Time, (seconds)	%OS	Rise Time, Tr (seconds)	Settling, Ts
HF-PID-ISE-5MF	2.00	2261*	26000
HF-PID-ISE-7MF	1.00	2340	8127
HF-PIDAW-ISE-T_i-5MF	0.29	2420	4160
HF-PIDAW-ISE-$\sqrt{T_iT_d}$	0.29	2421	4162
HF-PIDAW-ISE-T_d-5MF#	0.74	2367	3911
HF-PIDAW-ISE-T_i-7MF	0.41	2485	4189
HF-PIDAW-ISE-$\sqrt{T_iT_d}$ -7MF	0.04*	2556	4515
HF-PIDAW-ISE-T_d	0.89	2405	3887*

Note: # indicate for the best controller / * indicate the best performance by category

V. CONCLUSIONS

In this study, the simulation of HFPID based controller in regulating the temperature of the time-varying of steam distillation process has been benchmarked with PID based controller. The result has clearly revealed that the HFPID based controller namely HF-PIDAW significantly improved the temperature regulation of steam distillation process in term of providing fast settling time and minimal overshoot as compared with the best performance of PID based controller. Overall, based on ranking, HF-PIDAW-ISE -T_d-5MF is the most preferred controller in terms of producing better transient response, followed by others HF-PIDAW controllers consecutively.

VI. ACKNOWLEDGMENT

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VII. REFERENCES

[1] N. Kasuan, Z. Muhammad, Z. Yusoff, M. H. F. Rahiman, M. N. Taib, and Z. A. Haiyee, "Extraction of Citrus hystrix D.C. (Kaffir Lime) essential oil using automated steam distillation process: Analysis of volatile compounds," *Malaysian J. Anal. Sci.*, vol. 17, no. 3, pp. 359–369, 2013.

[2] M. Y. Abduh, E. Nababan, F. Ginting, J. Juliati, and H. Nugrahapraja, "Biodelignification of lemon peels using Aspergillus sp. to improve yield and composition of extxracted lemon oil," *IIUM Engineering Journal*, vol. 21, no. 2. pp. 55–66, 2020.

[3] M. Y. Abduh, E. Nababan, F. Ginting, J. Juliati, and H. Nugrahapraja, "Biodelignification Of Lemon Peels Using Aspergillus Sp. To Improve Yield And Composition Of Extxracted Lemon Oil," *IIUM Eng. J.*, vol. 21, no. 2, pp. 55–66, 2020.

[4] N. H. Hamidi, N. A. M. Alwi, H. Tarmalingam, S. S. A. Kutty, and S. N. N. M. Nor, "Effect of extraction time and temperature on total flavanoid contents of petai belalang (Leucaena leucocephala) seed pretreated by enzymatic hydrolysis," *Pertanika J. Sci. Technol.*, vol. 29, no. 3, pp. 1751–1761, 2021.

[5] X. Fei, W. Xiao-long, and X. Yong, "Development of energy saving and rapid temperature control technology for intelligent greenhouses," *IEEE Access*, pp. 1–1, 2021.

[6] S. R. Richter P, Sepúlveda B, Oliva R, Calderón K, "Screening and determination of pesticides in soil using continuous subcritical water extraction and gas chromatography-mass spectrometry.," *J. Chromatogr A. 2003 Apr 25;994(1-2)169-77.*

[7] S. H. R.M. Smith, "Supercritical Fluids in Chromatography and Extraction," *Elsevier Sci. 1 Ed. (Dec 11 1997).*

[8] P. P. Scalia S, Giuffreda L, "Analytical and preparative supercritical fluid extraction of chamomile flowers and its comparison with conventional methods.," *J. Pharm Biomed Anal. 1999 Nov;21(3)549-58.*

[9] B. R. R. Rao, P. N. Kaul, K. V Syamasundar, and S. Ramesh, "Chemical profiles of primary and secondary essential oils of palmarosa (Cymbopogon martinii (Roxb .) Wats var . motia Burk .)," vol. 21, pp. 121–127, 2005.

[10] O. B. Adegoke GO, "Storage of maize and cowpea and inhibition of microbial agents of biodeterioration using the powder and essential oil of lemon grass (Cymbopogon citratus)," *Int. Biodeterior. Biodegrad. 1996;37(1-2)81-84.*

[11] K. H. Ozel MZ, "Superheated water extraction, steam distillation and Soxhlet extraction of essential oils of Origanum onites.," *Anal Bioanal Chem. 2004 Aug;379(7-8)1127-33. Epub 2004 Jun 4.*

[12] A. C. . Ozel, M Z ; Gogus, F ; Lewis, "Subcritical water extraction of essential oils from Thymbra spicata," *J. Agric. Food Chem. Vol. 82, No. 3, 08.2003, p. 381-386.*

[13] X. Deng, C., Xu, X., Yao, N., Li, N., Zhang, "Rapid determination of essential oil compounds in Artemisia Selengensis Turcz by gas chromatography-mass spectrometry with microwave distillation and simultaneous solid-phase microextraction," *Anal. Chim. Acta*, vol. 556, no. 2, pp. 289–294, 2006.

[14] X. Deng, C., Mao, Y., Hu, F., Zhang, "Development of gas chromatography-mass spectrometry following microwave distillation and simultaneous headspace single-drop microextraction for fast determination of volatile fraction in Chinese herb.," *J. Chromatogr.*, vol. 1131, no. 1, pp. 193–198, 2006.

[15] O. . Catchpole, J. . Grey, K. . Mitchell, and J. . Lan, "Supercritical antisolvent fractionation of propolis tincture," *J. Supercrit. Fluids*, vol. 29, no. 1–2, pp. 97–106, Apr. 2004.

[16] Mohd Hezri Fazalul Rahiman, "System Identification Of Steam Distillation Essential Oil Extraction System." Phd Dissertation, Universiti Teknologi MARA Malaysia, 2009.

[17] S. Álvarez De Miguel, J. G. Mollocana Lara, C. E. García Cena, M. Romero, J. M. García De María, and J. González-Aguilar, "Identification model and PI and PID controller design for a novel electric air heater," *Automatika*, vol. 58, no. 1, pp. 55–68, 2017.

[18] W. Wu, C. Hsieh, B. Shi, X. Yang, and L. Yan, "Plantwide control for optimal operation of industrial-scale crude distillation unit processes," *Chem. Eng. Commun.*, vol. 0, no. 0, pp. 1–15, 2018.

[19] E. I. Andi Adriansyaha*, Shamsudin H. M. Aminb, Anwar Minarsoa, "Improvement Of Quadrotor Performance With Flight Control System Using Particle Swarm Proportional-Integral-Derivative (PS-PID)," *J. Teknol. UTM*, vol. 6, pp. 121–128, 2017.

[20] A. Dehghani* and H. Khodadad, "Self-Tuning Pid Controller Design Using Fuzzy Logic For A Single-Link Flexible Joint Robot Manipulator," *J. Teknol. UTM*, vol. 13, pp. 115–120, 2016.

[21] A. Adriansyah, H. Suwoyo, and Y. Tian, "Improving Wall-Following Robot Performance Using Pid-Pso Controller," *J. Teknol. UTM*, vol. 3, pp. 119–126, 2019.

[22] P. Taylor, J. Garrido, F. Vázquez, and F. Morilla, "Multivariable PID control by decoupling," *Int. J. Syst. Sci.*, no. August, pp. 37–41, 2014.

[23] M. Shamsuzzoha, "Robust PID controller design for time delay processes with peak of maximum sensitivity criteria," *J. Cent. South Univ.*, vol. 21, no. 10, pp. 3777–3786, 2014.

[24] A. N. M. M. Oktaf Agni Dhewa1,Tri Kuntoro Priyambodo2*, "Enhancement Of Stability On Autonomous Waypoint Mission Of Quadrotor Using Lqr Integrator Control," *IIUM Eng. J.*, vol. 23, no. 1, pp. 129–158, 2022.

[25] Y. Tian, Z. Cao, D. Hu, X. Gao, L. Xu, and W. Yang, "A Fuzzy PID-Controlled Iterative Calderon’s Method for Binary Distribution in Electrical Capacitance Tomography," *IEEE Trans. Instrum. Meas.*, vol. 70, 2021.

[26] C. Li, H. Zhao, S. Zhen, and Y.-H. Chen, "Control Design With Optimization for Fuzzy Steering-by-Wire System Based on Nash Game Theory," *IEEE Trans. Cybern.*, pp. 1–10, 2021.

[27] T. Holicki, C. W. Scherer, and S. Trimpe, "Controller Design via Experimental Exploration with Robustness Guarantees," *IEEE Control Syst. Lett.*, vol. 5, no. 2, pp. 641–646, 2021.

[28] M. Shamsuzzoha, "Robust PID controller design for time delay processes with peak of maximum sensitivity criteria," *J. Cent. South Univ.*, vol. 21, no. 10, pp. 3777–3786, 2014.

[29] K. J. Astrom and R. M. Murray, *Feedback Systems*. Princeton University Press Princeton And Oxford, 2012.

[30] Z. M. Yusoff, N. Dalila, K. Ashar, Z. Muhammad, N. F. Razali, and S. Azeehan, "Comparison Performance of Robustness Test using Intelligent Fuzzy based Controller for Simulation Study," *Int. J. Eng. Technol.*, vol. 7, pp. 154–158, 2018.

[31] J. Astrom and T. Hagglund, *PID Controllers:Theory, Design and tuning, 2nd ed.: Instrument Society of America (ISA)*. 1995.

[32] S. Das, I. Pan, and S. Das, "Performance comparison of optimal fractional order hybrid fuzzy PID controllers for handling oscillatory fractional order processes with dead time," *ISA Trans.*, vol. 52, no. 4, pp. 550–566, 2013.

[33] S. Gros, M. Zanon, R. Quirynen, A. Bemporad, and M. Diehl, "From linear to nonlinear MPC : bridging the gap via the real-time iteration," *Int. J. Control*, no. 1, pp. 1–19, 2016.

[34] Y. Zhou, B. Qi, S. Huang, and Z. Jia, "Fuzzy PID Controller for FOPDT system based on a hardware-in-the-loop simulation," *Chinese Control Conf. CCC*, vol. 2018-July, pp. 3382–3387, 2018.

[35] Z. Tian, Y. Ren, and G. Wang, "Fuzzy-PID controller based on variable universe for main steam temperature system," *Aust. J. Electr. Electron. Eng.*, vol. 00, no. 00, pp. 1–8, 2018.

[36] S. Tabatabaee, P. Roosta, M. S. Sadeghi, and A. Barzegar, "Fuzzy PID controller design for a heat exchanger system: The energy efficiency approach," *2010 Int. Conf. Comput. Appl. Ind. Electron.*, no. Iccaie, pp. 511–515, Dec. 2010.

[37] M. Petrov, I. Ganchev, and A. Taneva, "Fuzzy PID Control of Nonlinear Plants," no. September, pp. 0–5, 2002.

[38] R. De Keyser, C. I. Muresan, and C. M. Ionescu, "Autotuning of a Robust Fractional Order PID Controller," vol. 51, no. 25. pp. 466–471, 2018.

[39] Z. Wu, D. Li, and L. Wang, "Control of the superheated steam temperature: A comparison study between PID and fractional order PID controller," *Chinese Control Conf. CCC*, vol. 2016-Augus, no. 1, pp. 10521–10526, 2016.

[40] S. Zhao, S. Liu, R. De Keyser, and C. M. Ionescu, "The application of a new PID autotuning method for the steam/water loop in large scale ships,"

Processes, vol. 8, no. 2, 2020.
[41] M. Mahmud, S. M. A. Motakabber, A. H. M. Zahirul Alam, and A. N. Nordin, “Adaptive PID Controller Using for Speed Control of the BLDC Motor,” *IEEE Int. Conf. Semicond. Electron. Proceedings, ICSE*, vol. 2020-July, pp. 168–171, 2020.
[42] K. Premkumar, T. Thamizhselvan, M. Vishnu Priya, S. B. Ron Carter, and L. P. Sivakumar, “Fuzzy anti-windup pid controlled induction motor,” *Int. J. Eng. Adv. Technol.*, vol. 9, no. 1, pp. 184–189, 2019.
[43] A. Ramya, A. Imthiaz, and M. Balaji, “Hybrid Self Tuned Fuzzy PID controller for speed control of Brushless DC Motor Hybrid Self Tuned Fuzzy PID controller for speed control of Brushless DC Motor,” *Autom. J. Control. Meas. Electron. Comput. Commun.*, vol. 1144, 2017.
[44] J. M. G. de M. & J. G.-A. S. Álvarez de Miguel, J. G. Mollocana Lara, C. E. García Cena, M. Romero, “Identification model and PI and PID controller design for a novel electric air heater,” *Autom. J. Control. Meas. Electron. Comput. Commun.*, vol. 1144, 2017.
[45] Muhamad Hafiz Abd Jalil, “Model Reference Adaptive Control (MRAC) Controller Towards Temperature Regulation Improvement of Glycerin Bleaching Process,” University Technology MARA Malaysia, 2019.
[46] Karl Johan Astrom, *Feedback Systems*. Princeton University Press Princeton And Oxford, 2002.
[47] P. A. Ioannou and P. V. Kokotovic, “Instability analysis and improvement of robustness of adaptive control,” *Automatica*, vol. 20, pp. 583–594, 1984.
[48] H. Md Shariff, M. H. Fazalul Rahiman, R. Adnan, M. H. Marzaki, M. Tajjudin, and M. H. A.Jalil, “The Anti Windup PID Controller ISE Tuning Based for Small-Scale Steam Distillation System,” *J. Electr. Electron. Syst. Res.*, vol. 16, no. June 2020, pp. 94–99, 2020.