

DEVELOPMENT OF A COMPUTER-BASED DATA ACQUISITION AND PERFORMANCE ANALYSIS OF FUZZY-PID HYBRID TEMPERATURE CONTROL FOR TORREFACTION

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ABSTRACT

Malaysia produces on average 30,000 tonnes municipal solid waste (MSW) daily to these saturated disposal landfill. Therefore, Malaysia has initiated a Waste-to-Energy (WtE) treatment system project to be implemented near to sanitary landfills. But, pre-treatment of the MSW plays an important role before incineration. Unfortunately, MSW in its natural state is not an efficient method approach hence, processing treatments which enhance the properties such as moisture content (MC) and higher heating value (HHV) of the MSW are rising to attention. One of the processing treatment is known as torrefaction process which is a thermal decomposition process of MSW at a temperature between 130 °C to 300 °C. The main objective of this study is to compare and study the performance of hybrid fuzzy-PWM and PID controller on regulating the temperature level on the torrefaction process during the thermal decomposition. Each controller has its own downside effects in output response such as long rise time, high overshoot percentage and long settling time. This research aims to study the effect of PID and Fuzzy-PWM hybrid controller for temperature control during the torrefaction process. The PID controller is manually tuned resulting in 7 different forms of tuning parameters. The most suitable PID tuning is chosen based on shortest rise time, lowest percentage overshoot and lowest peak temperature. As for fuzzy controller, there are 5 different forms of rule bases established for fuzzy controller. The most suitable fuzzy controller is chosen based on shortest settling time, lowest overshoot percentage and lowest peak temperature. The best PID and fuzzy controllers are used to develop the hybrid controller. As a conclusion, the hybrid controller has the ability to perform temperature control at 130 °C and 150 °C by exhibiting shorter rise time by 30%, shorter settling time by 14% and lower overshoot percentage by 94% as compared to conventional PID or fuzzy controllers in the industry.

Keywords : MSW; PID; Torrefaction; Fuzzy controller

INTRODUCTION

Malaysia produces on average 30,000 tonnes municipal solid waste (MSW) daily to these saturated disposal landfill [1]. Therefore, Malaysia has initiated a Waste-to-Energy (WtE) treatment system project to be implemented near to sanitary landfills [2]. The first WtE plant in Landang Tanah Merah, Port Dickson is expected to be fully functional in June 2019. Ministry is looking forward each state at least construct one WtE facility by 2020 [3]. But, this treatment process without going through the pre-treatment operation (torrefaction). The pre-treatment able to solve the current issues such as the lower HHV due to high moisture content (MC), smoke emission, uneven composition and its heterogenous [3]. Due to the torrefaction, the temperature during the heating process is required to be kept stable for a duration of time via application of temperature controllers. Temperature controllers are applied in situations whereby the object such as MSW product is needed to remain heated or cooled at the desired temperature. In the industry, proportional-integral-derivative (PID) controllers are commonly used in existing temperature control systems. Most of the recent researches nowadays in torrefaction area are using stand-alone methods for storage their data. However, the PID system in the fast heating rate is not an optimization process control to achieve the desired parameters. But the PID controller still offers a wide range of application flexibility with relatively easy tuning control methods. However, the majorities of the PID [4] controllers introduce oscillatory effects and give high overshoot percentage which is undesirable in temperature control systems. Other than conventional PID controllers, there are other control methods which are implemented in a temperature control system such as fuzzy logic [5], artificial intelligence (AI) [6], adaptive PID [7], hybrid fuzzy PID [8] and others. The fuzzy logic controller comes after PID controller in terms of temperature control in the system applications. Fuzzy logic control is based on human expert decision making which is distinct compared to mathematical decision making of PID controller. Fuzzy logic offers a wide range of applications as well since the decision-making method can be easily tuned. However, in terms of temperature control, the fuzzy logic method can be slow in terms of rising time even though it does not introduce oscillatory effects and high overshoot percentage to the temperature control system. Hence, a hybrid controller of PID and Fuzzy-Pulse Width Modulation (PWM) can be implemented in order to provide an alternative solution to the downside of both controllers in terms of temperature control. The hybrid control would have the advantages of both controllers which produces minimum overshoots and undershoots, short rising time and short settling time. Therefore, the aim of this research is to compare and analyses the performance of a hybrid controller comprised with Fuzzy-PWM and PID control methods in regulating temperature during torrefaction process. Firstly a design and development of lab-scale heater for the torrefaction process has been fabricated. Secondly, develop PID controller by adding combination of PID and fuzzy-pulse width modulation (Fuzzy-PWM) control algorithm into the system. Since the project is modelled in an oven and heating process is performed inside a laboratory, the study is limited to temperature classification which is in range of 100 °C to 200 °C.

REVIEW OF PID AND FUZZY

PID [9] control system structure, the error signal, $e(t)$ generates the needed proportional,

integral, and derivative actions. Combining all resulting signals together, a control signal, $u(t)$ is obtained and applied to the model plant. The mathematical description of a PID control algorithm is as shown in Eq. 1:

$$u(t) = K_d e' + K_p e + K_i \int e dt \quad (1)$$

Where $u(t)$ is the output control force, K_d is the derivative constant gain, K_p is the proportional constant gain, K_i is the integral constant gain, e is the system error between the expected and actual outputs, e' is the derivative of the error and $\int e dt$ is the integral error. The output of $u(t)$ (The scale PID output) is being used to control the duty cycle of the generation of the generated PWM signal. Fuzzy controller acts in a way where it calculates the error value by the difference between set point value and current value which is similar to PID controller. The error value is used as the input function for a fuzzy controller. A fuzzy logic system is comprised of four major sections; fuzzifier, rule base, inference engine and defuzzifier. Fuzzification process involves the fuzzifier, rule base and inference system to calculate the membership value. Defuzzification process is executed in order to obtain the PWM value for the heating element which acts as the output for the temperature control system. A rule base can be used to adjust the output variable in fuzzy logic. The fuzzy rule base can consist of a simple condition and conclusion in an IF-THEN rule. Singhala, Shah and Patel, (2014) proposed that a fuzzy rule for the temperature control system. While Castillo et. al. (2019) proposed that a fuzzy controller optimization techniques are performed and compared.

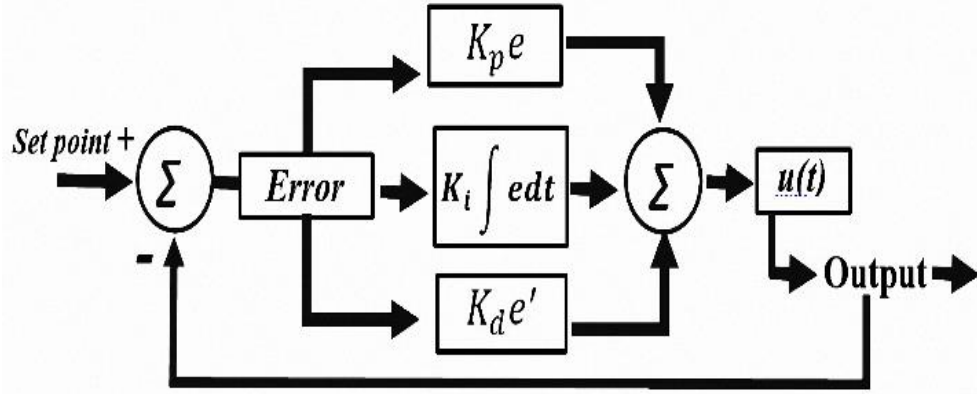


Figure.1: An illustration of a typical PID control system [9]

Table 1: Fuzzy logic rule for the temperature control. [5]

Rule Number	IF-THEN Statements	
	Antecedent	Consequence
1	IF (temperature is low or too low) AND (target value is warm)	THEN system is in the heating process
2	If (temperature is high or too high) AND (target value is warm)	THEN system is in the cooling process.
3	IF (temperature is warm) AND (target value is warm)	THEN system is in the heating process.

METHODOLOGY

The closed-loop oven heater system is configured with hardware as well as software components. The microcontroller acts as the temperature controller and performs the computation for the PID and fuzzy control algorithms. Solid state relay acts as an electronic switch which switches on or off when the small signal is applied across the control terminals. As shown in Fig. 2 the output of the SSR relay switch which is control the AC voltage applied to the oven heating coil and the hardware set up. The temperature of the oven was raised different temperatures from the range of room temperature to 200 °C at a heating rate of 0.5°C per second. A stainless steel probe K-type thermocouple is chosen since it is more related to the industry standard. The temperature is validated via an infrared (IR) digital thermometer (Aidbucks A530). The varying of AC voltage power supply is controlled by the on or off switching of solid state relay (SSR Relay). The small DC voltage applied to the terminals of the solid state relay is in terms of pulse width modulation (PWM) signal which is sent by the microcontroller. The microcontroller has PWM digital output signal pins which allow it to send PWM signals that vary the output voltage signal in the range of 0 V to 5 V. The percentage of PWM duty cycle is obtained and calculated using the formula as shown in Eq. 2.

$$\text{Duty cycl} = \frac{\text{Desired } ^\circ\text{C} - u(t) \text{ output}}{\text{Desired } ^\circ\text{C}} * 100 \quad (2)$$

Before the completed oven of the heating process begins, Fig. 3 shows the separated components used are tested in order to validate their reliability in terms of sensitivity and functionality. One of the most important components in the oven heater system is the thermocouple unit used to detect and measure the temperature level in the oven from time to time. Fig. 4 shows that temperature level detected by the thermocouple is shown on the data acquisition software monitor which is 34.5 °C. The temperature is validated via an infrared (IR) thermometer which shows a temperature of 34.4 °C.

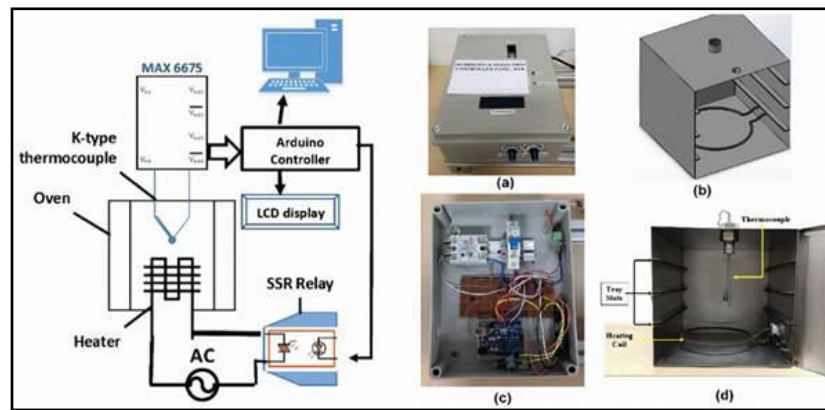


Figure 1: Block diagram for the closed-loop oven (a) LCD panel display (b) Isometric view of the oven heater design, (c) Controller, MAX6675 and SSR Relay, (d) Oven with K-type thermocouple

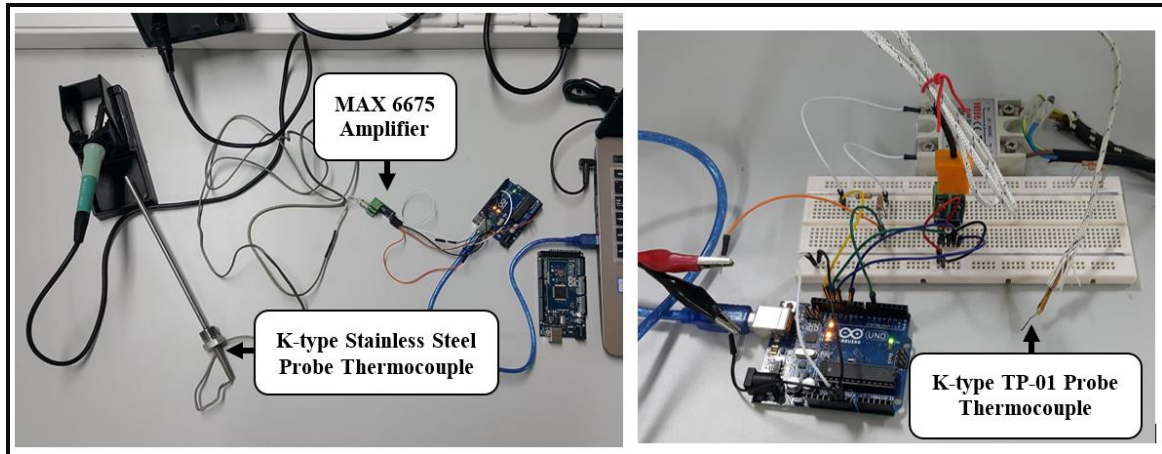
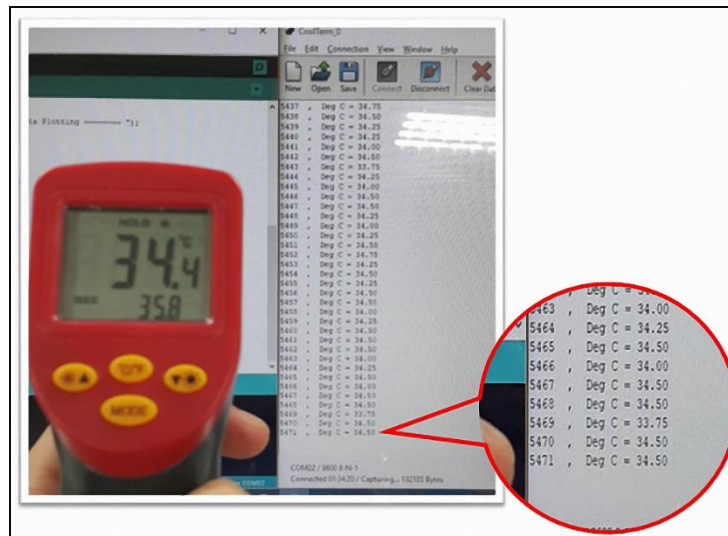


Figure 3: Reliability testing of K-type stainless steel probe thermocouple



(b)

Figure 4: (a) Validation of temperature measurement of thermocouple with infrared (IF) thermometer gun

The oven heater is tested by supplying different PWM duty cycle in heating up to a temperature of 103 °C which is a standard oven drying temperature measurement in ASTM D4442. But the system was tested using 130 °C and 150 °C. The microcontroller acts as the temperature controller and performs the computation for the PID and fuzzy control algorithms. Solid state relay acts as an electronic switch which switches on or off when the small signal is applied across the control terminals. The output of the relay then switches the AC voltage applied to the oven heating coil. The Figure 5 shows a flow chart for a hybrid PID and Fuzzy control algorithm in microcontroller. The performance of PID and Fuzzy controllers are analysed in terms of rise time, settling time, percentage overshoot as well as output energy efficiency. The controller which exhibit short rise time, short settling time, minimum overshoot percentage.

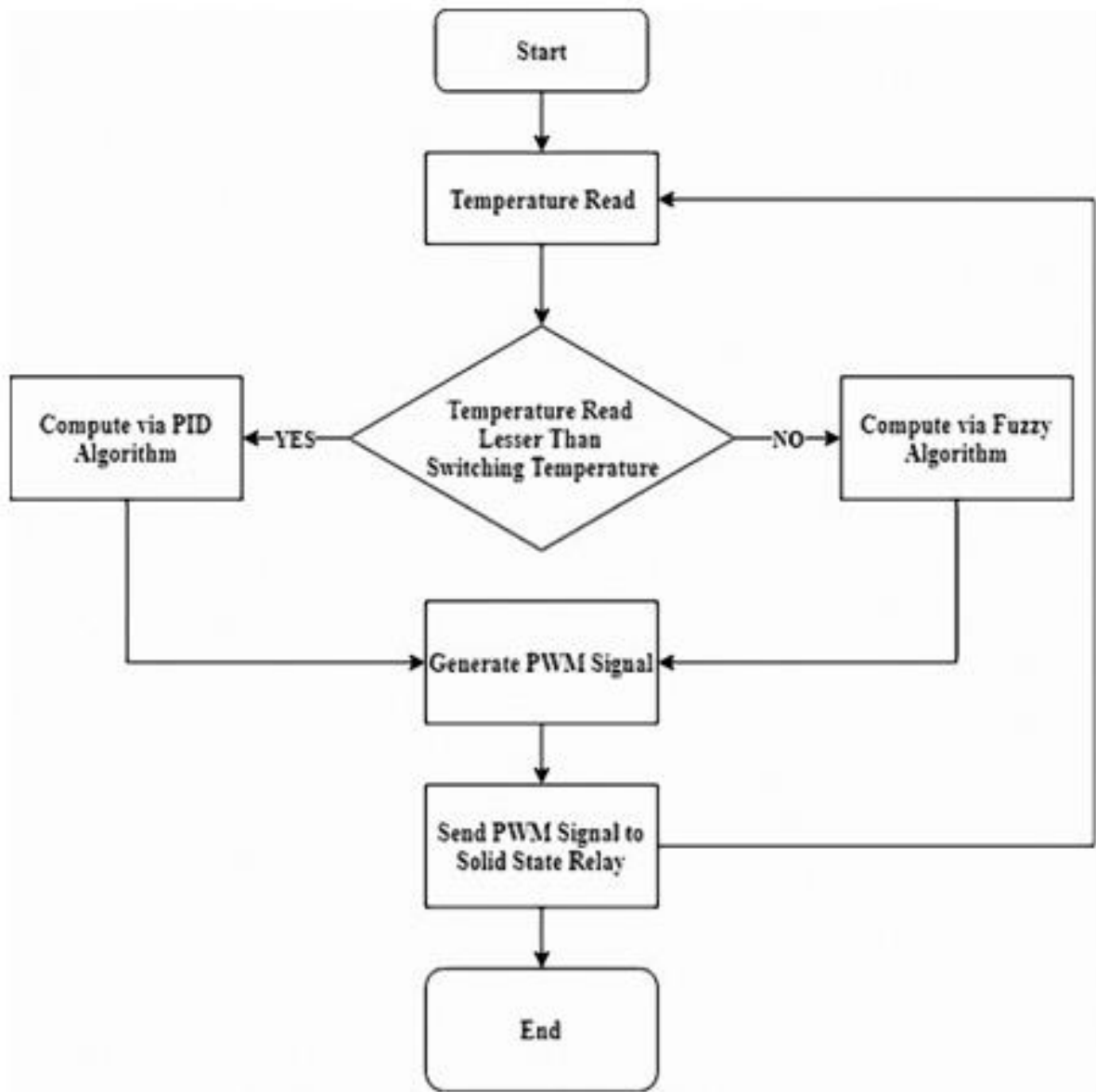


Figure 5: Flowchart diagram for programming of the temperature controller

The most suitable PID controller and fuzzy controller are chosen based on the stated parameters. When both controllers have been selected, a hybrid controller is formed by integrating both controllers into it. The hybrid controller possesses the capabilities of both controllers and temperature control can be done by switching the type of controller used based on the current and desired temperature levels within the oven. Table 2 shows that there are a total of 5 forms of rule base made and tabulated in order to compare and obtain the best fuzzy controller for temperature control. The IF-THEN condition for the rule base is in terms of gap percentage (%). For example, in Rule Base 1, IF the gap percentage between the temperature read and set point temperature is within 0% to 5% margin, THEN the PWM duty cycle supplied will be 30%.

Table 2: Summary of the set of conditions made for each fuzzy controller

Fuzzy Rule	Temperature Set of IF-THEN condition with their PWM duty cycle supply									
Rule Base 1	0 – 5	5 – 20	20 – 30	30 – 40	40 – 50	50 – 60	60 – 70	70 – 100		
PWM Output (%)	30	40	50	60	70	80	90	100		
Rule Base 2	0 – 10	10 – 20	20 – 30	30 – 40	40 – 50	50 – 60	60 – 70	70 – 80	80 – 90	90 – 100
PWM Output (%)	10	20	30	40	50	60	70	80	90	100
Rule Base 3	0 – 5	5 – 10	10 – 20	20 – 40	40 – 60	60 – 80	80 – 100			
PWM Output (%)	30	40	50	60	70	80	90			
Rule Base 4	0 – 5	5 – 15	15 – 25	25 – 50	50 – 70	70 – 85	85 – 95	95 – 100		
PWM Output (%)	30	40	50	60	70	80	90	100		
Rule Base 5	0 – 10	10 – 20	20 – 30	30 – 40	40 – 50	50 – 60	60 – 70	70 – 80	80 – 100	
PWM Output (%)	20	30	40	50	60	70	80	90	100	

Table 3: Tuning Parameters made to PID controller

PID Controller Tuning	Proportional, k_p	Integral, k_i	Derivative, k_d	Description
1	0.9	0.3	0.8	Initial tuning
2	0.45	0.3	0.8	K_p decreases (↓)
3	1.3	0.3	0.8	K_p increases (↑)
4	0.9	0.15	0.8	K_i decreases (↓)
5	0.9	0.45	0.8	K_i increases (↑)
6	0.9	0.3	0.4	K_d decreases (↓)
7	0.9	0.3	0.12	K_d decreases (↓)

Table 3 shows than a total of 7 sets tunings' parameters with K_d , K_p and K_i for the PID controller to be tested, in order to obtain the best PID controller tunings for temperature control.

RESULTS AND DISCUSSION

The temperature control results of PID controller and fuzzy controllers were obtained, the most suitable step response characteristics for controller tuning and rule base is calculated in terms of their rise time, settling time, peak temperature value, peak time and overshoot

percentage. Table 4 shows that the comparison was made between 5 forms of fuzzy rule base conditions set, each rule base output step response is calculated and tabulated. For all rule bases, the percentage overshoot exhibited is low which is in the range of 0.8% to 3.1%. Due to low overshoot exhibited, the fuzzy controller can be said to be a suitable controller for when it is almost reaching the desired set point temperature level in terms of shortest settling time, low percentage overshoot and low peak temperature value. While Table 5 a comparison made between 7 forms of PID tunings parameter, the tuning parameter which offers shortest rise time, lowest peak temperature value, as well as lowest percentage overshoot, is Tuning 4 with PID constants of $K_p = 0.9$, $K_i = 0.15$ and $K_d = 0.8$. PID controllers with Tuning 1, Tuning 3, Tuning 5 and Tuning 6 are not chosen due to their undesirable output step response characteristics. Henceforth, both PID and fuzzy controllers chosen is integrated into designing the hybrid PID and fuzzy-PWM controller.

Table 4: Comparison of different fuzzy controller rule bases set

Fuzzy Controller Rule Bases	Rule Base 1	Rule Base 2	Rule Base 3	Rule Base 4	Rule Base 5
Rise Time, t_r (s)	168.47	-	158.82	176.40	194.72
Settling Time, t_s (s)	378	-	420	420	846
Peak Value ($^{\circ}\text{C}$)	132.00	119.25	134.00	131.75	131.00
Peak Time (s)	306	350	287	312	729
Percentage Overshoot (%)	1.5	-8.3	3.1	1.3	0.8

Table 5: Tuning Parameters made to PID controller

PID Controller Tuning	Tuning 1	Tuning 2	Tuning 3	Tuning 4	Tuning 5	Tuning 6	Tuning 7
Rise Time, t_r (s)	128.1	124.1	125.5	120.6	128.9	124.2	129.2
Settling Time, t_s (s)	648	790	793	454	667	419	412
Peak Value ($^{\circ}\text{C}$)	140.8	142.0	142.5	140.3	141.0	142.0	142.5
Peak Time (s)	232	214	237	230	242	242	239
Percentage Overshoot (%)	8.3	9.2	9.6	7.9	8.5	9.2	9.6

Table 6: Tuning Step response characteristics for PID, fuzzy and hybrid controllers for 130 °C set point temperature

PID Controller	Fuzzy Controller	PID Controller	Hybrid Controller	
			70% Switching	80% Switching
Rise Time, t_r (s)	143	193	169	156
Settling Time, t_s (s)	433.6	670	478	651
Peak Time, t_p (s)	285	338	301	269
Peak Value (°C)	139.5	133.25	133.5	135
Percentage Overshoot (%)	7.3	2.5	2.7	3.8

Table 7: Tuning Step response characteristics for PID, fuzzy and hybrid controllers for 150 °C set point temperature

PID Controller	Fuzzy Controller	PID Controller	Hybrid Controller	
			70% Switching	80% Switching
Rise Time, t_r (s)	169	252	211	176
Settling Time, t_s (s)	453	656	546	565
Peak Time, t_p (s)	300	795	675	403
Peak Value (°C)	155	150	150.75	150.25
Percentage Overshoot (%)	3.5	0.2	0.5	0.2

Table 8: Summary of energy consumed by each controller during oven heating process

Energy Consumption (kWh)	PID Controller	Fuzzy Controller	Hybrid Controller	
			70% Switching	80% Switching
	22,784	19,156	20,192	21,100

The hybrid controller is compared with the conventional PID controller and fuzzy controller. The results are calculated and tabulated in Table 6 and Table 7. According to the Table 7, the hybrid controller with 80% switching levels produces an output with short rise time, short settling time, low percentage overshoot and low peak temperature and peak time. Table 8 represents the energy consumption which was exhibited by each controller is measured with the amount of voltage and current supplied to the heating coil over a period of time.

Different set point temperature would have different switching temperature depending on the switching levels of the hybrid controller. In Fig. 6 and Fig. 7 shown that the set point temperature are 130 °C, the hybrid controller with switching levels of 70% and 80% will switch controllers at 91 °C and 104 °C. In Fig. 8, the set point temperature is 150 °C, the hybrid controller with switching levels of 80% will switch controllers at 120 °C. All the measurement are taken at a sampling rate of 5 seconds over a fixed duration of 900 seconds.

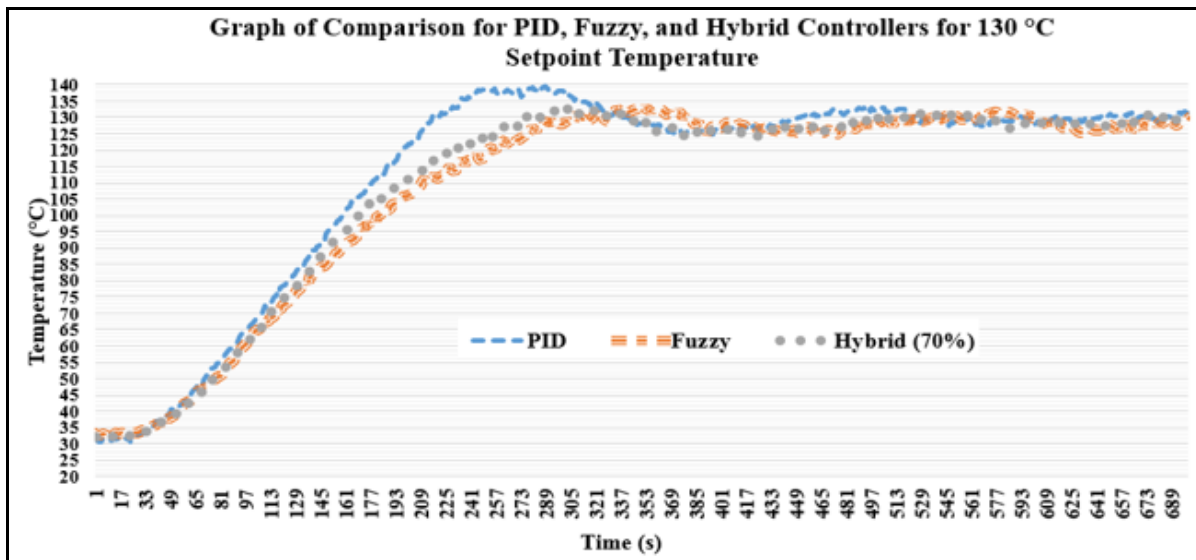


Figure 6: Flowchart diagram for programming of the temperature controller

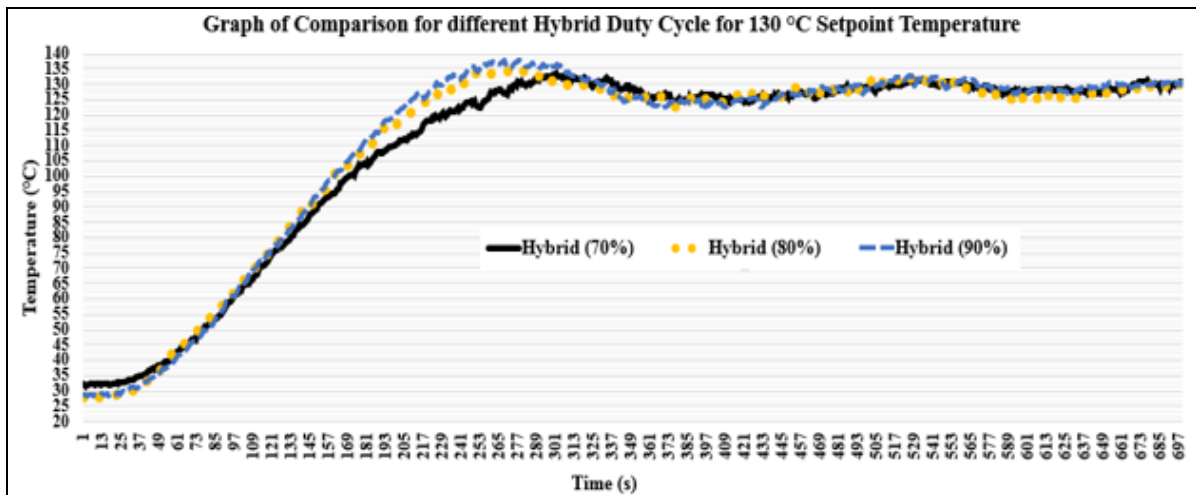


Figure 7: Flowchart diagram for programming of the temperature controller

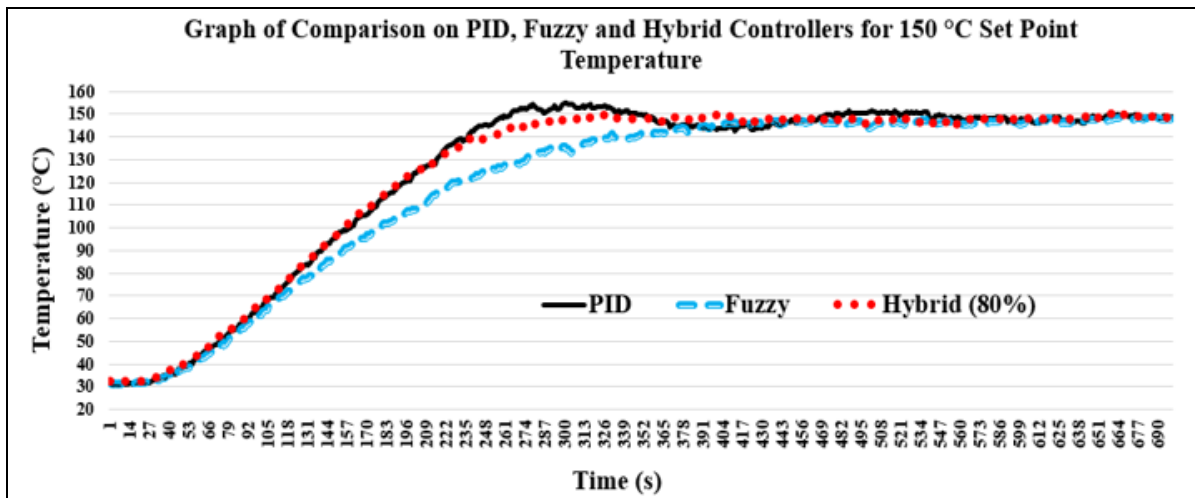


Figure 8: Flowchart diagram for programming of the temperature controller

CONCLUSION

As a result, the hybrid PID and fuzzy-PWM controller possesses the advantage of both conventional controllers in controlling the oven temperature. The hybrid controller exhibits better step response characteristics, especially in eliminating percentage overshoot during heating to the desired temperature level. Not only that, the hybrid controller also offers high flexibility in terms of design, high level of efficiency and higher resistance against unmeasured external disturbance, noises, measurement delays as well as lags in the real environment. A zero crossing detector can be designed and is used to find the AC waveform crossing the zero (0) volt. This experiment was chosen 0.5°C per second to evaluate the effect of PID and fuzzy. Torrefaction is very important as a pre-treatment to the biomass because it can reduce the moisture content and produce a low-molecular-weight oxygen-containing volatile components to improve the HHV. There are three (3) parameters are being effected on biomass structure, operation residence time, heating rate, and the size of biomass. The effect of these parameters of torrefaction influence on the yield and quality of pyrolysis oil. Thus, intensive research on the heating rate between 10-200 °C per second should be studied. Lack of study on optimization of these three (3) parameters for the moisture remover. The optimization of these three (3) parameters of the torrefaction can be optimized using central composite design (CCD) [10]. The influence of the parameters should be investigated after torrefaction chemistry is understood adequately.

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REFERENCES

- [1] H. S. Chua, Mohammed J. K Bashir, K. T. Tan, Chua. H. S, *AIP Conference Proceedings* **2124** 020016 (2019)
- [2] Zi Jun Yong, Mohammed J.K. Bashir, Choon Aun Ng, Sumathi Sethupathi, Jun Wei Lim and Pau Loke Show, *MDPI Processes* **7** 676 (2019)
- [3] Uemura Y, Omar WN, Tsutsui T, Yusup SB, *Fuel* **90** (25) 85–91 (2011)
- [4] Kambiz Arab Tehrani and Augustin Mpanda, *Intechopen* 213-227 (2012)
- [5] L. A. Zadeh, *Information and Control* **12** 94-102 (1968)
- [6] Rupali Kamble, Prof. Deepali Shah, *International Journal of Research - Granthaalayah* **6** (6) 178-188 (2018)
- [7] Foltin, Martin & Sekaj, Ivan. Proceedings of the 7th WSEAS International Conference on Automation & Information, Cavtat, Croatia, June 13-15 pp156-160 (2006).
- [8] I Anshory, I Robandi, W Wirawan and J Jamaaluddin, *Journal of Physics: Conference Series* **1402** 033080 (2019)
- [9] Najidah Hambali, Alaniah Ab. Rahim Ang, Abdul Aziz Ishak, Zuriati Janin, IEEE International Conference on Smart Instrumentation, Measurement and Applications, ICSIMA 2014 7047441 (October 2015).
- [10] Kah Yung, H.S. Chua, J. K. Bashir, F.Y.C. Albert, Sunil Govinda, *J.Mech.Cont.& Math. Sci. Special Issue-1*, 259-270 (2019)