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Process Control in Torrefaction: Design and Experimental Investigation of a Custom Oven using Fuzzy Logic Algorithms

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ABSTRACT

In heating systems, overshoot refers to the phenomenon where the temperature exceeds the intended setpoint prior to stability, resulting in inefficiencies, potential deviations from expectations, and safety hazards. This project introduces a custom-made designed oven (CMDO) utilising Fuzzy Logic Control (FLC). It analyses the behaviour of the CMDO and implements 36 FLC-based rules to minimise overshoot, optimising factors such as rise time and settling time. Experimental studies on the oven are being conducted to analyse its behaviour with varying PWM (Pulse Width Modulation) across a temperature range of 100 to 500 degrees. The oven's performance was evaluated by collecting data using a K-type thermocouple sensor, with temperature readings recorded in a CSV file. The collected data were analysed to assess oven performance, followed by fine-tuning if the performance was deemed unsatisfactory. The implementation of FLC has resulted in an average improvement of overshoot by up to 90% across temperatures ranging from 100 to 400 degrees, with a significant enhancement in settling time at temperatures below 200 degrees. However, temperatures above 300 degrees have exhibited a slight increase in settling compared to conditions without FLC. The results indicate that torrefaction is a more effective pre-treatment method for municipal solid waste (MSW) than the conventional thermal drying process. The torrefaction results were compared with previous research, revealing similar trends and thereby validating the operation and yield of the developed system.

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1. Introduction

Demand for precise temperature control has become increasingly important in industries involved in thermochemical applications such as a thermal pre-treatment torrefaction which plays an important role in production of biofuel [1] .The key features of torrefaction are thermochemical applications, a more hydrophobic and grindable product. Torrefaction process is a thermal treatment process is conducted at atmospheric pressure with a temperature range of 200°C to 300°C. This process transforms biomass into high quality and biofuel with high efficiency [2]. To guarantee consistent product quality, energy efficiency and maximisation of economic viability, temperature regulation during torrefaction is the main point to be focused on. Awaludin Martin *et al.,* assert that a torrefaction process can enhance the higher heating value (HHV) [3]. When HHV is low, the incineration cannot maintain its temperature. Torrefaction is a pretreatment method used to reduce moisture and improve the characteristics of materials in order to increase energy production. Torrefaction is a thermochemical process that involves isothermal pyrolysis of municipal solid waste (MSW) to reduce volatiles and water (moisture) contents, thereby improving some fuel properties such as density and easier grindability [4]. There are several ways for analysing torrefied materials, including proximal analysis, ultimate analysis, and calorific analysis [5]. Aside from that, the primary characteristics of a torrefaction process are temperature, gas flow rate, and residence time [6].

A precise measurements and regulation of temperature and flow rate are essential in torrefaction process systems. Research finding results indicate that torrefaction markedly enhances the hydrophobicity of biomass, with the degree of enhancement dependent on the biomass type and torrefaction temperature [7]. A minor fluctuation in temperature control is needed for the control system Torrefaction as a pre-treatment has beneficial effects, such as reducing the oxygen to carbon (O/C) and hydrogen to carbon (H/C) ratios of municipal solid waste (MSW), hence enhancing gasification efficiency and perhaps improving fuel and supply reliability[8]. A study by Banaget *et al.,* demonstrated that torrefaction is an excellent method for treating solid wastes, specifically food waste and plastics, for biofuel production. Torrefaction transforms these feedstocks into char, which possesses advantageous qualities as a fuel source. The majority of the physical and chemical features of the sample were improved, particularly in reducing moisture content and volatile matter, while simultaneously increasing the carbon content of the sample [9]. Analytical techniques such as proximate analysis and thermogravimetric analysis (TGA) are frequently utilised to assess the characteristics of torrefied materials. The studies must comply with ASTM standards, specifically ASTM E7852:2015, to ascertain the moisture content (MC), volatile matter (VM), fixed carbon (FC), and ash content (ASH) of municipal solid waste (MSW) materials [10] .

Several temperature controllers now available in the market may be appropriate for application in a torrefaction process system. These temperature controllers comprise the Yokogawa PLC controller [11] and the OMRON PLC and PID controller [12], both of which are competitively priced. Additionally, there are studies and experiments made on temperature controllers utilising a Raspberry Pi, which may be more pertinent to the controller employed in this project. Ate and Abdelrahim developed a Raspberry Pi-controlled temperature regulation system to maintain a steady temperature within a chemical reactor vessel at the appropriate level [13]. Perdanasari *et al.,* developed an advanced system with a Raspberry Pi 4 as the primary controller. The developed system is a control mechanism for regulating temperature, humidity, and ammonia levels in egg-laying hen farms, utilising the principles of the Internet of Things (IoT) [14]. The PID controller is the primary technique employed in temperature control applications [15,16]. Their susceptibility to errors from noise and disturbances renders PID controllers prone to inaccuracies, such as prolonged settling time.

Fuzzy logic control (FLC) operates based on human reasoning to execute decisions. Variables have values ranging from 0 to 1 which represents the degree of true and false. These variables are known as linguistic variables. Each linguistic variable will be described by a membership function which will have its designated degree of membership depending on what is the temperature of the system for example. Human or expert knowledge are being implemented into fuzzy rules where decision making will take place[17,18]. Fuzzy sets and fuzzy logic constitute the foundation of fuzzy mathematics. In addition to mathematics, Fuzzy Logic is extensively utilised throughout other industries, including chemical science, agriculture, and domestic applications [19] . Several steps should be emphasised during the fuzzy inference process. Initially, a concise input will be provided. Upon detecting the precise input, the fuzzification process will ensue, during which the crisp input will be transformed into linguistic variables by the application of membership functions. Consequently, rule evaluation will be conducted, during which IF-THEN rules will convert fuzzy input into fuzzy output within the fuzzy inference engine. Finally, the imprecise output from the fuzzy inference engine will undergo a defuzzification procedure, wherein it will be transformed into a precise output utilising membership function[20]. This research focuses on implementation of Fuzzy Logic Based control system for customed designed oven for torrefaction process. To ensure reliable torrefaction process, the system seeks to increase temperature stability, reduced overshoot and improve overall efficiency. By utilising FLC, this study aims to provide a viable alternative to traditional PID control methods by overcoming issues and challenges of torrefaction process.

2. Methodology

2.1 Fuzzy Logic Algorithm

The control system's block diagram is illustrated in Figure 1.

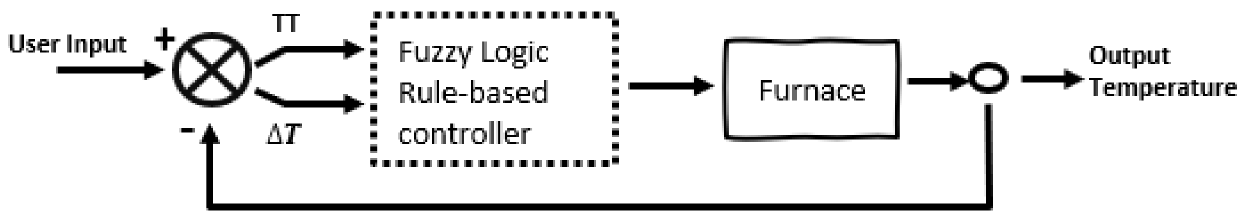


Fig. 1. Block diagram of furnace temperature control

where TT is the desired temperature specified by the user, ΔT is the change in temperature measured in degrees Celsius between the current temperature and user target temperature.

The temperature fuzzy variable is divided into fourteen (14) fuzzy sets: Minimum(MIN), Bare Minimum(BM), Minimum Heat(MH), Low Heat(LH), Gentle Heat(GH), Moderate Heat(MH), Stable Heat(SH), Balanced Heat(BH), High Heat(HH), Intense Heat(IH), Very Intense Heat(VIH), Strong Heat(SH), Near Max heat(NMH), and Max. while the change of temperature (ΔT) is divided into nine (9) sets: 0%-9%, 10%-19%, 20%-29%, 30%-39%, 40%-49%, 50%-59%, 60%-69%, 70%-79%, and >80%. Table 1 presents the temperature variables and their corresponding values within a fuzzy set. The number of inputs in this system has an input temperature sensor and the change in temperature measured in degrees Celsius between the current temperature and user target temperature. The fuzzy domain set variables can be seen at Table 2. The domain pulse width modulation (PWM) signal outputs of the temperature control are divided into fourteen (14) sub-domains as listed in Table 2.

Table 1
Temperature fuzzy rule set variable

Temp Diff °C Temp°C	Between 0 and 10	Between 10 and 20	Between 20 and 30	Between 30 and 40	Between 40 and 50	Between 50 and 60	Between 60 and 70	Between 70 and 80	Above 90
0 to 99	MIN	BM	MH	GH	MH	STH	HH	VIH	MAX
100 to 199	MIH	MH	BH	HH	IH	SM	VIH	NMH	MAX
200 to 299	LH	STH	BH	HH	IH	VIH	SH	NMH	MAX
300 to 400	LH	BH	BH	HH	IH	VIH	SH	NMH	MAX
400 to 500	VIH	VIH	VIH	VIH	SH	NMH	NMH	NMH	MAX
>500	NMH	NMH	MAX	MAX	MAX	MAX	MAX	MAX	MAX

Table 2
The fuzzy rule set variable for the PWM temperature control

Fuzzy rule	MIN	BM	MH	LH	GH	MH	SH	BH	HH	IH	VIH	SH	NHM	MAX
PWM signal outputs	1%	3%	5%	11%	15%	20%	30%	40%	50%	60%	70%	80%	90%	100%

Fuzzy rules are undergoing evaluation through data collecting from the oven at various temperatures for study. Following investigation, regulations are being adjusted based on the obtained data to achieve optimal oven performance. When the oven's output is unsatisfactory, fuzzy rules are modified until the desired performance is achieved. Upon achieving performance benchmarks, rules are integrated into the system, and more data collecting occurs for subsequent analysis of the applied rules. Upon the completion of data collection, both datasets, with and without FLC, will be subjected to comparative analysis and further examination. Fourteen distinct PWM pulses were supplied to the furnace to determine the heating rate of the temperature control. The 14 waveforms were restructured within the heating rate domain to derive a linear equation, facilitating the calculation of PWM pulses corresponding to the specified heating rate, which is required for the user. Figure 2 illustrates the project's methodology, begins with the identification of the issue statement and the execution of an extensive literature review on existing control methods and their limitations.

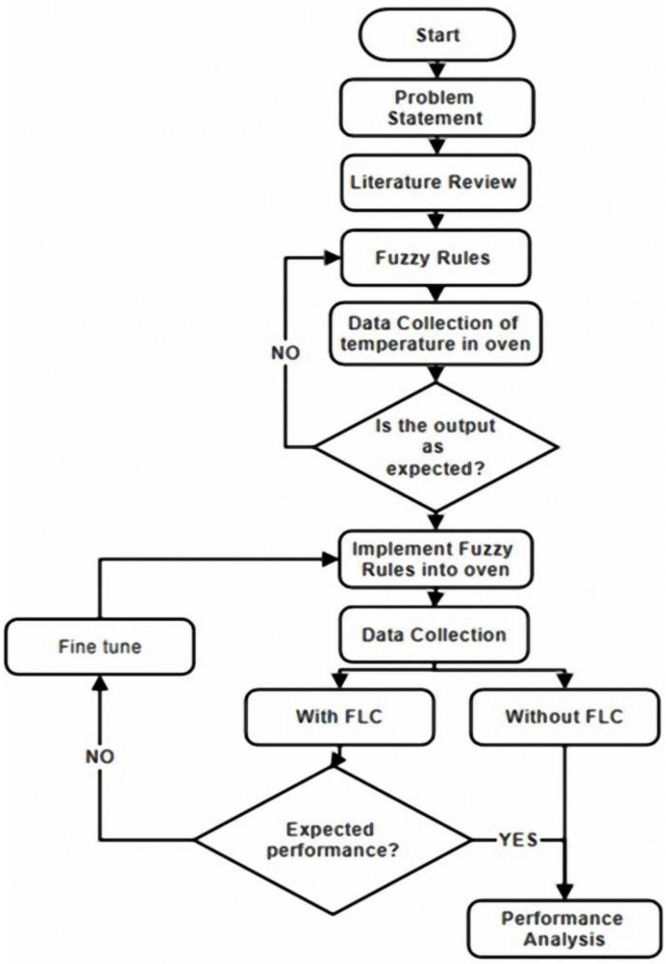


Fig. 2. Flow chart of methodology

2.2 Preliminary Moisture Content Assessment

Kumar *et al.,* was employed ASTM E-871 standard method to determine the moisture content [21]. Taib, R. M. *et al.,* carried out a study on the high moisture content's influence on the biochar [22]. Therefore, it is crucial to pre-treat the moisture contents [23]. The moisture content was determined using Eq. (1). The drying pre-treatment was conducted in an IKA Oven 125 to facilitate a comparison with the results from this custom-made furnace. The duration parameter was used 160°C at 6 hours [24].

$$\textit{Initial Moisture content (MC\%)} = \frac{W1-W2}{W1} \times 100 \tag{1}$$

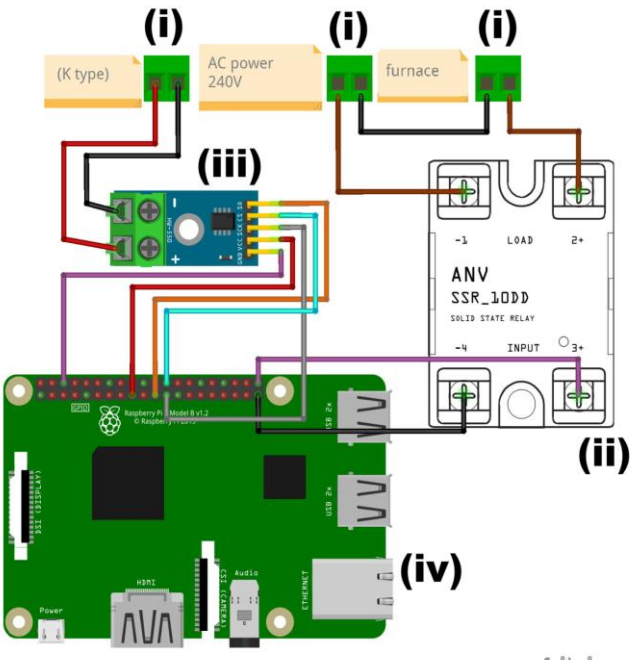
whereas the initial dry feedstock was computed by subtracting the initial dry weight of the feedstock from its first wet weight.

2.3 Material MSW Experiment Preparation

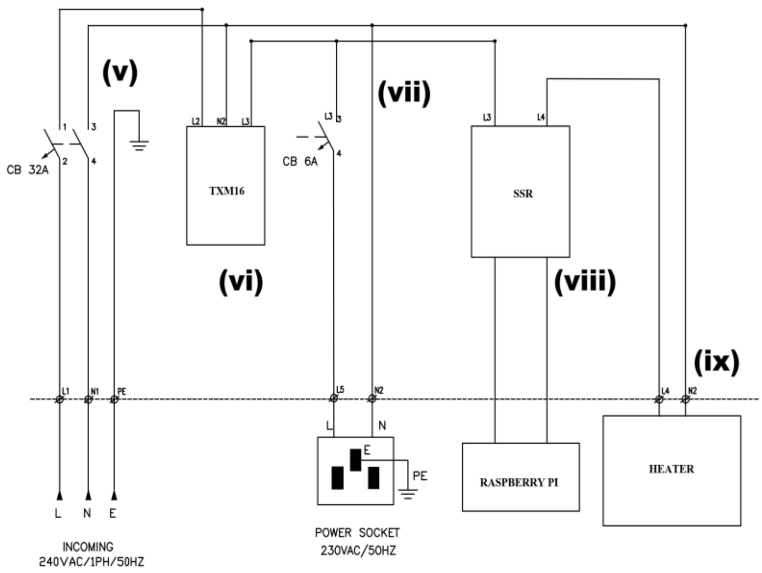
Cheng *et al.,* [25] conducted a study that published the municipal solid waste composition data in the journal Sustainability. The study examined the characteristics of municipal solid waste produced in three major Malaysian municipalities: Kuala Lumpur, Penang, and Melaka. A 200g MSW feedstock blend was used in the pre-heat treatment experiments. The largest portion of the pie represents organic food waste, accounting for 56.96% of the total mass. This category is further divided to show the specific materials and their contributions: apple skin, mango skin, carrot, rice, cabbage, and orange skin, each with their corresponding percentages and masses. The remaining portions of the pie chart represent plastic (16.46%), diapers (15.19%), and paper (11.39%). Metals, glass, wood, and others were exclusive in these experiments.

2.4 Diagram Connection of Raspberry Pi

Figure 3(a) shows the connection of raspberry pi with all the components used for this entire system with K type thermocouple sensor connecting to MAX6675 ADC module connecting to the raspberry pi for data collection and real time temperature updates. The MAX6675 driver connects to the GPIO pins: GPIO 9 is connected to the DO pin, GPIO 8 is connected to the CS pin, GPIO 11 is connected to the CLK pin, Broadcom SOC pin 6 is connected to the ground, and Broadcom SOC pin 17 is connected to 3.3Vdc power. With AC power source of 240VAC connecting to SSR (Fotek 40A solid state relay (SSR)) and oven, raspberry pi is responsible for the switching of PWM of the oven using the SSR controlling the temperature of oven. Fritzing is used to draw the schematic diagram. Figure 3(b) illustrates the single line diagram of the electrical connection for the oven panel, which is supplied by a 240VAC single-phase power source, with a 32A circuit breaker and a 6A circuit breaker for the power socket that powers the Raspberry Pi.



(a)



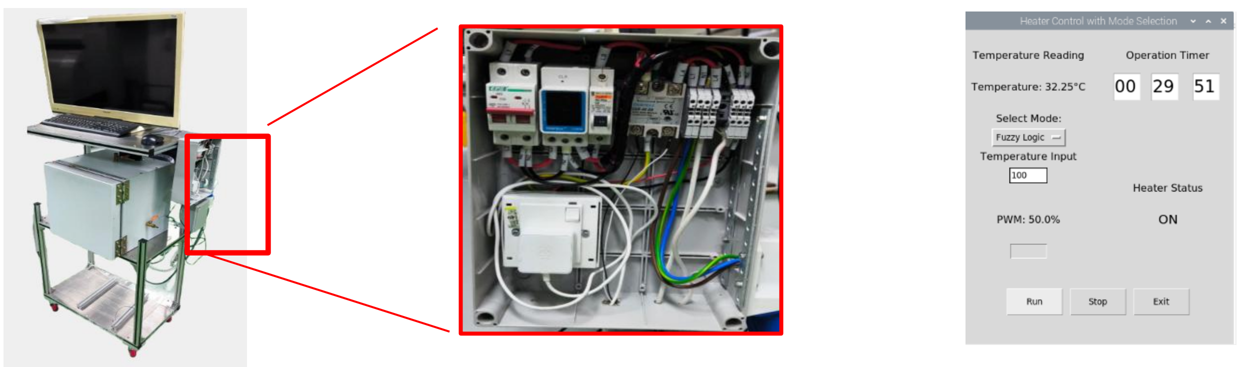
(b)

Fig. 3. The Schematic diagram of circuit connection. (a) Internal Raspberry Pi 3 wiring connection, (b) Internal power wiring connection, (i) Terminal connector, (ii) Fotek 40A solid state relay, (iii) K-type thermocouple MAX6675 driver, (iv) Raspberry Pi 3, (v) Miniature Circuit Breaker (MCB), (vi) Current and voltage meter, (vii) Earth Leakage Circuit Breaker (ECLB), (viii) Fotek 40A solid state relay, (ix) Custom made furnace

3. Results

3.0 Custom-Made Furnace

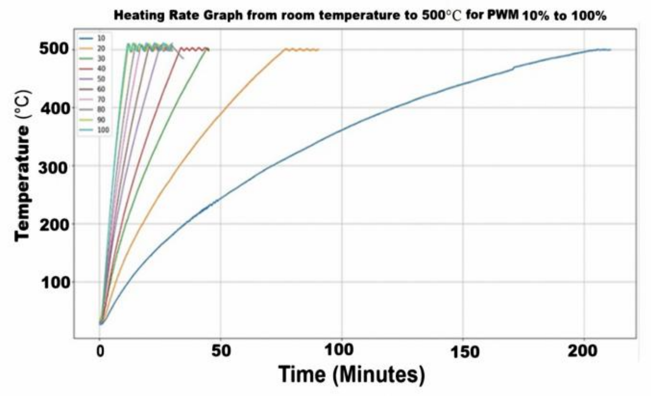
Figure 4(a) shows the overall setup of the oven on top of a customed made aluminium profile stand with monitor and keyboard being connected to raspberry pi for controlling and data collection. Powering the entire system is the electrical panel shown at Figure 4(b) with single line diagram showcasing the overall connection of the system with electrical supply of 240VAC single phase and 32A circuit breaker and 6A circuit breaker for power socket powering the controller (raspberry pi). Figure 4(c). displays a Python programme GUI that includes an option for users to select several heating modes. The heating rate is an adjustable parameter that requires user input for temperature, measured in °C /min.



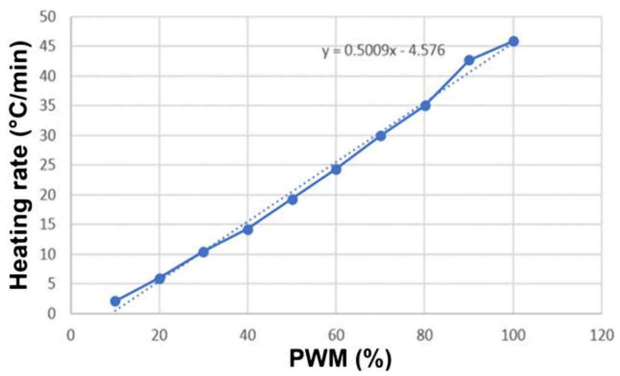
(a) (b) (c)

Fig. 4. (a) overall setup, (b) single line diagram, (c) Python GUI

3.1 Pulse Width Modulation (PWM) Experiment



(a)



(b)

Fig. 5. (a) combine plot of oven from 10 to 100% PWM (b) Equation of PWM% heating rate

Figure 5 (a) above shows the composite plot from 10 to 100% PWM with 10% PWM having a substantially slower steady state time compared to higher PWM percentage. With higher PWM percentage such as 80% and above have a significantly faster steady state time with oven temperature reaching 500°C at a much faster period. Based on these collected data, it was developed a linear equation of $y = 0.5x - 4.576$, where x is the PWM (%) and y is the heating rate (°C/min). This equation represents the behaviour of the oven relative to heating rate and PWM (%). With higher PWM having a high heating rate and with a lower PWM having a lower heating rate summarising the behaviour of the oven.

3.1 Different PWM (%) Responses from 100°C to 500°C

Figure 6 illustrates the combined plot of PWM 100% responses from 100°C to 500°C, indicating that lower temperatures, such as 100°C, exhibit a greater overshoot compared to higher temperatures, specifically 400 to 500°C. Elevated temperatures, ranging from 400 °C to 500°C, exhibit less overshoot because attaining these higher temperatures necessitates greater more power to heat up, leading to a reduced overshoot compared to lower temperatures.

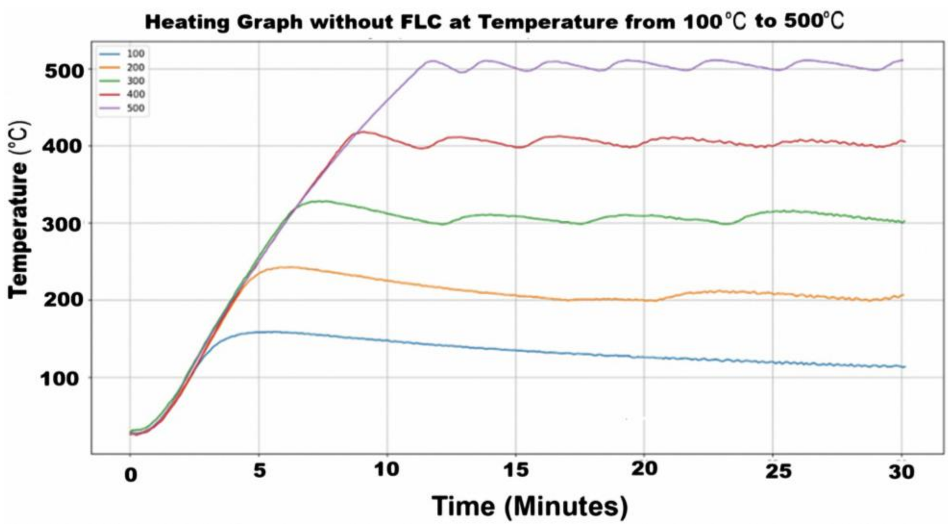


Fig. 6. 100% PWM responde from 100°C to 500°C

3.2 Pulse Width Modulation (PWM) Control with a Fuzzy Logic Algorithm

Figure 7 illustrates the combined temperature plot with FLC ranging from 100°C to 400°C. The temperatures ranging from 100°C to 400°C exhibit minimal overshoot following the implementation of a temperature control system. Nevertheless, at elevated temperatures, the settling time increases with temperature control due to the regulated environment; the rate of temperature rise is slower, particularly at set temperatures exceeding 300°C, while lower temperatures, such as 100°C and 200°C, exhibit superior overall performance under FLC.

The step response from 100 to 400°C, using FLC, exhibits minimal overrun across all temperatures. As previously stated, high temperatures exhibit a prolonged settling period in contrast to lower temperatures, as evidenced by lower temperatures, such as 100°C, attaining the designated temperature at a significantly faster rate than higher ones.

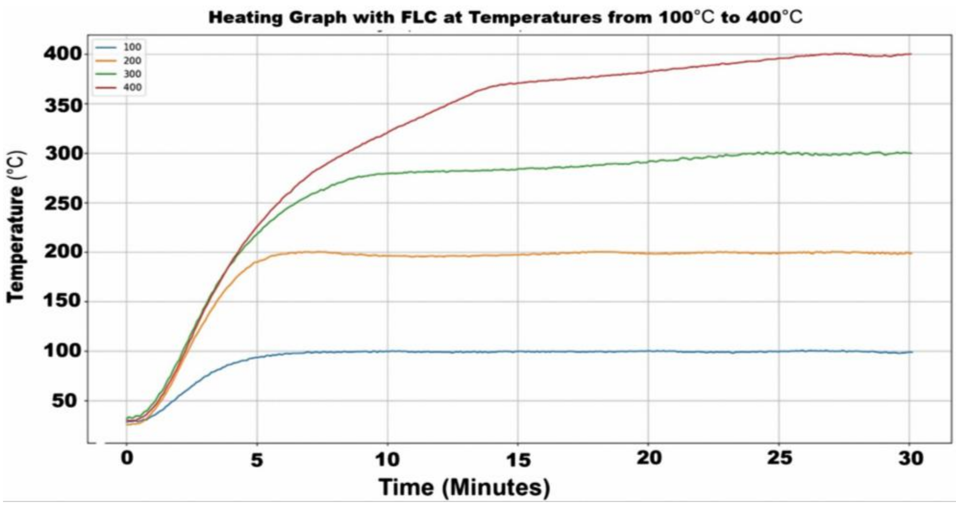


Fig. 7. FLC PWM(%) responses at 100°C, 200°C, 300°C and 400°C

3.3 Damping Responses of a Fuzzy Logic Algorithm

Table 3 indicates that, in without the presence of FLC, rise times at high temperatures become longer due to the additional duration necessary to attain the significantly higher set temperature. The settling time at lower temperatures is significantly greater than at higher temperatures, attributable to a higher overshoot; for instance, at 100°C, the overshoot is 33.66%. In contrast, at 300°C, the settling time is reduced due to a smaller overshoot, indicating that the temperature can attain the set point more rapidly. Nevertheless, elevated temperatures will lead to increased settling time due to the more energy required for the oven to reach the specified high temperature. Increased temperature correlates with less overshoot.

With FLC, the rise time will likewise increase as temperature increases, as the higher temperature requires additional energy to achieve heating. The settling time increases with the rise in set temperature. Nevertheless, the overshoot at all temperatures is almost 0%. When comparing scenarios with and without FLC, the overshoot has been markedly reduced making it advantageous for the torrefaction process, while the settling time has notably improved, particularly at lower temperatures ranging from 100°C. Upon comparison of both tables, FLC has effectively lowered overshoot by 97.65% at 90.24% at 200°C. Higher temperatures of 300 and 400°C have demonstrated enhancements approaching 100%. FLC has enhanced settling time by up to 80.79% at 100°C and 69.03% at 200°C. Marginal increase in settling time at high temperatures over 300°C.

Table 3
Damping performance FLC implementation

	Without FLC			FLC implementation		
Temp (°C)	Rise time (S)	Settling time(S)	Overshoot (%)	Rise time (S)	Settling time(S)	Overshoot (%)
100	24.935	277.226	33.66	35.016	53.257	0.79
200	39.112	201.789	18.45	40.810	62.525	1.80
300	45.441	142.572	6.72	82.298	147.254	0.01
400	68.468	179.796	3.10	146.237	267.667	0.02

3.4 Damping Responses of a Fuzzy Logic Algorithm

Table 4 presents a comparison between the industrial oven IKA 120 and the custom oven (thermal treatment employed in this experiment; the results show weight reduction percentages of 51.34% and 52.38%, respectively.

Table 4
Verification of moisture pre-treatment process

Experiments	IKA oven 125	Custom-made furnace (thermal treatment)	Custom-made furnace (Torrefaction treatment)
Weight before pre-treatment	200 grams	200 grams	200 grams
Weight after pre-treatment	97.23 grams	95.25 grams	91.68 grams
Moisture Loss (%)	51.34%	52.38%	54.16%

4. Conclusions

This study employed a Raspberry Pi controller, a Fotek 40A solid state relay (SSR), a MAX6675 driver, a K-type thermocouple, a customised electric heating element, and several safety components to demonstrate the construction of a lab-scale fixed bed torrefaction dryer. The torrefaction dryer operated within a temperature range of ambient to 400°C, achieving a maximum heating rate of 45°C/min. A linear equation was established and integrated into the programming to calculate the requisite PWM (Pulse Width Modulation) for producing the appropriate heating rate. The moisture analysis was found to differ by approximately 2% (thermal treatment) and 3% (Torrefaction treatment) when compared to IKA 200.

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