Microcontroller-Driven Temperature Control for Superior Coffee Roasting

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Microcontroller-Driven Temperature Control for Superior Coffee Roasting

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Abstract: *This research developed an automatic coffee bean roasting machine using stainless steel 304 and an Arduino Mega 2560 microcontroller. The machine's frame, made of stainless steel 304, features a door for easy access. A repurposed grill heating element serves as the roaster. Inside, a stainless-steel wire mesh cylinder holds the beans and rotates via a step motor connected to an axis. A tray at the bottom collects the coffee bean flakes. The study experimented with three roast levels: light, medium, and dark. For a light roast, the beans were roasted at 200-250 °C for 375 seconds. The medium roast was done at the same temperature range but for 400 seconds. The dark roast required a temperature of 200-265 °C for 440 seconds. The Arduino Mega 2560 was programmed to automate the heating and motor control. The results showed consistent coffee beans with good taste and a strong coffee aroma.*

Keywords: Coffee Roasting; Roasting machine; Controller; Temperature control.

1. INTRODUCTION

The development of tools and equipment to facilitate agricultural work is crucial for increasing efficiency, improving product quality, and reducing production costs. Modern technologies help manage resources by reducing labor and time, thereby increasing income and productivity. For example, a coconut coir compressing machine [1] compresses coir into bricks for easier storage and transport, helping farmers manage waste and earn extra income. Similarly, a cocoa bean crusher [2] improves efficiency in separating cocoa beans from pods on small-medium farms in the Philippines, significantly reducing the time required.

Coffee is a highly popular agricultural product, valued for its unique taste and aroma. Coffee consumption has become a cultural staple, making high-quality production a priority for many producers and distributors. The flavors of coffee arise from various factors, including brewing methods, environmental conditions, and roasting techniques. Roasting has three primary levels: light, medium, and dark, each identified by the color and surface texture of the beans. Light roasted beans are light brown with no oily surface, medium roasted beans are rich brown with a slight sheen of oil, and dark roasted beans are deep black with heavily oily surfaces. These differences result from varying roasting durations, significantly impacting flavor profiles [3,4,5].

In 2007, J.A. Hernández studied the heat and mass transfer processes during the roasting of Colombian Arabica coffee beans [6]. The research identified two phases: drying and roasting. The drying phase occurs at temperatures below 160°C, while roasting happens between 160°C and 260°C. The study used hot air flow to roast Colombian green Arabica beans, with experiments conducted at a constant air velocity of 4 m/s and air temperatures ranging from 190°C to 300°C for 10 minutes. Results were analyzed for weight loss and temperature over time, with a model calculating the output air temperature (Tcas).

In 2013, Henry Schwartzberg focused on reducing energy consumption in coffee roasting [7]. Schwartzberg suggested heating the Catalytic afterburner feeds within the afterburner itself instead of the roaster furnace, potentially decreasing energy usage by 30% to 40% through sequential heat transfer from the roaster stack gas to different components.

In 2019, Satrijo, Yeni, and Mira researched the effects of temperature and roasting time on the quality of ground Robusta coffee using a Gene Café roaster [8]. The study used a randomized block design with two factors: roasting temperature (225°C and 250°C) and roasting time (10, 15, and 20 minutes). Analysis showed that higher temperatures and longer roasting times decreased water content, antioxidant activity, yield, and color, while increasing ash content, caffeine levels, browning index, and sensory qualities (aroma and taste). The best results were achieved with a roasting temperature of 225°C and a roasting time of 20 minutes.

This research involves the design and development of a coffee bean roasting system using a microcontroller to automatically control the desired roasting levels. A microcontroller-driven temperature control is essential for this coffee bean roasting system to ensure precise and consistent roasting levels. By automating temperature control, the system can accurately achieve the desired light, medium, and dark roast profiles, crucial for enhancing the flavor and aroma of Arabica coffee beans. This precision helps maintain high-quality standards, meeting consumer expectations and industry demands. Additionally, the ability to consistently reproduce specific roast levels increases efficiency and reduces human error, leading to better resource management and improved product quality. Experiment was conducted to find the best temperature and time for roasting Arabica coffee beans at three different levels: light roast, medium roast, and dark roast. Due to the continuous gaining in popularity among consumers worldwide, this research is of great importance in the industry by helping enhance the quality of coffee, which, in return, greatly satisfies both new and old consumers.

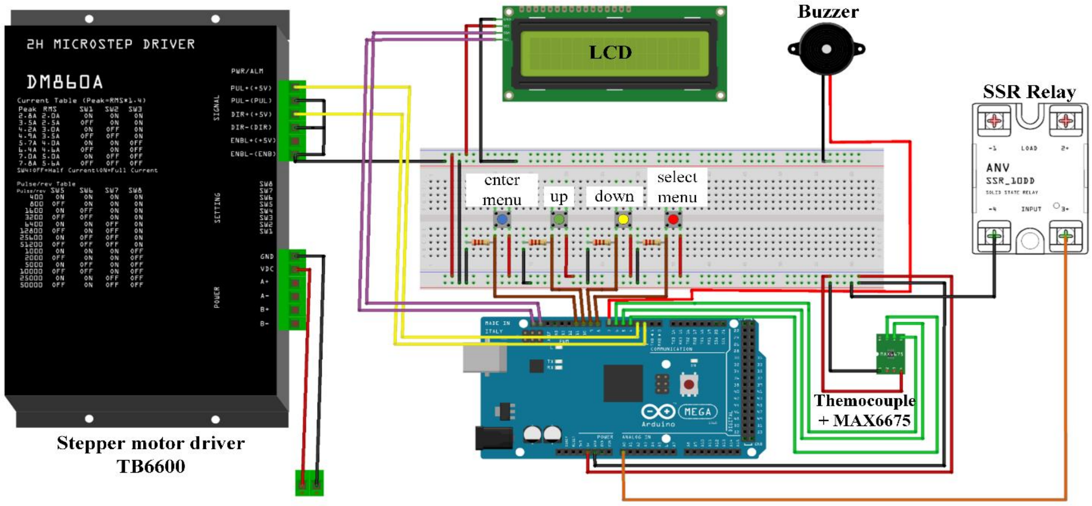

Fig. 1. Circuit connection of the various devices for the coffee bean roasting machine.

2. PRINCIPLE

The design and construction of the coffee bean roasting machine using a microcontroller to control the temperature and roasting time. In this research, we use the microcontroller called "Arduino Mega" which control the entire system's operation. The connection and control of various devices are shown in Fig.1. The operating principle of each device are as follow:

2.1 Thermocouple

Thermocouple can work with multiple different applications such as engines, heating system and hydraulics. Inside the thermocouple there are 2 different thermocouple materials connected at one end and the other end is connected to a terminal block then a voltmeter can be used to read the voltage difference between the 2 thermocouple materials as seen in Fig.2. When the thermocouple is connected to the voltmeter and applies heat on the junction, it causes the atom and molecule to be excited which form the material structure and due to the difference in heat from one end to the other, this allows the free electron to escape to the colder side.

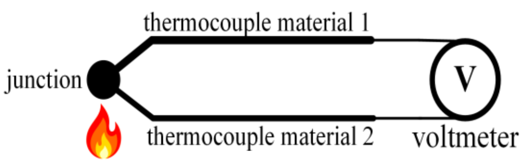

Fig. 2. Thermocouple structure.

Thermocouples are available in different temperature ranges which can be categorized by the 4 letters: J, K, E and T. Each type uses a different type of material which serves many different purposes in terms of temperature reading such as Type J ranges from 0 celsius to 760 celsius and uses Iron + Constantan as their main material. Type K ranges from -200 celsius to 1260 celsius and uses Nickel-Chromium + Nickel-aluminum as their main material. Type E ranges from -200 celsius to 860 celsius and uses Nickel Chromium + constantan as their main material. Type T ranges from -200 celsius to 370 celsius and uses copper + constantan as their main material. Among these, the most commonly used one is Type K.

2.2 Analog to Digital Converter

Analog to Digital Converter or ADC is a system that converts an analog signal, such as light entering camera, into a digital signal. An ADC can also convert analog input of either voltage or current into a digital number representing the magnitude of the voltage or current. The output is a two's complement binary number that is proportional to the input given. In this research, the thermal couple output is a voltage which is an analog signal in which uses to process in the Arduino which needed to be converted into digital signal. In this study, max6675 is chosen for converting the analog output from the thermal couple and send the digital bits to Arduino mega 2560 as seen in Fig.3. The max6675 ADC specifically addresses this need by integrating cold junction compensation and converting thermocouple type K signals into a 12-bit SPI™-compatible digital format. This format provides precise temperature readings with a resolution of 0.25 degrees Celsius, supporting temperatures up to 1024 degrees Celsius. The device ensures accuracy within specified limits, notably between 0 and 700 degrees Celsius, and is packaged in a compact 8-pin SO format, making it suitable for various industrial and measurement applications. Max6675 has a library that is compatible with all architectures so you should be able to use it on all the Arduino boards. To verify accuracy, a thermometer is used to compare alongside the thermocouple type k, yielding consistent results, as depicted in Fig. 4. The thermometer read temperatures at a slower rate compared to the thermocouple, however measurement is very similar.

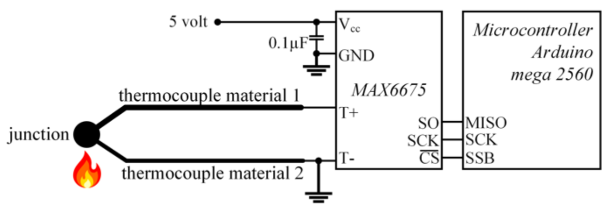

Fig. 3. Circuit with max6675.

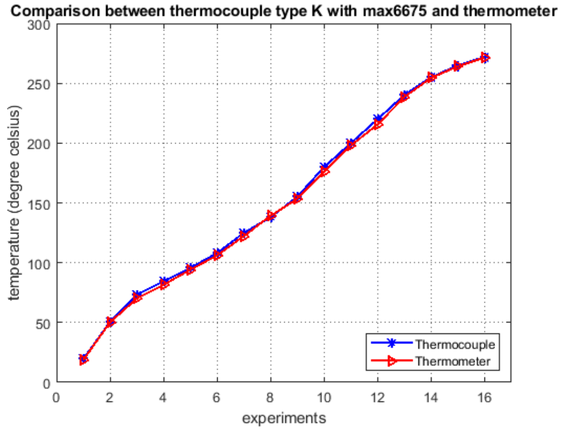

Fig. 4. Comparison between thermocouple type K with max6675 and thermometer.

2.3 Solid-State Relay

A Solid-State Relay (SSR) is an electronic device that functions as a switch without mechanical contacts. It is used for cutting or connecting circuits. SSRs are semiconductor devices that operate similarly to relays but without the clicking sound or mechanical wear associated with traditional relays. They do not have physical contacts, which eliminates the risk of contact arcing and allows for quieter operation. The operation of a SSR can be understood in two main parts as seen in Fig.5 when viewed from the outside: the control part and the complete circuit part. In the control part, when a direct current (DC) voltage between 3-32V is applied, an LED sends a signal to trigger the Triac, which then switches the circuit in the complete part. This functionality is like a relay but offers advantages such as faster circuit switching, absence of mechanical contacts, reduced noise, and longer lifespan. SSRs can handle higher current loads compared to traditional relays and are more durable over time, as they do not suffer from contact erosion or arcing. In this context, Solid State Relays are used to control the operation of heating coils, ensuring precise and stable temperature control during coffee bean roasting. This capability is crucial for achieving consistent and high-quality roasting results in coffee production.

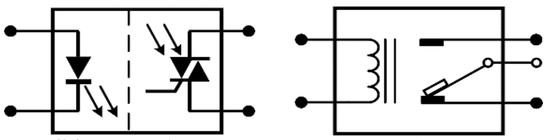

Fig. 5. Solid-State Relay.

2.4 TB6600 Stepper motor driver

A stepper motor is a brushless DC electric motor that divides a whole rotation into equal steps, providing precise control over its location. To control a stepper motor, a driver like the TB6600 is used. The TB6600, as shown below in Fig.6, is compatible with Arduino and other microcontrollers that can generate a 5V digital pulse signal. It has a power input range of 9 to 42VDC and can provide up to 4A peak current. The driver allows you to manage the speed and direction using 7 micro-step settings and 8 current control options, all of which are programmable via DIP switches, allowing it to achieve a controlled environment that's perfect for a roasting coffee bean.

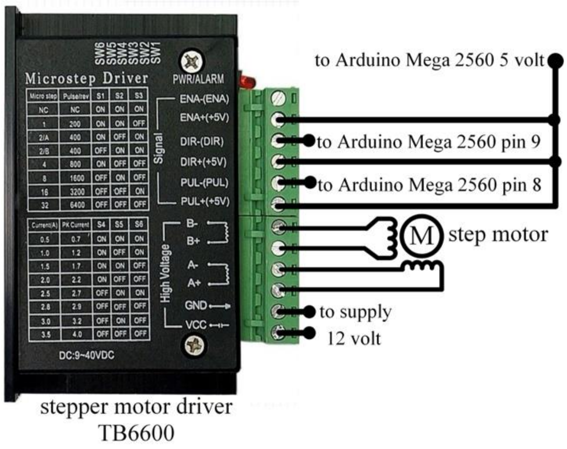

Fig. 6. TB6600 stepper motor driver.

Stepper motor speed is proportional to the frequency of pulse signals given to the driver. The desired rotational speed can be calculated using the formula provided in Equation (1).

$$N = \frac{\theta s}{360} \times f \times 60 \quad (1)$$

N is speed of the motor output shaft in rpm, θs is step angle in deg/step, f is pulse frequency in Hz. The following illustrates the relationship between pulse frequency and motor speed, as shown in Fig. 7.

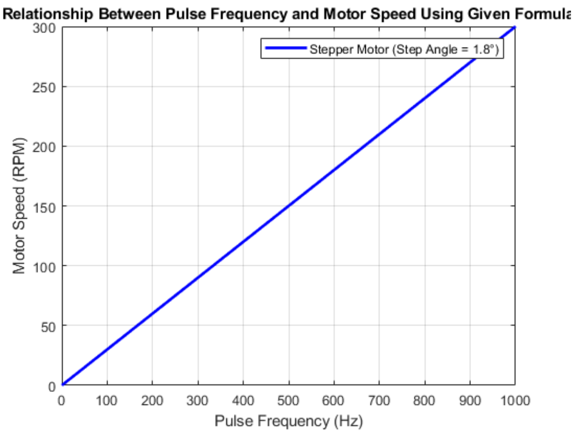

Fig. 7. The relationship between pulse frequency and motor speed.

3. METHODOLOGY

3.1 Coffee Roaster Design

In the design process, the heating element of an electric grill was taken out and used to make a coffee bean roasting machine to reduce the costs of coffee machines and as a learning experience. The heating element was then changed to be used to roast coffee beans, and a grating cylinder was placed into a frame with the possibility of the cylinder being removed for cleaning easily. The frame is made from stainless steel 304 with its walls insulated with materials. A door is placed in front for ease of access. The prototype of the coffee bean roasting machine is shown in Fig. 8.

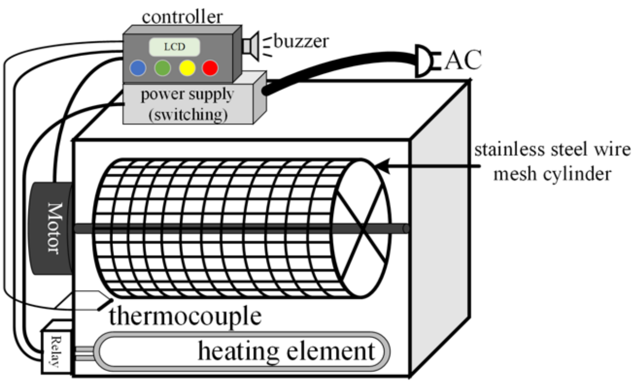

Fig. 8. The prototype of the coffee bean roasting machine.

3.2 Coffee Bean Roasting Experiment

The coffee bean roasting machine is experimented on to find different results. A tray was inserted at the bottom of the oven to catch coffee bean flakes. To test this machine a temperature sensor type thermocouple type K was placed inside the bottom of the oven. 100 grams of coffee beans are placed in a 5 mm stainless steel wire mesh cylinder and a constant rotation speed of 50 revolutions per minute ensures continuous and uniform screening, then the heat is turned on inside to oven in a variety of temperatures, the smell and color were observed upon completion. Experiment results are shown in Table 1.

The Agtron scale was used for the measurement of the color of the coffee beans after the roast. It is a color measurement system to evaluate the color of coffee beans after a roast, with the higher the number the lighter the roast, and the lower the number the darker the roast. With above 75 being a light roast, a 75 – 55 being a medium roast and a 55 – 25 being a dark roast.

The results of the light, medium, and dark roast is compared with coffee beans that are not roasted and the Agtron value. Fig.9 is light beans with an Agtron value of 102.6, Fig.10 is Medium roast beans with an Agtron value of 68, and Fig.11 is Dark beans with an Agtron value of 35.19.

The medium roasts use a temperature of 200-250 degrees Celsius with a time of 400 seconds giving an Agtron value of 68. The characteristic of this roast is that the color of the bean is dark brown with a first crack sound, the smell of almond, with a bitter and sour taste.

The dark roast uses the temperature of 200-250 degrees Celsius with a time of 440 seconds with an Agtron value of 35.19 the characteristic of the dark roast consists of a Dark brown color, easiest to grind, smells like dark chocolate, and no sour taste.

With the results obtained temperature and time are important in roasting coffee which can be written in a graph format with the comparison between temperature and time in each roasting mode. In Fig.12 the blue line represents a light roast, the red line indicates a medium roast, and the black line represents a dark roast.

Fig. 9. The results of the light roast.

Fig. 10. The results of the medium roast.

Fig. 11. The results of the dark roast.

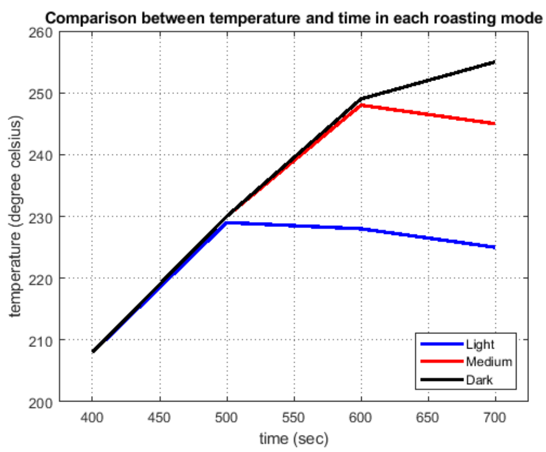

Fig. 12. The measured temperature versus time in each roasting mode.

Table 1. Results of roasting tests on 100 grams of Arabica coffee beans

Number	Temperature (degrees Celsius)	Time (seconds)	Agtron value (Agtron scale)	Characteristics of coffee beans
1	30-50	100	151.2	White color like coffee beans before roasting Beans are hard, sticky, and hard to grind.
2	50-100	200	144.1	Very light brown starts to smell a little bit like coffee, starts to change color
3	100-200	300	127.4	Light brown, little coffee smell
4	200-250	375	102.6	Light red-brown color, first time cracking, crisp acidity, a mellow body, and bright flavors.
5	200-250	400	68.0	Cinnamon brown color, easy to grind, smells like almond, bitter and sour taste.
6	200-265	440	35.19	Dark brown color, easiest to grind, smells like dark chocolate, no sour taste

Table 2. Weight loss ratio for different coffee roast levels

Trial No.	Initial Weight (grams)	Final Weight Light Roast (grams)	Weight Loss Ratio (%) Light Roast	Final Weight Medium Roast (grams)	Weight Loss Ratio (%) Medium Roast	Final Weight Dark Roast (grams)	Weight Loss Ratio (%) Dark Roast
1	100	87	13	85	15	82	18
2	100	88	12	84	16	81	19
3	100	86	14	85	15	82	18
4	100	87	13	83	17	80	20
5	100	88	12	84	16	81	19
6	100	87	13	85	15	82	18
7	100	89	11	83	17	80	20
8	100	87	13	84	16	81	19
9	100	88	12	85	15	82	18
10	100	87	13	84	16	81	19

3.3 Coffee Roaster Machine Efficiency

The efficiency of a coffee roaster is considered a critical measure of its performance, determining whether the roaster is cost-effective overall. Coffee roaster efficiency is evaluated by its roasting efficiency and the proportion of weight loss of the coffee beans from their initial weight. Since both mechanisms are interrelated, the roasting efficiency and the weight loss ratio [9] of the coffee beans from the roaster are calculated using Equations (2) and (3) as follows:

$$\text{Weight Loss Ratio} = \frac{W_{Loss}}{W_{initial}} \times 100\% \quad (2)$$

$$\text{Roasting Efficiency} = \frac{\text{W}_{\text{initial}} - W_{Loss}}{T \times E} \times Q_{output} \quad (3)$$

Where $W_{initial}$ is initial weight of the coffee beans (grams), W_{Loss} is weight loss during roasting (grams), Q_{output} is quality score of the roasted coffee beans (e.g., Agtron Scale or other quality indicators), T is time taken for roasting (seconds) and E is energy used for roasting (watts)

Based on the results from 10 trials using the coffee roasting machine, the average findings are presented in the Table 2. The average findings are as follows: The initial 100 grams of coffee beans resulted in an average weight loss ratio of 12.6% for light roast, 15.8% for medium roast, and 18.8% for dark roast. Then, use these values to calculate the roasting efficiency using Equation (3). The light roast has an efficiency of 91.4%, the medium roast has an efficiency of 82.4%, and the dark roast has an efficiency of 72.3%.

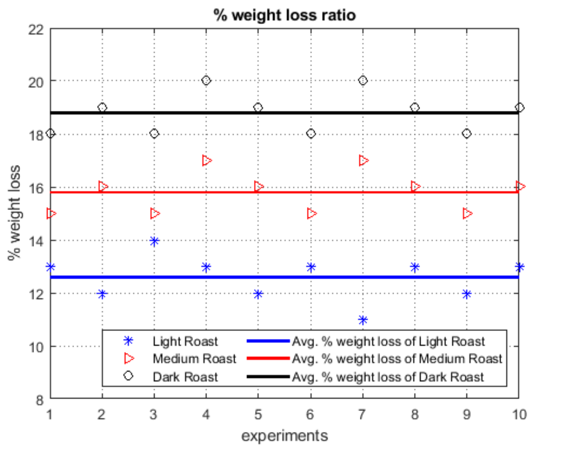

Fig. 13. Comparative weight loss ratios for different coffee roasting levels.

Fig. 13 shows that dark roasting results in greater weight loss compared to light and medium roasting. This is due to the higher temperatures and longer roasting times associated with dark roasts, which lead to more moisture and volatile compounds evaporating from the beans. As a result, the weight of the beans decreases more significantly in dark roasting than in light and medium roasting.

4. THE ROASTING PROCESS

From the previous experiment on determining the best temperature and time for roasting coffee beans, the value then can be used to help design program for controlling arduino mega 2560 to write a flowchart that explains the program needed to run the roasting system as seen in Fig. 14.

"Start" button initiated the start of the program which then display the outputs of "Welcome Coffee Please Enter". To officially start the program, press the blue button as mention on a note down below. After the "blue" button is pressed, it will display an output saying "Coffee roaster selector mode". The mode selection can be navigated using the green and yellow buttons to scroll up and down.

The available modes are as mention below:

1. Light mode
2. Medium mode
3. Dark mode
4. Motor mode

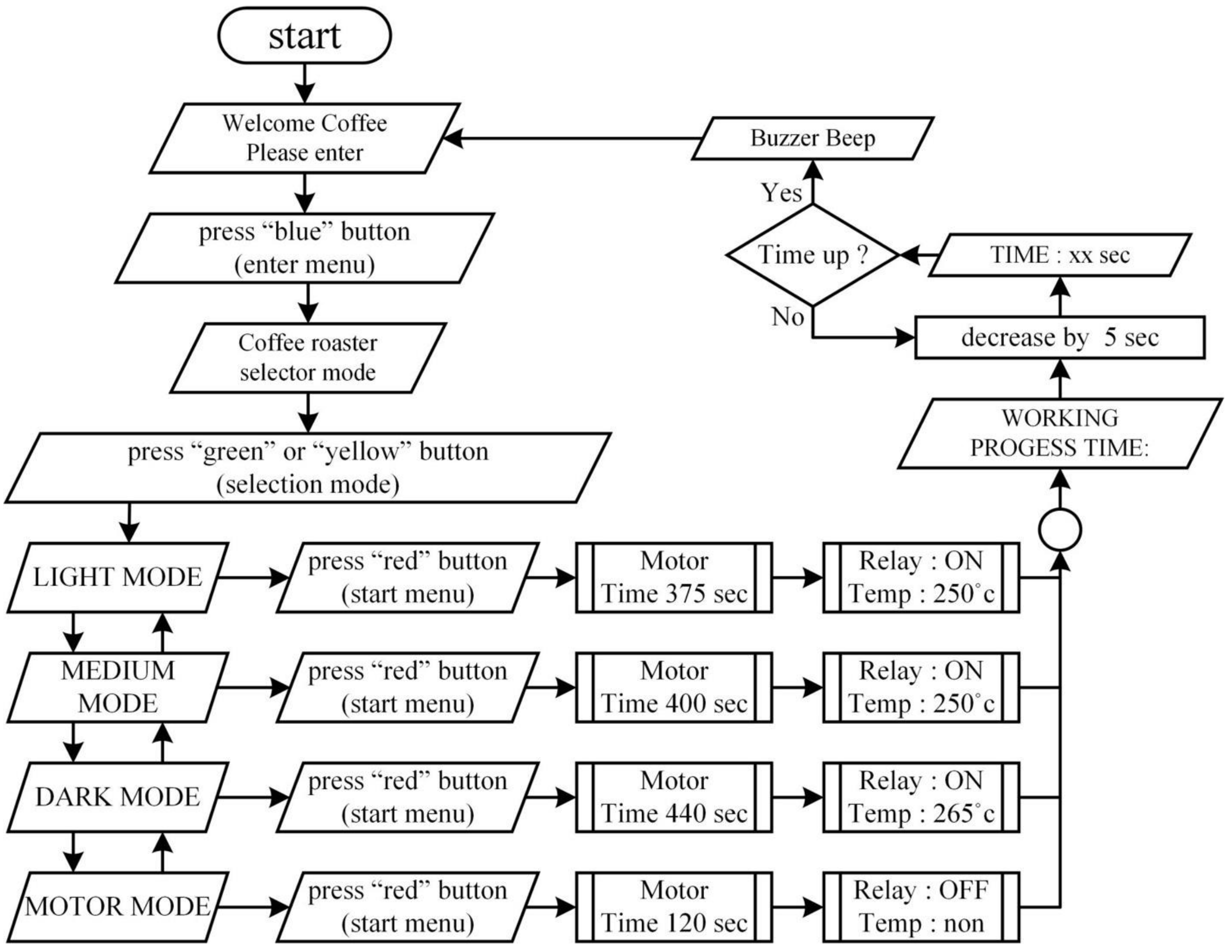

Fig. 14. Coffee bean roaster operation diagram.

In light mode, the motor operates for 375 seconds to continuously roast the beans. The relay is turned on until 240 degrees Celsius and if the temperature drops below the 230 degrees mark, the relay will automatically turn back on to ensure consistent and accurate light roast. In Medium mode, the motor operates for 400 seconds to continuously roast beans until perfection. The relay mode turns on until 240 degrees Celsius ensure consistent and accurate medium roast. In Dark mode, the motor operates for 550 seconds to achieve a perfect deep roast.

The relay is activated at temperatures not exceeding 265 degrees Celsius to ensure consistent maintenance of the desired roasting mode. In motor mode, the motor will run at a consistence speed for another 2 minutes, without any more heating, to help the bean fully remove the flakes.

After choosing the preferred method of roasting, the LCD screen displays "working process time: Time remaining," showing the countdown of the roasting duration, updating every 5 second until the time ran out. When the time is up, the buzzer sound notifies the ending of the process for 5 second which will automatically turn off after and return to the first page "Welcome Coffee Please enter".

5. CONCLUSION

This research aims to design and develop a coffee roasting machine that automatically controls temperature and time during roasting. The automatic system uses an Arduino Mega 2560 to control the heating element by reading the temperature from the temperature sensor Thermocouple Type K. For the light and medium roast, the temperature in the oven must be between 200-250 degrees Celsius, to obtain this temperature the heating element will be turned off before reaching 250 degrees and will turn on before reaching 200 degrees keeping a temperature inside the oven of 200-250. For dark roast, the temperature in the oven is between 200-265 degrees Celsius with the same method for keeping that temperature. The time in each coffee roast varies with each mode. The light mode roasts the coffee beans for 375 seconds, the medium mode roasts the coffee beans for 400 seconds, and the dark mode roasts the coffee beans for 440 seconds. Additionally, a motor mode is made to cool down the coffee beans in which the heating element is off, and the stainless-steel wire mesh cylinder is spinning. This causes the coffee bean flakes to fall to the tray at the bottom of the oven which makes it easy to clean up.

The oven is made of stainless steel 304, with a door attached for access on the sides. There is a stainless-steel wire mesh cylinder in the center of the oven that is rotated at 50 revolutions per minute for roasting. This cylinder can be removed easily to be cleaned. A tray is placed at the bottom of the oven to catch the coffee bean flakes that fall from the spinning cylinder, this tray is also removable for cleaning. The materials used for this machine are cheap, and simple to produce with the programming being a basic program. In total the cost of the coffee bean roasting machine is lower than most automatic coffee bean roasters in the market and easier to roast coffee beans than most manual coffee bean roasters. The results of the roasted coffee beans are consistent with a nice coffee smell and great taste and color which is in accordance with the Agtron scale.

6. REFERENCES

[1] Art M. Dalma, Mercedith B. Denoyan, and Neil Caesar M. Tado, Design, Fabrication, and Performance Evaluation of Village-Type Coconut Coir Dust Compacting Machine, in 8th International Exchange and Innovation Conference on Engineering & Sciences, Kyushu University, Fukuoka, Japan, 2022.

[2] May Rose B. Osoteo, Lois Y. Pajaron, and Arfelyn A. Paque, Development of Cacao Pod Crushing Machine, in 7th International Exchange and Innovation Conference on Engineering & Sciences, Kyushu University, Fukuoka, Japan, 2021.

[3] Andueza, S., Maeztu, L., Dean, B., de Peña, M. P., Bello, J., & Cid, C. (2002). Influence of water pressure on the final quality of arabica espresso coffee. Application of multivariate analysis. Journal of Agricultural and Food Chemistry, 50, 7426–7431.

[4] Andueza, S., Vila, M. A., Peña, M. P., & Cid, C. International Exchange and Innovation Conference on Engineering & Sciences (2007). Influence of coffee/water ratio on the final quality of espresso coffee. Journal of the Science of Food and Agriculture, 87, 586–592.

[5] Belitz, H.-D., Grosch, W., & Schieberle, P. (2009). Coffee, tea, cocoa. In H.-D. Belitz, W. Grosch, & P. Schieberle (Eds.), Food Chemistry (4th ed., pp. 938–951). Leipzig: Springer.

[6] Herna ́ndez, B. Heyd, C. Irles, B. Valdovinos, G. Trystram (2007). Analysis of the heat and mass transfer during coffee batch roasting. Journal of Food Engineering 78, 1141–1148.

[7] Schwartzberg, H. (2013). Batch Coffee Roasting; Roasting Energy Use; Reducing That Use. In: Yanniotis, S., Taoukis, P., Stoforos, N., Karathanos, V. (eds) Advances in Food Process Engineering Research and Applications. Food Engineering Series. Springer, Boston, MA. https://doi.org/10.1007/978-1-4614-7906-2_10

[8] Saloko S, Sulastri Y, MuradRinjani M (2019) The effects of temperature and roasting time on the quality of ground Robusta coffee (Coffea rabusta) using Gene Café roaster. Biosci Biotechnol Biomet. https://doi.org/10.1063/1.5141310

[9] A.K. Zaalouk, "Evaluation of Local Machine Performance for Threshing Bean", Agricultural Engineering Department, Faculty of Agriculture, Al-Azhar University, 2009.