DEVELOPMENT AND PERFORMANCE EVALUATION OF A LIQUEFIED PETROLEUM GAS-POWERED FLUIDIZED COFFEE ROASTER

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PENGEMBANGAN DAN EVALUASI KINERJA PENYANGRAI KOPI FLUIDISASI BERTENAGA LIQUEFIED PETROLEUM GAS

Dadang Dayat HIDAYAT[1], Ari RAHAYUNINGTYAS[1], Diang SAGITA*[1], Maulana FURQON[1], Arie SUDARYANTO[1], Dadang GANDARA[1], Taufik YUDHI[1], Nandang JAENUDIN[1]

[1]Research Centre for Appropriate Technology, National Research and Innovation Agency

Tel: 6285719002251; E-mail: diang.sagita@gmail.com

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ABSTRACT

In this study, a fluidized coffee roaster has been successfully designed, constructed, and tested. This prototype has a capacity of 500 grammes per batch to aid small-scale coffee shops in roasting coffee beans. This fluidized coffee roaster is easy to use, cheap and has an appropriate capacity for the small business requirements. The coffee roasting components of the machine consisted of a blower (600 watts), a heat exchanger, a jet burner, a cylindrical roasting chamber, a chaff and dust collector, and a frame. At a range of airflow of 4-6 m/sec, the average temperature increase in the furnace and roasting chamber was 26 °C and 7.8 °C per minute, respectively. Performance tests revealed that the developed fluidized coffee roaster had been able to roast Robusta and Arabica coffee to light, medium, and dark roasting levels. For Robusta coffee, the time required to achieve light, medium, and dark levels were 8.18, 9.85, and 12.03 minutes, respectively, with final roasting temperatures for each level of 209 °C, 220 °C, and 248°C. For Arabica coffee, the time required was 5.32, 7.67, and 11.72 minutes, respectively with the final roasting temperatures of 207 °C, 210 °C, and 218 °C.

ABSTRAK

Dalam penelitian ini, fluidized coffee roaster telah berhasil dirancang, dibangun, dan diuji. Prototipe ini berkapasitas 500 gram per batch untuk membantu kedai kopi skala kecil dalam memanggang biji kopi. Penyangrai kopi terfluidisasi ini mudah digunakan, murah, dan memiliki kapasitas yang sesuai untuk kebutuhan usaha kecil. Komponen mesin sangrai kopi terdiri dari blower (600 watt), penukar panas, pembakar jet, ruang sangrai silinder, pengumpul kulit ari dan debu, dan rangka. Pada kisaran aliran udara 4-6 m/detik, kenaikan suhu rata-rata di dalam tungku dan ruang pemanggangan berturut-turut adalah 26 °C dan 7,8 °C per menit. Uji kinerja menunjukkan bahwa fluidized coffee roaster yang dikembangkan telah mampu menyangrai kopi Robusta dan Arabika hingga tingkat penyangraian ringan, sedang, dan gelap. Untuk kopi Robusta, waktu yang dibutuhkan untuk mencapai level light, medium, dan dark masing-masing adalah 8,18, 9,85, dan 12,03 menit, dengan suhu akhir penyangraian masing-masing level 209 °C, 220 °C, dan 248 °C. Untuk kopi arabika, waktu yang dibutuhkan masing-masing adalah 5,32, 7,67, dan 11,72 menit dengan suhu akhir penyangraian 207 °C, 210 °C, dan 218 °C.

INTRODUCTION

Coffee is one of popular beverages that have been consumed in more than 70 countries *(Kristanti et al., 2022; Sagita et al., 2022; Velasquez et al., 2018)*. Coffee roasting is the final stage in preparing green bean coffee before grinding, brewing, and consumption. *Green beans* coffee is ripe coffee cherries that have been pulped, hulled, and dried. Before roasting, green beans are green in colour, dense, practically flavourless, and have a beany and grassy aroma. Also, green beans do not smell like coffee. Coffee roasting is a chemically complex process *(Baggenstoss et al., 2008; Chandrasekar & Viswanathan, 1999; Clarke, 1987; Petracco & Viani, 2005; Schenker & Rothgeb, 2017; Zimmermann et al., 1996)*.

Dadang D. Hidayat, M.Eng.Sc.; Ari Rahayuningtyas, M.Sc; Diang Sagita, M.Sc.; Maulana Furqon M.Eng.; Arie Sudaryanto, M.Agr.; Dadang Gandara; Taufik Yudhi; Nandang Jaenudin.

Coffee roasting is a complex heat transfer process responsible for chemical, structural, physical and sensory changes (Darmajana, Hidayat, et al., 2022). The coffee bean undergoes numerous chemicals and physical changes during roasting process *(Baggenstoss et al., 2008; Petracco & Viani, 2005)*. The bean changes in size and colour, produces and loses different volatiles, and produces the well-known coffee flavour *(Dorfner et al., 2004; Hernández et al., 2008; Schenker & Rothgeb, 2017)*. The roasting process aims to augment aroma and flavour; it develops about 800 to 1000 aroma compounds. Roasting can also most significantly increase solubility *(Pérez-Martínez et al., 2008)*. The roasting procedure affects the sensory properties of brewed coffee based on panellist preferences *(Darmajana, Wulandari, et al., 2022*).

There are three main stages in roasting, i.e., drying, browning, and development. The drying stage typically lasts 4–8 minutes. It ends at the temperature of 160 °C with the traditional drum. The drying stage is essential for the bean to get energy because the last roasting stage is exothermic, producing heat. At this point, the coffee begins to smell like toasted bread and hay. This is when the smell-making chemicals start to convert into aroma compounds. Browning occurs as the impact of the Maillard reaction. In the Maillard reaction, reducing sugars and amino acids react to make hundreds of different aromas and colour compounds known as melanoidin. At this point, the roast slows down on its own, and flavour development occurs. When the browning process is complete, the coffee starts to pop. This is called the first crack, which means the development stage has begun. During the development stage, the reaction releases heat, and the coffee starts to crack. The energy built up during the drying and browning stages can cause cracks. Development time is when the desired aroma compounds are developing. At the development stage, the roast must slow down; otherwise, the roasted coffee will be smoky. Depending on the desired flavour profile and roast degree, the development stage usually takes 15–25% of the roasting time *(Latvakangas, 2022)*.

There are different roaster configurations, such as fluidized beds and drum roasters. Usually, drum roasters are used for small roasters *(Hidayat et al., 2020)*, while fluidized bed roasters are used for large roasters. Fluidized bed roasters keep the beans in the air using a blower and roast them inside the roasting chamber, while drum roasters heat beans with hot gas in horizontal or vertical drums with paddles *(Wang & Lim, 2015)*. The roasting procedure most significantly influences the formation of coffee flavour. Subpar roasting techniques can ruin even the highest-quality green coffee beans. There are no guidelines for creating a specific roast of coffee, and each roaster uses a different set of roasting techniques.

Baggenstoss et al. (2008) stated that convection is essential for heat to move when roasting coffee beans because it controls how fast and evenly the beans roast. Fluidized-bed roasters, which use convective heating almost exclusively, can make coffee with a low density and a high yield *(Eggers & Pietsch, 2001)*. On the other hand, coffees roasted in drum roasters mainly use conductive heat transfer and have less soluble solids, more burnt flavour, and more volatile loss than coffees roasted in fluidized bed roasters *(Nagaraju et al., 1997)*. Roasting beans requires a high temperature/long time (HTLT) combination. Because of the high temperatures and longer roasting time (15–18 minutes), some beans get burned, oil and char build up on the walls of the cylinder, and fires happen. Also, the equipment is hard to clean after it has been used, which gives the roasted beans an unpleasant, smoky taste.

Several patents for high temperature/short time (HTST) roasting have been disclosed. The fluidized bed roaster is one of these and is used for extensive roasting of beans used to make instant coffee. The coffee beans in an air roaster float on a bed of hot air in the roasting chamber, keeping the temperature steady throughout the process. A separate section in air roasters captures the chaff, preventing the material from smoking and altering the flavour of the batch. A typical air roaster can roast a batch of green coffee beans in six to eight minutes, whereas the drum method can take up to fifteen. Due to their short time of roasting, air-roasted beans have a purer flavour than drum-roasted beans. Air-roasted beans are roasted "to temperature," a far more exact method for determining when a batch is done roasting. Thus, the roaster can simply replicate batches of coffee beans, recreating the same colour, flavour profile, and aroma *(Latvakangas, 2022)*. Product consistency and improved process parameter control are benefits of fluidized bed roasters. However, handling medium and small batches might be challenging with these devices. In addition, most coffee roasters using hot air use more electricity than the average residential capacity of 900 watts. Therefore, for this study, a fluidized coffee roaster that can hold 500 grammes and runs on liquefied petroleum gas was designed and constructed to support small and medium-sized enterprises.

MATERIALS AND METHODS

The stage for the development of fluidized coffee roaster was carried out by design and prototyping method as also used by many previous publications *(Hidayat et al., 2020, 2021; Sagita et al., 2021)*.

These methods consisted of a general description, sizing and determining the main components, creating technical drawings, manufacturing, and performing the functional test.

Design of the machine

The primary considerations in developing this fluidization-type roaster were a simple design, locally necessary materials, and ease of operation and maintenance. The amount of electricity needed is less than 900 watts, which is about the same as the average amount of electricity used in the community. This coffee roaster is designed for a batch size of 500 grammes. The blower and heat source that use liquefied petroleum gas need 600 watts of electricity. This coffee roaster has a cyclone system for collecting chaff and dust. Figure 1 depicts an illustration of the equipment design.

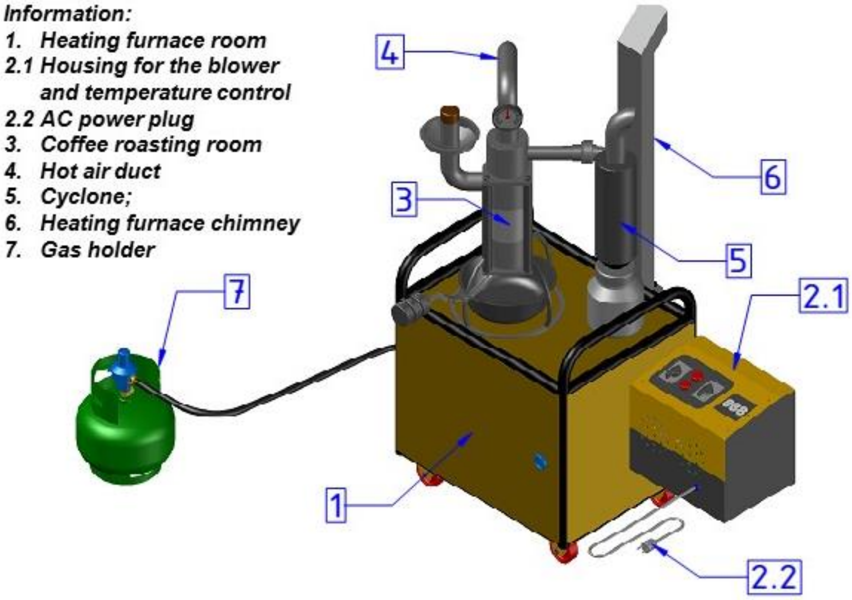

Fig. 1 - An isometric view of a fluidized coffee roaster design

Principle of operation

The blower forces air through a heat exchanger into a pipe inside the roasting chamber to the bottom of the roasting chamber as shown in figure 2.

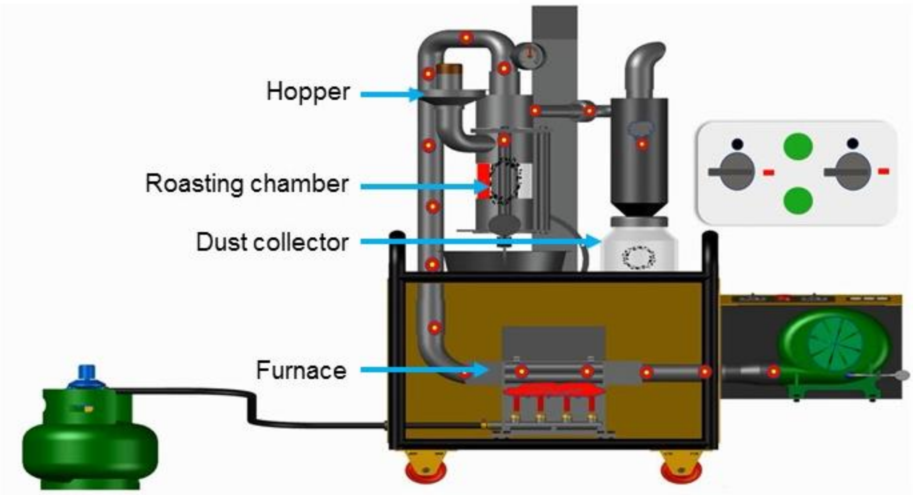

Fig. 2 - Schematic diagram of the roasting principle in the machine

After hitting the bottom of the roasting chamber, the hot air flows back into the chamber to blow the coffee. The hot air that enters the roasting chamber heats the beans through convection, while the evacuated air pressure allows the beans to circulate throughout the chamber, resulting in a uniform mixing and roasting. The temperature of the beans is measured using a thermocouple and digital thermometer. A chaff and dust collector is located in the upper portion of the chamber to collect the chaff and dust that are expelled from the roasting chamber during the roasting process.

Compared to the beans, the chaff and dust of the beans are light enough to rise into the collector. A separator member separates the chaff and dust from the evacuating air, and a cover member directs the chaff and dust into the glass collector and permits further air evacuation from the coffee roaster. At the end of the roasting process, the gas line is shut off to prevent further heating, and the roasted beans are removed from the roasting chamber.

Design consideration

Some considerations taken into account in designing a fluidized roaster system are the type of material used for tool construction, some physical characteristics of green bean coffee, the ratio of the volume of the green bean coffee chamber to the volume of the roasting chamber, the roasting capacity, the temperature of the roasting chamber, the temperature of the heat source, and the necessary electrical power

Heating furnace and blower room

The design of heating furnace room and the blower housing is presented in figure 3. It was made from an iron plate with a thickness of 1.8 mm. The frame was made from an iron pipe with a diameter of 32 mm; the length, width, and height of the heating furnace room were 616 mm, 500 mm, and 503 mm, respectively; and the length, width, and height of the blower room were 350 mm, 263 mm, and 300 mm, respectively. The dimensions of the frame were 632 mm in length, 512 mm in width, and 630 mm in height. The turning radius at the end of the top frame was 63.5 mm.

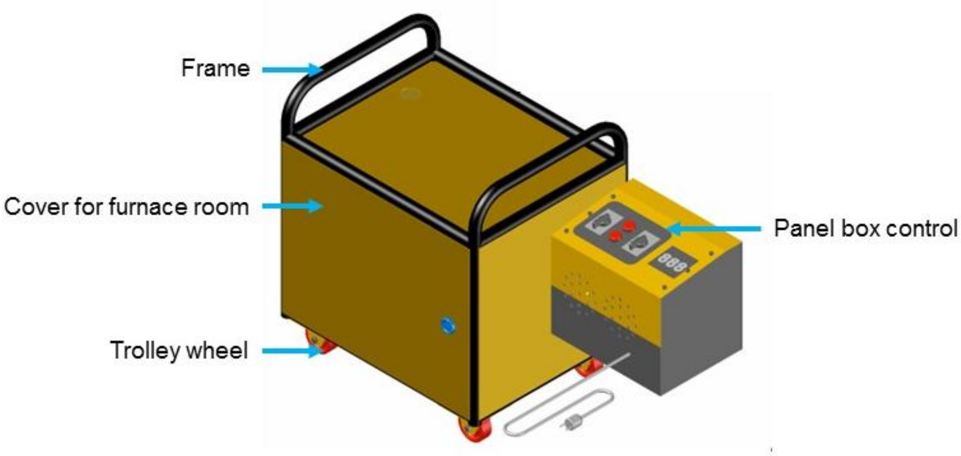

Fig. 3 – Design of heating furnace and blower rooms

Coffee roasting room and hot air duct

The frame of the roasting chamber design is shown in figure 4. This part was constructed from stainless steel 304. The roasting chamber comprises a 110 mm diameter 304 stainless steel pipe and a 110 mm diameter glass globe of a kerosene lamp (Petromax). The diameter of the base of the frame was 300 mm. The hot air supply pipe was made of stainless steel and had a 51 mm diameter.

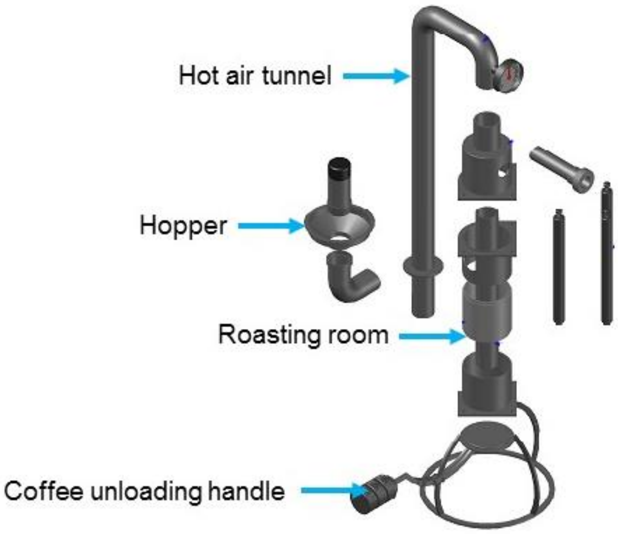

Fig. 4 - Coffee roasting room and hot air duct

Chaffs and dust collector

Material components for the chaff and dust container comprises a stainless-steel pipe with a diameter of 110 mm and a length of 300 mm, as well as a stainless-steel pipe with a diameter of 51 mm and a length of 87 mm. The chaff and dust collection container is a mason jar with a 110 mm top diameter, a 150 mm bottom diameter, and a 190 mm height. The design of this part is presented in figure 5.

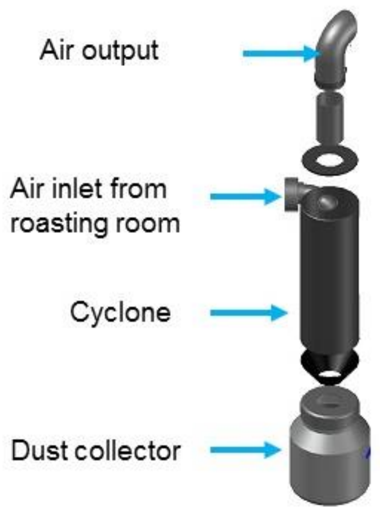

Fig. 5 - Chaff and dust collector

Heating furnace and chimney

The heating furnace comprises a heat exchanger heated by a jet burner fuelled by liquefied petroleum gas. The heat exchanger was constructed from five pieces of iron pipes with threaded iron axles; each iron pipe had a diameter of 25.4 mm and a length of 250 mm. The screw configuration of the heat exchanger was intended to increase the heated surface area to create sufficient heat for the roasting process. The higher the heat transfer efficiency, the greater the overall contact area of the heat exchanger. The chimney had a height of 750 mm and was built of 100x40 mm hollow iron. The exploded view of the heat exchanger and jet burner is shown in figure 6.

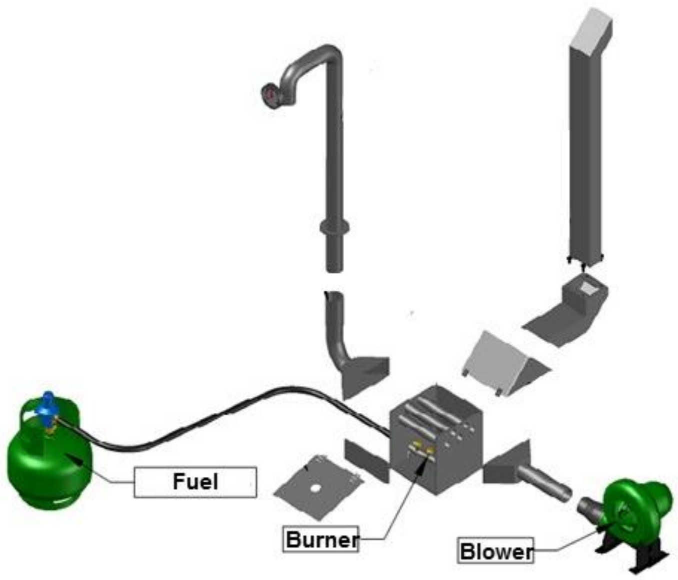

Fig. 6 - Heat exchanger and jet burner

Roasting chamber design

The roasting drum had a capacity of 500 grammes per batch, a bulk density of 0.72 g/mL for green beans, a 50% increase in volume for roasted beans, and a 20% decrease in mass for roasted beans.

Bulk density and percentage of volume growth are required so that the roasting chamber can handle coffee beans whose volume will increase as a result of the roasting process.

Heat exchanger design

The screw type heat exchanger consists of five units of steel pipes with an inside diameter of 25.4 mm, a length of 250 mm and a thickness of 3 mm. Each pipe has a worm screw inside to ensure air can receive more heat as it passes through this pipe. The worm screw inside the steel pipe is made of solid steel with a shaft diameter of 10 mm and a length of 250 mm. The helical spiral's thickness is 2 mm. The illustration of the heat exchanger is shown in figure 7.

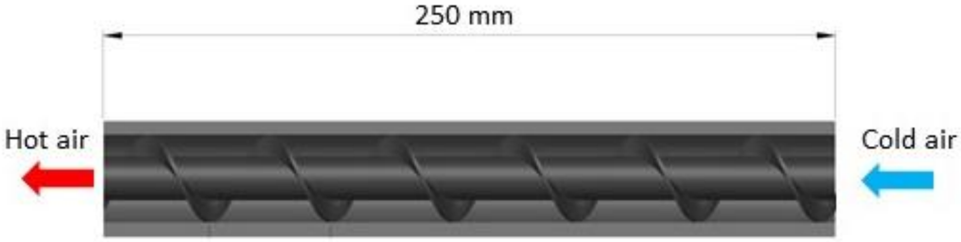

Fig. 7 - Heat exchanger design

Evaluation of the fluidized coffee roaster

The evaluation of the prototype was performed under two conditions (with and without loads). Tests under no-load conditions were carried out to investigate air flow and temperature in the heat exchanger and roasting chamber during heating in the absence of coffee beans. Tools used for observing the temperature was Arduino-based data logger with thermocouple type K (accuracy of 0.5 °C).

Performance tests with load condition were conducted using two types of green coffee beans i.e., Robusta and Arabica coffee. The initial moisture water content of the sample coffee beans ranged between 10-12% wet basis. The evaluation was performed to evaluate the coffee roaster in the context of producing the three levels of roasted coffee (light, medium, and dark). The parameters observed consisted of the time required to reach each level, cracking time, cracking temperature, and final temperature (after the desired roasting level was achieved). Based on the preliminary studies, light levels were obtained 1 minute after 1st crack, the medium was obtained 3 minutes after 1st crack and dark levels were obtained 5 minutes after 1st crack. Each level has been validated by comparing it to L* a* b* colour standard for each level in the preliminary studies.

The coffee roasting procedure for each treatment was started under the same conditions, where the temperature in the roasting room reached 180 °C. After that, the green coffee beans (temperature 30 °C) were added and consequently, the temperature in the roasting chamber dropped below 110 °C. Then the temperature in the roasting room rose again over time.

RESULTS

The prototype of fluidized coffee roasting machine

The prototype of fluidized coffee roasting machine developed in this study is shown in figure 8, and the specifications of the machine are presented in table 1.

Fig. 8 - The prototype of a fluidized coffee roaster

Table 1

The specifications of a fluidized coffee roaster prototype

Parameters	Value/type	Unit
Overall dimensions	982 x 500 x 1390	mm
Roasting Chamber	1948	mm^3
Chaff and dust collector	Ø 60 x 110	mm
Blower	220-380 V, 50-60 Hz, 600 watt, 16000 rpm	-
Burner	Jet burner	-
Fuel	LPG	-
Temperature sensors	Roasting chamber and bean	-
Roasting capacity	500	g

According to a calculation based on the size of the planned roaster and the volume and mass and shape of the coffee bean, the space taken up by the roasted green coffee bean was 28.23% of the total volume of the roasting chamber. Previous publications *(Hadzich et al., 2014)* claimed that the green bean to roasting chamber volume ratio was between 24 and 32%; the current findings of the study demonstrated that the proportion fell within this range. According to another source *(Nagaraju et al., 1997)*, the ratio of green bean to roasting chamber capacity can reach up to 40%. The relationship between the volume of green beans and that of the roasting chamber ensures that the roasted green beans receive sufficient heat and that the coffee roasting process is not interrupted. The mass reduction percentage for roasted beans regulates airflow, so that roasted beans are not transported to the chaff and dust collector.

The heat exchanger consisted of five cylinders, each containing a screw, and had an area of 105 mm2 iron plate with a thickness of 2 mm, a 3.89 x 10^4 mm^2 iron plate with a thickness of 3 mm, and a 78.5 mm^2 iron shaft with a length of 1250 mm; The temperature generated in the heat exchanger reached 650 °C, and 220 °C in the roasting chamber.

Fluidized coffee roasting performance

Figure 9 depicts the performance of a fluidized roaster manufactured under no-load conditions. It was shown that the temperature in the heat exchanger and roasting chamber increased with the time. The temperature in the heat exchanger achieved the temperature of about 650 °C, while the temperature in the roasting chamber was about 200 °C. Generally, the coffee beans were fed into the roasting chamber when the temperature was about 180 °C. By using this fluidized roaster, the targeted temperature value could be reached only in 12 minutes, about 6 minutes faster than using the drum type coffee roaster developed by *Hidayat et al. (2020)*.

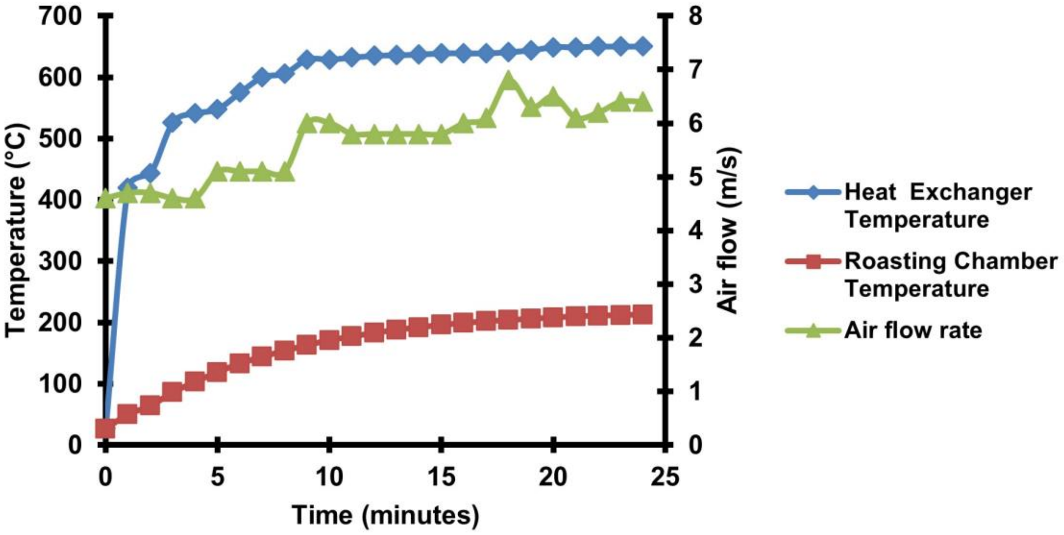

Fig. 9 - Performance of a fluidized roaster fabricated under no-load conditions

Figure 10 present the performance of fluidized coffee roaster using two different type of coffee beans (Robusta and Arabica). At a range of air flow 4-6 m/sec, the average temperature rise in the furnace and roasting chamber was 26 °C and 7.8 °C per minute, respectively.

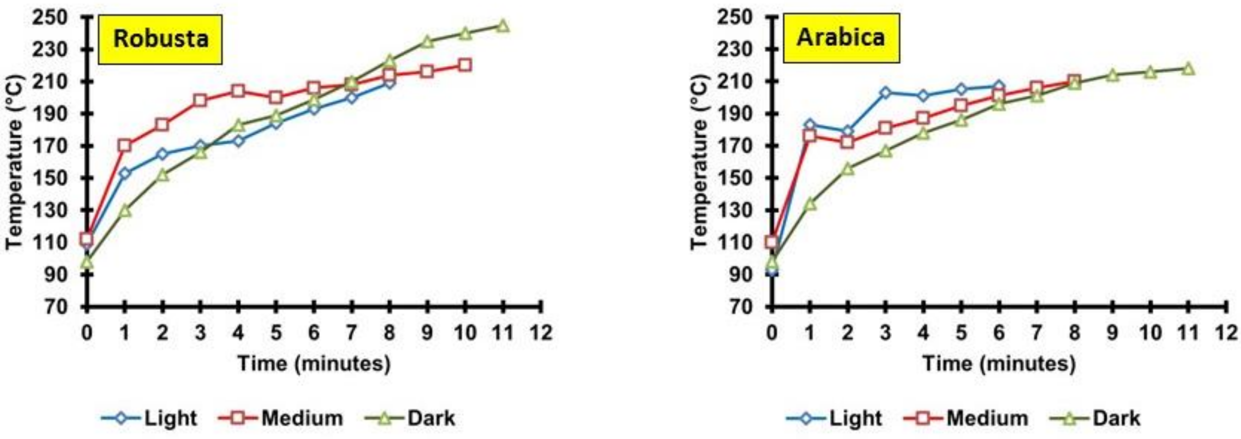

Fig. 10 - Performance of fluidized coffee roaster during roasting process

At all roasting degrees (light, medium, and dark), the cracking time of Robusta coffee during roasting was longer than that of Arabica coffee.

Table 2 shows that the temperature at which Robusta coffee cracked was higher than that of Arabica coffee. The only time Arabica coffee cracked at a higher temperature was when it was lightly roasted.

Table 2

Performance of fluidized roaster on Robusta and Arabica Coffee at various roasting degree

Description	Robusta			Arabica		
	light	medium	dark	light	medium	dark
Cracking time, minute-second	7'11"	6'51"	7'2"	4'19"	4'40"	6'43"
Cracking temperature, °C	201	208	210	205	195	201
Total time required, minute-second	8'11"	9'51"	12'2"	5'19"	7'40"	11'43"
Final roasting temperature, °C	209	220	248	207	210	218

Total time required to achieve the desired roasting level was different between Robusta and Arabica. Robusta coffee required longer time to reach the desired level of roasting compared to Arabica coffee. This was due to the difference in cracking time, where the faster the cracking time was achieved, the faster the desired roasting level was obtained. This result was in line with previous studies which use drum-type coffee roasters, where it was found that the cracking time and total roasting time of Arabica coffee beans were relatively shorter compared to Robusta coffee beans (*Hidayat et al., 2020)*. According to *Hidayat et al. (2020)*, this occurred due to the difference in hardness, where the green Robusta bean was harder than the green Arabica bean. The final coffee beans temperature for both varieties increased from light to dark. Furthermore, Robusta coffee reached a greater final roasting temperature at light, medium, and dark roasting degrees.

From the data, it was also found that roasting process using this fluidized coffee roaster gave shorter total time compared to the roasting process using drum type coffee roaster developed by *Hidayat et al. (2020)*. This happens because in the fluidized type, the coffee beans receive heat evenly over their entire surface due to the exhaled hot air. Heat is also transmitted by convection to all coffee beans, where in the drum type roaster, coffee receives most of the heat by conduction from the drum.

CONCLUSIONS

The fluidized coffee roaster was developed and constructed for small-scale farmers as an economical, simple, and easy-to-operate machine with the capacity to roast 500 grammes of coffee beans. This fluidized roaster consisted of heating furnace room, housing for the blower and temperature control, coffee roasting room, hot air duct, cyclone, heating furnace chimney, and gas holder. At a range of airflow of 4-6 m/sec, the average temperature increase in the furnace and roasting chamber was 26°C and 7.8°C per minute, respectively. The time and temperature of cracking of Robusta coffee were 7’11’’, 6’51’’, and 7’2” at temperature of 201°C, 208°C and 210°C, respectively, and for Arabica were 4’19”, 4’40”, and 6’43”, at temperature of 205°C, 195°C, and 201°C.

This fluidized roaster was able to roast Robusta coffee beans to a light, medium and dark roast in 8'11", 9'51", and 12'2" minutes with final roasting temperature of 209°C, 220°C, and 248°C, while for Arabica coffee, the time required was 5'19", 7'40", and 11'43" minutes with final roasting temperature 207°C, 210 °C, and 218°C, respectively. This fluidized coffee roaster can be used by the small coffee shop business with appropriate capacity.

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