DEVELOPMENT AND EVALUATION OF DRUM COFFEE ROASTING MACHINE FOR SMALL-SCALE ENTERPRISES
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PENGEMBANGAN DAN EVALUASI MESIN PENYANGRAI KOPI TIPE DRUM UNTUK USAHA SKALA KECIL

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ABSTRACT

The design, manufacture and evaluation of a drum coffee roasting machine had been carried out. The aimed of the study was to develop a small-scale drum roaster to meet the demand of the small enterprises at design and function. The development stage consisted of sizing of the main components, creating technical drawings, determination of component materials, manufacture and performance test. The dimension of the roaster drum was 168.28 mm in diameter and 250 mm in length; the capacity of the roaster was 750 gram/ batch. Results of the test determined that the coffee roasting machine had worked well as expected. The preheating time was 15-22 minutes at a drum speed of 67.5 rpm. The initial loading temperature was 180°C. The test using arabica coffee bean reveals that the average crack time was 8.78 minutes, development time was 2.35 minutes, decreasing mass and increasing volume ranged from 19.80 – 20.30 % and 49.97 – 54.85 % respectively. The average crack time of Robusta coffee bean was 10 minutes; development time was 3 minutes, decreasing mass and increasing volume ranged from 10.87 – 14.90 % and 44.93 – 56.20 %, respectively. The required time to roast Arabica green coffee bean to the light-medium and medium-dark level was 11.3 and 12.38 minutes respectively, besides for Robusta green coffee beans was 13.00 and 14.00 minutes respectively.

ABSTRAK

Desain, manufaktur, dan evaluasi mesin penyangrai kopi tipe drum telah dilakukan. Tujuan dari penelitian ini adalah untuk mengembangkan drum roaster skala kecil untuk memenuhi permintaan usaha kecil dalam desain dan fungsi. Tahap pengembangan terdiri dari penyesuaian komponen utama, pembuatan gambar teknis, penentuan bahan komponen, pembuatan prototipe dan uji kinerja. Diameter drum roaster adalah 168.28 mm dan panjang 250 mm; kapasitas drum adalah 750 gram/batch. Hasil tes menentukan bahwa mesin penyangrai kopi telah bekerja dengan memuaskan seperti yang diharapkan. Waktu pemanasan awal adalah 15-22 menit pada kecepatan drum 67.5 rpm. Suhu pemuatan awal adalah 180°C. Tes menggunakan biji kopi Arabika mengungkapkan waktu retak rata-rata adalah 8.78 menit, waktu pengembangan adalah 2.35 menit, penurunan massa dan peningkatan volume berturut-turut berkisar antara 19.80 – 20.30% dan 49.97 – 54.85%. Rata-rata waktu retak biji kopi Robusta adalah 10 menit, waktu pengembangan adalah 3 menit, penurunan massa dan peningkatan volume berturut-turut berkisar antara 10.87 – 14.90 dan 44.93 – 56.20%. Waktu yang diperlukan untuk menyangrai biji kopi Arabika ke tingkat light-medium dan medium-dark berturut-turut adalah 11.3 dan 12.38 menit, sementara untuk biji kopi Robusta berturut-turut adalah 13.00 dan 14.00 menit.

INTRODUCTION

The heat in a rotating drum is transferred by conduction, as the beans come into direct contact with hot metal surfaces, and convection, as the hot air flows through the drum. As the drum rotates above a heat source, the coffee beans continuously move during the process, effectively aiding in even more roast *(Hoffmann, 2014; Rao, 2014)*. The roasting process of rotating drum needs high temperature and a long time (HTLT).

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The drum roaster is one of the most commonly used roasters today, especially by craft roasters and small-scale enterprises, because it allows them to roast at relatively slower speeds. The drum roaster consists of a roasting drum which rotates horizontally with a spiral flight running along the inside of the drum to axially mix the beans *(Hoffmann, 2014; Schwartzberg, 2002)*.

A small roaster usually uses drum roasters, where beans rotate in a drum heated beneath either with direct or indirect flame. Roasting with this type of machines is very stable; they have high durability and are easier to construct. Nevertheless, there are some disadvantage of this type of roaster such as the need for high temperatures during roasting, roasting time takes up to 18 minutes which can cause some beans to scorch and often leave oil and char deposits on the chamber walls *(Eggers and Pietsch, 2008; Nagaraju et al., 1997; Putranto and Chen, 2012)*.

A coffee roasting drum can be manufactured from different types of metal. Some alternative materials for roasting drum are chromium stainless steel, alloy steel, stainless steel and carbon steel. Material compatibility for the roasting drum can be seen from the amount of thermal coefficient expansion; the less amount of expansion due to temperature change the better. Mild steel is more used than stainless steel because the amount of thermal coefficient expansion of mild steel 11.7×10^{-6} $(°C)^{-1}$ is smaller than that of stainless steel, 17.3×10^{-6} $(°C)^{-1}$. Furthermore, the use of stainless steel can cause hot spots, resulting in scorching of the coffee beans *(ASTM, 2000; Bolay et al., 2010; Paulig, 2017)*.

Besides materials, some other essential parameters in designing roasting drum are volume, the ratio between length and diameter (L/D ratio) and drum speed. The typical roaster has an optimum load that works the best. One of the previously published paper reported that for small scale drum roaster its optimum volume is 600-750 grams *(Coffee Navigated, 2019)*. Most of the commercial drums have an equal ratio of diameter to length. Disproportionate L/D ratio will affect the quality of the roasted coffee produced if at the same time having an inconsistent heat down the length of the drum and poor bean recirculation in the drum *(Coffee Navigated, 2019)*. Some previously published papers report that L/D ratio for small scale roaster, which has a capacity less than 1 kg, ranges between 1-1.5 *(Coffee Navigated, 2019)* and for medium scale roaster, which has a capacity up to 10 kg, the length of the drum has to be no higher than 25% of diameter *(Home Roasting Coffee Community, 2006)*. The minimum percentage of headspace in the drum is 55% of drum volume. It is needed to allow an efficient roasting process and facilitating an optimum expansion of the beans *(Bolay et al., 2010)*.

Drum speed is also an essential parameter in designing the roaster. If the drum speed is plodding, then the beans will be in touch with the drum longer; as a result, the coffee beans will get burnt. On the other hand, if the drum speed is very high, the coffee beans will stick to the drum wall all the time due to centrifugal forces and they will also get burnt. To prevent the centrifugal force from counterbalancing gravity and causing coffee beans to stay at the drum wall without falling, then the roasting drum has to rotate with an RPM smaller than $(30/\pi)(g/r)^{0.5}$, where g is gravitational acceleration, and r is the drum radius *(Coffee Navigated, 2019)*.

Most of the small-scale coffee entrepreneurs in Indonesia still use relatively simple equipment; so that their processed products are less competitive. This study aimed to develop a small-scale drum roaster that is safe and reliable having the ability to be easily reproduced and being able to meet the demand from the small enterprises in terms of design and functioning, so that they produce standard quality coffee.

MATERIALS AND METHODS

The development stage of the drum coffee roasting machine consisted of a general description of the roasting machine, sizing of the main components, creating technical drawings, determination of component materials, manufacture, and performance test of the constructed prototype. Before the design stage, the measurement of physical properties of green and roasted coffee bean was conducted.

Physical properties of the green and roasted bean

Physical properties of green and roasted coffee bean are required to calculate the capacity of a roaster, primarily to determine the dimension of the roasting drum, cooling tray, motor power to drive the roasting drum and agitator of the cooling plate. Table 1 shows the physical properties of Arabica and Robusta green and roasted coffee bean as a result of the preliminary study.

Table 1

Physical properties of Arabica and Robusta coffee bean

Physical properties	Arabica			Robusta		
	Green Bean	Light to Medium	Medium to Dark	Green Bean	Light to Medium	Medium to Dark
Moisture content (%)	13.08	6.54	6.24	11.22	7.56	6.12
Weight (g)	0.22	0.17	0.17	0.16	0.14	0.13
Bulk density (g/cm^3)	0.69	0.35	0.31	0.72	0.40	0.32
Mass decrease (%)	-	19.80	20.30	-	10.87	14.90
Volume increase (%)	-	49.97	54.85	-	44.93	56.20

Description of coffee roasting machine design

The roasting machine consists of at least five essential components, i.e. rotating drums, electric motor, the heat source, exhaust fan and cooling tray. Rotating drum has a function as a roasting chamber, in which the bean kept inside will be turned horizontally and mixed axially by spiral fins along the inside of the drum. There are two motors used in this roaster; one used to drive the roaster drum, and the other used to drive the agitator of the cooling tray.

The gearbox was used to couple the electromotor to the roaster drum. Another gearbox was used to couple the electromotor to the propeller of the agitator. The heat source used was a ceramic infrared heater (*Gasolec*) that use liquified petroleum gas as fuel. The exhaust fan has a double function, i.e. to suck hot air from the inside of drum chamber and to suck the chaff and dust from the cooling tray. The cooling bin has a function to collect the hot roasted bean from the roaster drum and to cool it. As an illustration, the drum roaster to be manufactured is presented in figures 1 and 2.

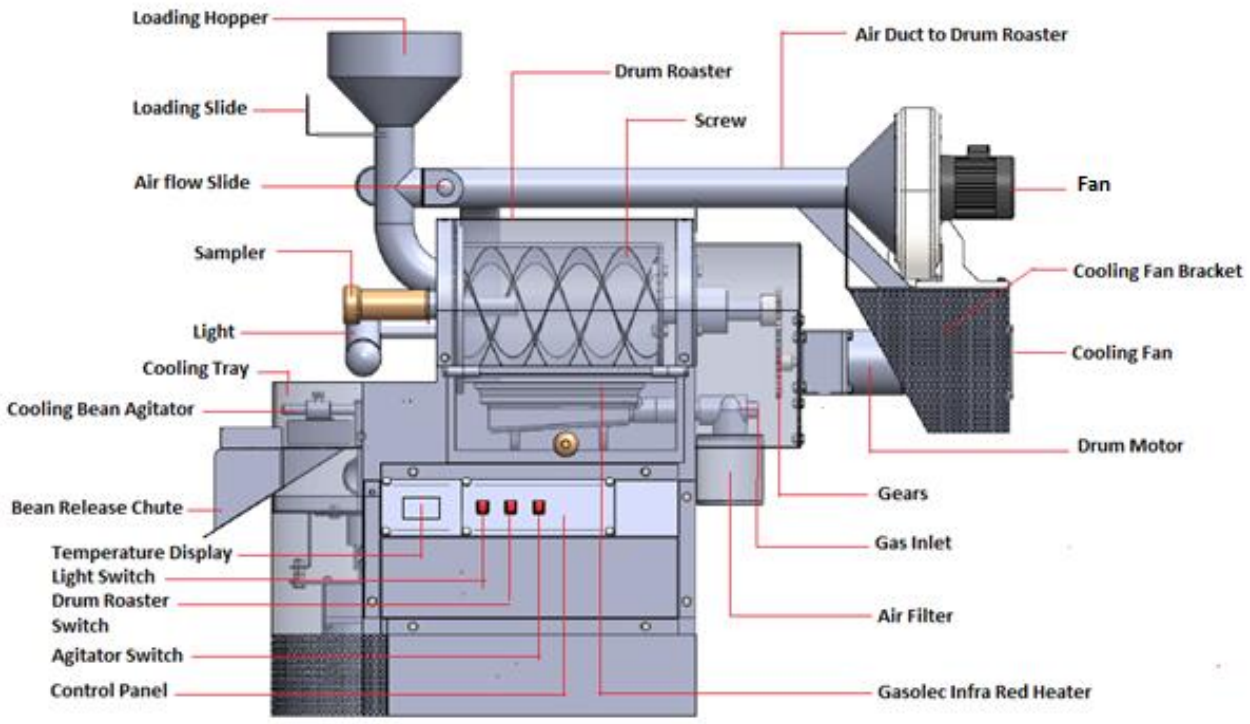

Fig. 1 - Front view of a drum roaster design

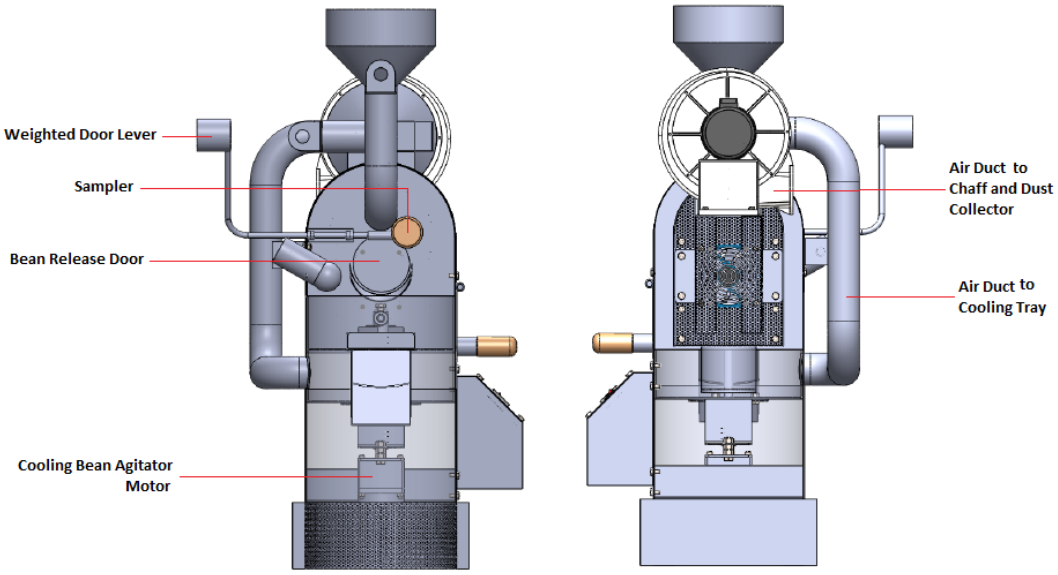

Fig. 2 - Left and right-side views of a drum roaster design

Sizing of the main components

Main components sizing was based on the engineering of Arabica coffee beans. The capacity of a roasting machine to be designed was 750 grams, and the temperature was set up to 500°C.

Drum roaster

- Dimension

The volume of a drum roasting machine was determined using the following equation formula *(Bolay et al., 2010; Mohsenin, 1986).*

$$V = \frac{m}{\rho} \tag{1}$$

Where, V is the volume of green beans (cm^3);
m is mass of green beans (kg); and ρi is bulk density of green beans (kg/cm^3).

The volume of green beans to be roasted is 1.09 litres. Volume increasing from green bean to roasted bean (light to medium) was 1.5; thus, the net amount of green bean was 1.635 litres. To anticipate the different range of green bean density, the safety factor considered was 2, and the correction factor was 1.4. The calculated drum roaster volume was 4.58 litres, and rounded to be 5 litres. The drum roaster dimensions for 5 litres of green beans were: length (L) = 25 cm, outer diameter (Φ_{od}) = 16.83 cm, inner diameter (Φ_{id}) = 16.15 cm.

- Drum speed

The optimum drum speed was determined by using the following formula *(Coffee Navigated, 2019)*. The optimum drum speed ranges between 10-25%, less than $30/\pi$ $(g/r)^{0.5}$.

$$D_s = \frac{30}{\pi} \times \sqrt{\frac{g}{r}} \tag{2}$$

Where, D_s is drum speed (rpm); g is gravitation (9.81 m/s^2); and r is inner radius of roaster drum (0.08 m).

The calculated drum speed using equation (2) was 105.7 rpm, but most of the home roaster design used the optimum speed 25% less than D_s. Based on the calculation, the optimum speed chosen was 79.3 rpm. The available gear ratio in the market was 1:10, 1:20, 1:30 and 1:40; with the electromotor rpm of 1350, then the rpm of every gearbox would be 135, 67.5, 45, and 33.75 respectively. Referring to the calculation, the gearbox used for the roaster that would be designed was 1:20, then the drum speed was 67.50 rpm.

- Power requirement

The power requirement was determined using the following equation *(Khurmi and Gupta, 2005)*.

$$P = \frac{2 \times \pi \times n \times T}{60} \quad (3)$$

$$T = m_d \times g \times r \quad (4)$$

Where:

P is power requirement (J/s);
T - Torsion (N.m);
m_d - total mass of roaster drum and coffee bean (kg);
r - the radius of roaster drum (m).

The result of calculation determined that the required power was 24.74 J/s. The electromotor type used to drive the drum roaster was M425-402, 25 W, 220 V, 50/60 Hz, 4-pole, 1400 rpm, Gear Ratio 1:20.

Loading hopper

The dimension of loading hopper, as shown in figure 3, was determined using the following equations *(Zegarelli, 2007)*.

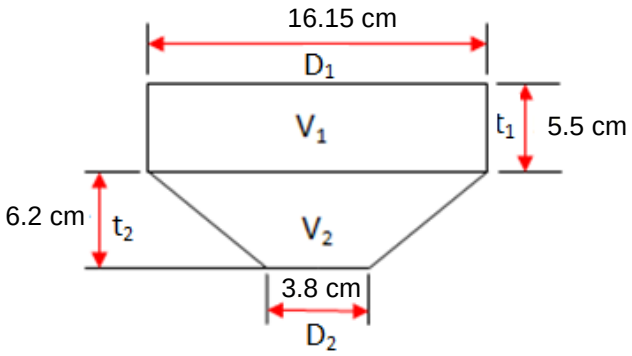

Fig. 3 - Cross-section of the loading hopper

$$V_1 = \pi \times \frac{D_1^{\,2}}{4} \times t_1 \quad (5)$$

$$V_2 = \frac{1}{3}\pi \times t_2 \left[\left(\frac{D_1}{2}\right)^2 + \left(\frac{D2}{2}\right)^2 + \left(\frac{D_1}{2}\right)\left(\frac{D2}{2}\right) \right] \quad (6)$$

$$\sum V = V_1 + V_2 \quad (7)$$

Results of calculation show that the volume of loading hopper (ΣV) was 1672.4 cm^3 or 1.67 litres while the loading volume target of the coffee bean was 750 gram or 1087 cm^3 or 1.09 litres. This means that the hopper capacity exceeded the volume target of the coffee to be roasted so that the coffee bean could be entirely placed in the hopper.

Cooling tray

Table 1 showed that the mass decrease of Arabica bean from green bean to light-medium and medium-dark roasted bean ranged from 19.8-20.3 % and the volume increase of that was between 49.97-54.85 %. The average mass decrease and volume increase of arabica green bean after roasting was 20.05 % and 52.41 % respectively. Cooling tray parameters to be calculated were dimension and power requirement.

- Dimension

The volume of 1.087 litres of green arabica bean after roasting would become 1.65 litres. Results of calculation found that the diameter and height of the cooling tray were 21.74 cm and 7.8 cm, respectively. The volume of the cooling plate was determined as follows *(Mohsenin, 1986; Zegarelli, 2007*).

$$V_{ct} = \frac{\pi \times D^2}{4} \times t \quad (8)$$

Where, V_{ct} is the volume of the cooling tray (cm^3); D is the diameter of the cooling tray (cm); and t is the height of the cooling tray (cm).

- Power requirement

The mass of 750 grams arabica green bean after roasting would become 607.15 grams. The power requirement of the cooling tray to drive the agitator was determined using equation (3-4) *(Khurmi and Gupta, 2005)*. Mass of agitator propeller and green coffee bean was 1.16 kg; the radius of agitator propeller was 0.112 m. Results of calculation determined that the required power of the agitator motor was 8.98 J/s. The electromotor type chosen to drive the agitator propeller of the cooling tray was M315-402, 15 J/s, 220 V, 50/60 Hz, 4-pole, 1400 rpm.

Energy consumption

The energy required to heat the drum roaster and the green bean was determined by the following equation *(Gupta, 1999)*. The temperature was designed up to 500°C, and the ambient temperature was 30°C.

$$\Delta Q = m_{dr} \times C_{st} \times \Delta T + m_{gb} \times C_{gb} \times \Delta T \quad (9)$$

where:

ΔQ is the energy consumption (Joule);
m_{dr} - mass of the roaster drum (3.5 kg);
m_{gb} - mass of green bean (0.75 kg);
C_{st} - heat capacity of stainless steel (500 J/kg^{o}C);
C_{gb} - heat capacity of green bean coffee (330 J/kg^{o}C).

Results of calculation showed that the energy needed to roast the green coffee bean was around 224 Kcal/hr. The burner used to roast the coffee bean was ceramic burner plate S8 Ø1.30 mm of Gasolec infrared heater with the capacity of 3000 Kcal/hr, and fuel consumption of 270 grams liquefied petroleum gas per hour.

Airflow

Drum roasters require a fan; otherwise, it will produce an extremely uneven roasted bean, since it relies only on conductive heat and a little of radiant heat to roast. Too high airflow will risk the coffee bean get roasted quicker on the outside than in the core, on the other hand, too low airflow will risk an uneven heat distribution and as a result, will produce an uneven roasted bean *(Home barista, 2013)*. The specification of the fan used was: power 150 J/s, voltage 220 V, frequency 50 Hz, flow rate 2.5 m^3/min.

Evaluation of the coffee roasting machine

The constructed coffee roasting machine was performed with and without loads. At the unload performance, the roaster was operated with the fan off and on. The temperature was set up to 180°C, and after the set temperature was reached, the fuel-gas was stopped. The machine performance with loads of 750- grams was conducted against two varieties of coffee beans, i.e. Arabica and Robusta green coffee beans. The parameters evaluated consist of processing temperature in the drum, time to achieve a light-medium colour qualification, time to achieve a medium-dark colour qualification, crack time and development time. Crack time is the time it takes for the coffee beans to crack. Development time is the duration from the first crack to the unloading of roasted coffee *(Coffee Navigated, 2019)*. The sample of the green coffee bean was taken from coffee farmers located in Cupunagara village (Latitude 6° 46' 57.71"S, Longitude 107° 41' 37.15"E, and elevation 1153 MAMSL), Cisalak sub-district, Subang district, West Java province. The green coffee bean samples were roasted up to reach light-medium and medium-dark degrees.

RESULTS

The prototype of the coffee roasting machine

Figure 4 shows the designed coffee roasting machine that was manufactured. Table 2 shows the specifications of the roasting machine.

Fig. 4 - The prototype of a coffee roasting machine

Table 2

Specifications of a coffee roasting machine prototype

Parameter	Specification
Overall dimension	1040 × 530 × 810 mm
Weight	50 kg
Roaster drum	Ø 168 mm, length 250 mm
Roaster drum motor	M425-402, 25 J/s, 220 V, 50/60 Hz, 4-pole, 1400 rpm, gear ratio 1:20
Fan	150 J/s, Ø 2", 2.5 m^3 / min
Cooling tray	Ø220 mm, height 78 mm
- Net volume	750- gram green coffee bean
- Motor	M315-402, 15 J/s, 220 V, 50/60 Hz, 4-pole, 1400 rpm
Temperature display	TC 4 series, max 500°C
Thermocouple Sensor	MAX6675 Module + K Type, 12-Bit, 0.25^{0}C Resolution, Temperature Ranging 0^0-700^{0}C, App. For Arduino, Raspberry
Burner	Gasolec infrared heater, ceramic burner plate S8 Ø1.30mm
Fuel consumption	270 g/h, liquefied petroleum gas

Performance test of coffee roasting machine

The roasting device was heated up to 180°C, then the gas was stopped. After stopping the gas, the temperature still increased. Figure 5 shows that at the position of the fan ON, the temperature was 186°C, and at the state of the fan OFF, the temperature reached 196°C.

At the position of the fan ON the temperature increased and decreased faster than that of the fan OFF. The average time required to reach the temperature 180°C of the fan ON and OFF was 15 and 22 minutes respectively.

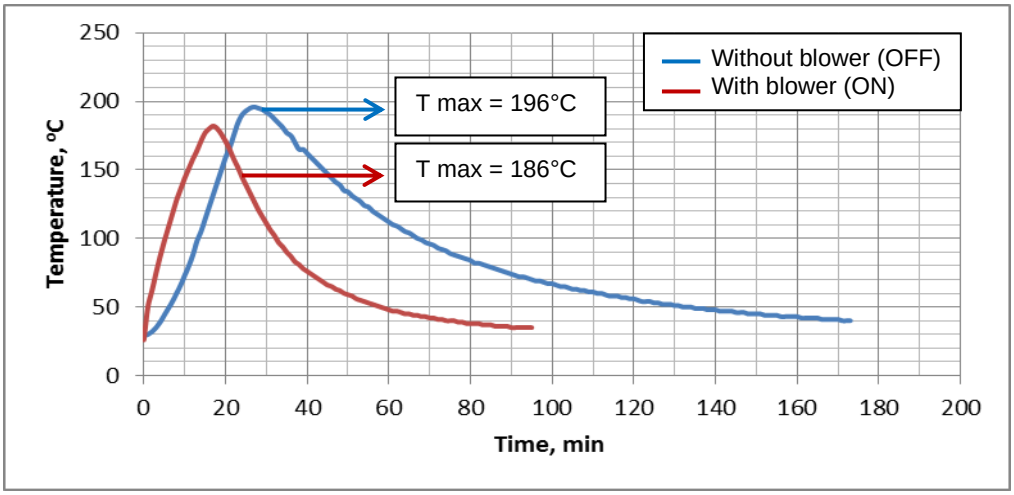

Fig. 5 - Unloaded performance of the roaster with blower ON and OFF

Heating beans is not only relying on power-setting during the roasting but also on the temperature of roaster before the coffee beans are charged. Preheating time is not only relying on a type of roaster design but also on operator habits and experience to get a certain quality of the roasted coffee bean product *(Coffee Navigated, 2019)*.

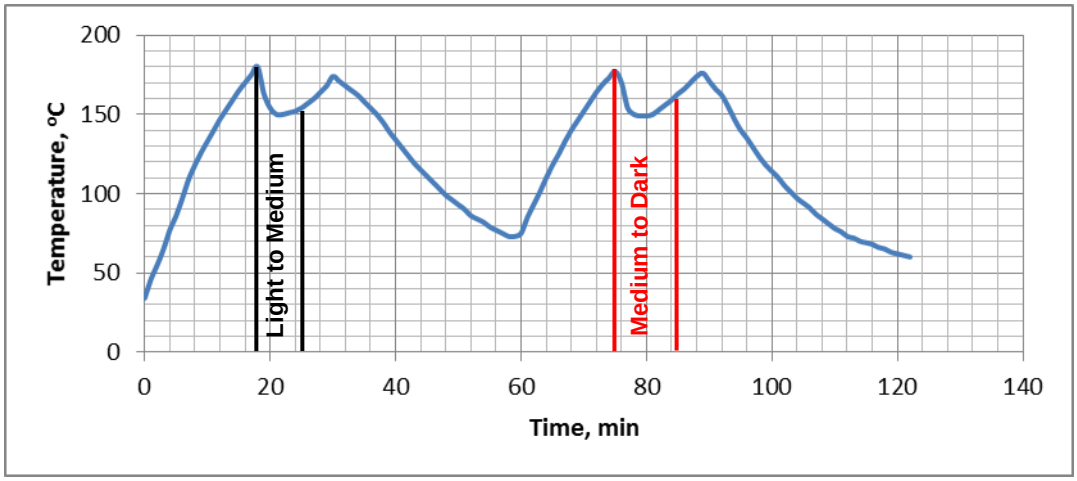

Fig. 6 - Roaster performance of Arabica coffee bean roasting process

Figure 6 shows that the changes from green coffee beans (moisture content of 13.08 ± 0.13 %) to light-medium levels of roasted Arabica coffee beans (moisture content of 6.54 ± 0.26 %) required 11.3 minutes. The crack and development times were 8.78 and 2.35 minutes, respectively.

The ratio between development time and total roast time was 21.14%. The decrease in mass and increase in volume were 19.80 and 49.97%, respectively. It was required 12.38 minutes to produce medium-dark levels of roasted Arabica coffee beans. The crack and development times were 9.08 and 3.30 minutes, respectively; the development time of medium-dark roasted coffee bean was 23.08 %.

The decrease in mass and increase in volume were 20.30 and 54.85%, respectively. One of the previously published paper reported that the weight loss of a light roast is around 11-13%, and of real dark is 20-22% *(Coffee Navigated, 2019)*.

The different results of this study and those of the previous report *(Coffee Navigated, 2019)* were suspected due to the difference in moisture content before roasting, the treatment before roasting, e.g. preheating and also the different geographical areas where the green coffee bean yielded. First crack and development time as a finding of this study was below that of the previous study *(Fadai et al., 2017; Rao, 2014)*.

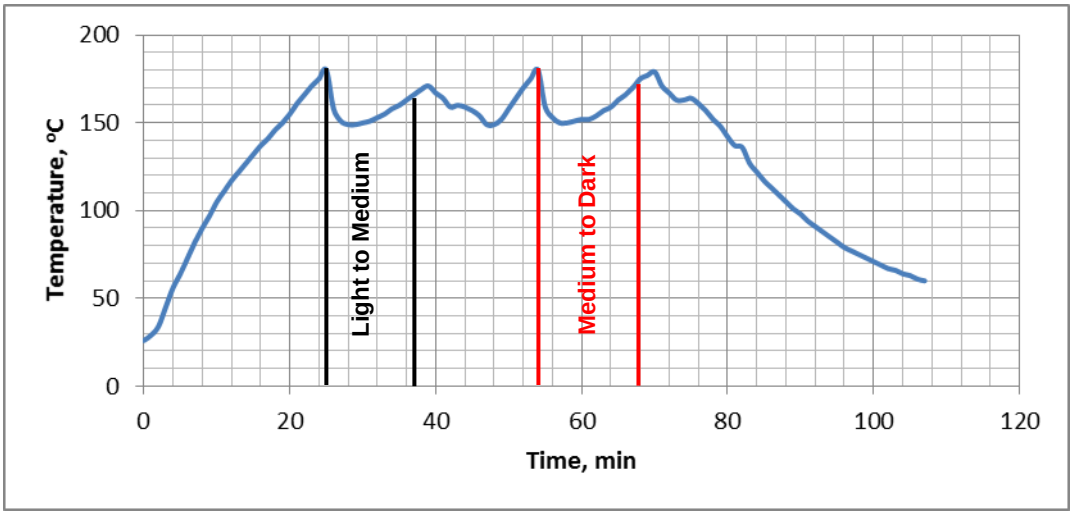

Fig. 7 - Roaster performance of Robusta coffee bean roasting process

Figure 7 shows the time requirement for green coffee beans (moisture content of 11.22 ± 0.11 %) to reach light-medium levels of roasted Robusta coffee beans (moisture content of 7.56 ± 0.52 %). It was 13 minutes (more than the roasting time of Arabica coffee beans). The crack and development times were 10.00 and 3.00 minutes, respectively; the ratio between development time and total roasting time was 26.66%. The decrease in mass and increase in volume were 10.87 and 44.93 %, respectively. 14.00 minutes were necessary to produce medium-dark levels of roasted Robusta coffee beans. The crack and development times were 10.00 and 4.00 minutes, respectively; the development time of medium-dark roasted coffee bean was 28.57%. The decrease in mass and increase in volume were 14.90 and 56.20% respectively.

The crack time, development time and total time of roasting of Arabica coffee bean were relatively shorter than that of Robusta coffee bean; this happened because of the difference in hardness. The results of the preliminary study showed that the green Robusta bean was harder than the green Arabica bean; the hardness value of green Robusta and Arabica coffee beans was 17.70 ± 5.91 kgf and 17.67 ± 2.83 kgf, respectively. The drum speed of the designed roaster was operated at rpm of 67.5 rpm. The speed was within the range of mostly small roaster drum speed, i.e. 50-77 rpm *(Coffee Navigated, 2019)*.

CONCLUSIONS

A prototype of small drum roasting machine was designed, manufactured and evaluated successively for different varieties of green coffee bean. The roaster capacity was 750 gram per batch. The overall dimension of length, width and height were 1040 mm, 530 mm and 810 mm respectively. The size of the roaster drum was 152 mm of diameter, 250 mm of length, and 50 kg of weight. The motor of 25 J/s drove the drum roaster while motor 15 J/s drove the agitator of the cooling tray. Both of the roaster drum and agitator motor was coupled to a gearbox with the ratio of 1:20 and 1:40 respectively. The rotation of roaster drum and cooling tray agitator was 67.5 and 35 rpm respectively. The temperature of the roaster was set up to 500°C, and the type of burner used was a ceramic burner plate of infrared heater. The heat source was liquefied natural gas with the fuel consumption of 270 gram per hour.

The prototype has technically worked well based on the results of the performance test. The preheating time ranged from 15-22 minutes. The test using arabica coffee bean reveals that the average crack time was 8.78 minutes, development time was 2.35 minutes, decreasing mass and increasing volume ranged from 19.80 - 20.30 % and 49.97 - 54.85 % respectively. The average crack time of Robusta coffee bean was 10 minutes; development time was 3 minutes, decreasing mass and increasing volume ranged from 10.87 - 14.90 and 44.93 - 56.20 %, respectively. The required time to roast Arabica green coffee bean to the light-medium and medium-dark level was 11.3 and 12.38 minutes respectively, besides for Robusta green coffee beans was 13.00 and 14.00 minutes respectively.

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