Design and construction of an electrically powered coffee roasting machine

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Abstract. Coffee has been identified as a crop that has the potential to generate foreign earning for local investors but the cost of imported roasting machine is very high thus making it unaffordable for interested agripreneurs. This project detailed the development of coffee roaster using locally available materials thus reducing the cost of processing as well as achieving optimum quality. The roasting capacity of the roaster is 25kg. The roaster consists of a roasting drum, paddles on a speed reduction gear powered by electric motor, frame, cooling fan and cooling unit with control board unit. The roaster attained a temperature of 200°C, 250°C and 300°C in 5, 7 and 10 minutes respectively.

1. Introduction
Roasting consist in a partial pyrolysis of the coffee beans. The organic matter is degraded without a flame. The flavour and taste of coffee is revealed during this process and this is a crucial phase of the process that gives the coffee its final characteristics. Depending on the region and culture, people like coffee more or less roasted. In practice roasting consists in heating the coffee at a temperature of around 200-230°C in 15-20 minutes. Faster roasting can be achieved by increasing the temperature at higher levels. A precise monitoring of temperature and visual control of the coffee has to be done to stop roasting at the exact state desired. Slower roasting tends to reduce the coffee quality [1]. The roasting process can be divided into three consecutive stages: drying, roasting or pyrolysis and cooling.

The beans are to be dried and the traditional way is sun drying. Coffee beans can be spread on the ground, on plastic, textile foil or on concrete surface. Industrial drying can also be employed but this is energy intensive. The drying phase consumes 84 % of the total energy needed for the whole coffee process. Solar dryers can also be used. The dried bean can be stored, further processed, sold or exported. Before roasting, its shell has to be removed. Unlike other food products, the goal in coffee roasting is to produce a uniform result from the outer layer of the bean through to the inner heart of the bean. No dark, caramelly
outside, soft and chewing inside for coffee. In specialty coffee, the roast master is generally trying to maximize flavour development.

Designs of a coffee roaster can vary from single wall drum, double wall drum, solid cylinders, perforated cylinders, drum-less fixed chamber air roasters, fluid bed style without agitators, air roasters with agitators, oven pack burners, gas jet burners, radiant flame burners, multi-style burners, high velocity air, medium velocity air, fixed air speeds, adjustable air speeds, cooling with water quench, cooling without water quench, sample extraction during roasting, no sample extraction during roasting, fast roast times, medium roast times, conventional roast times, manual controls, semi-automatic controls, fully automatic controls, profile controls with five set points, with 30 set points, roasters with aroma valves, roasters without aroma valves, downdraft coolers, updraft coolers etc. Nigeria produced 2100 tons of unroasted coffee in 2013. In 2015 consumption was 836 tons, with prediction of consumption increasing to over 1000 tons in 2020, 23% higher than 2015 [2].

1.1 Methods of coffee roasting.

a. The typical way for traditional roasting is using a pan on a normal wood stove. Good homogeneity of roasting is not always easy to reach with this technique. Being able to roast coffee with higher quality in an affordable and ecological way would help producers to improve their income and thus quality of life.

b. Drum with blades, batch process is the most commonly used technology to roast coffee. A horizontal cylindrical drum rotates with the coffee inside. Blades ensure a good mixing of the coffee for an even roasting. The heat source is usually provided below the drum with natural gas. Some roasters, usually small models, are heated up with electricity. An air flux is fed into the roaster to bring heat per convection. It also helps remove the “silver skin”. This small layer falls off the grain during roasting. Its high nitrogen content and faster thermal degradation tend to modify the coffee taste.

c. Fluidized bed, continuous process Fluidized bed consists in maintaining the coffee beans in suspension thanks to a strong air flux fed below the coffee beans. Although it is not necessarily the case, this technique enables the roasting to be a continuous process. The advantage of using a fluidized bed is that the bean heating is more homogeneous thanks to heat transfer through convection. This technology is more advanced and rather applied in industrial roasting.

2. Materials and Methods

The art of constructing roasting machines lies in the design selection and control of such variable factors as time, temperature, air flow, roast chamber packing density of coffee to air space, bean motion within the roasting chamber, heat transfer ratios, drum or roasting chamber materials, etc.

2.1 Material Selection

Stainless steel material was used to construct the components that have direct contact with coffee bean which includes: roasting drum, paddles, main shaft, cooling chamber with shaft and stirrer. Other components were made of mild steel, for construction of frames and galvanized steel material for side covers and air duct.

Materials used were sourced locally at Surulere market and Sawmill garage market, Ilorin, Kwara State. Selection of materials were critically based on hygiene, strength, availability, machinability and malleability for components to be machined and cold work, rigidity, durability, corrosiveness and maintainability to ensure longer machine life span and affordability of the roaster.

2.2 Components Design and Consideration
2.2.1 Roasting Chamber Design

i. Inner Roasting Drum design

Factors taken to consideration for design of roasting drum are edibility of the end product, volumetric capacity, thermal properties of the drum materials and also durability. Since coffee bean will be in direct contact with the roasting chamber, all contact material used were stainless steel. The drum is expected to process 30 kg of coffee beans per batch operation.

ii. Design requirement / assumption

- Process 25kg of green coffee bean at approximately 10% - 12% mc (wb)
- Drum volume to green coffee ratio to be between 24% - 32%, [1].
- Account for thermal expansion
- Maintain mixing standards so as to reduce over-, under-, and uneven roasting.
- Cylindrical drum.
- Initial Moisture content of the coffee.

iii. Drum Dimension calculation

The volume of the green coffee to process per batch was determined using equation 1.

\[
V_{gc} = \frac{m_{gc}}{\rho_{gc}} \quad (1)
\]

Where,

\( V_{gc} \) is the absolute volume of green coffee at 12% mc
\( m_{gc} \) is the mass of green coffee at approximately 12%mc
\( \rho_{gc} \) is the absolute density of green coffee at 12%mc given as 1.25g/ml [3].

From equation 1,

\[
V_{gc} = \frac{25000}{1.25} = 0.02 \text{m}^3
\]

Equation 2 was used to determine volumetric capacity of the roasting drum. 28% was used being the average of the green coffee to drum volume ratio range.

\[
\frac{V_{gc}}{V_d} = 28\% \quad (2)
\]

Where, \( V_d \) is the volume of the roasting drum

\[
V_d = \frac{0.02}{0.28} = 0.0714 \text{m}^3
\]

Diameter to length ratio was taken to be 66%, [1].

\[
\frac{D}{L} = 66\% \quad (3)
\]

Where,

\( D \) is the drum diameter
\( L \) is the drum length

Using equation 3 and 4, length and diameter of the roasting drum was calculated.
Substituting for D in equation 4 from equation 3

\[ L = \sqrt[3]{\frac{4V_d}{\pi 0.66^2}} \]  

Substituting for L in equation 3

\[ D = 0.592 \times 0.66 = 0.3907 \text{m} = 391 \text{mm} \]

The isometric view of the roaster is presented in Figure 1 below.

iv Outer Roasting Drum
The outer roasting drum was made of stainless-steel sheet of 3mm thickness. This serves as covering and as well housing for the heating elements used as heat source, this was lagged with fibre glass to prevent heat loss with a detachable conical hopper as shown in Figure 1.

2.2.2 Heat Source
The four units of 2000W heating elements was used as heat source which has the capacity to heat up the roasting air space from room temperature to 200\(^\circ\)C and 300\(^\circ\)C in approximately 6mins and 10mins respectively. Provision was also made for temperature controller to maintain pre-set temperature for roasting as desired.

2.2.3 Shaft and Paddle
The main shaft carrying paddles was made of stainless solid shaft of \(\varnothing30\text{mm}\). The paddle was made of 2mm thick stainless sheet welded to stainless bolt with its nut welded to the main shaft with provision for jam nut for possible paddling angle adjustment. Eight paddles were attached for stirring the coffee.
while roasting. The shaft rotating at 58rpm was in direct coupling with a speed reduction gear powered by 0.75 kW electric motor.

2.2.4 The Hopper

The capacity, angle of repose and coefficient of friction between green coffee (12% mc wb) and stainless steel been 0.34 as reported in [4] size and space were important factors considered. The hopper was made of stainless-steel sheet, square frustum with a throat measuring 305mm at the top and 104mm at the base and also the throat, having total of 155mm vertical height including the throat. It was simply installed into the provision on top of the drum assembly by placement without fastener. Provision was made for a manual sliding cover at the coupling point to drum to prevent the beans from been thrown out during roasting operation.

2.2.5 Frame

The frame is a load carrying unit majorly made of 50mm mild steel angle bar to provide rigidity and stability of the roasting unit and other components support/attachments including pillow bearing carrying paddles shaft, control unit, electric motor and speed reduction gear box, cooling fan compartment and cooling unit.

2.2.6 Cooling section

The cooling section consists of a centrifugal fan assembly, fan housing made of 2mm galvanized steel sheet, air duct also made from the same material. The electrically powered fan sucks air at ambient and blows through the air duct into the base of the cooling unit. The cooling drum was made of 2mm stainless steel sheet with cover base and open top. There is provision for stainless vent capable of hold the smallest possible roasted coffee bean through which the air at ambient is forced through the just roasted coffee beans thereby creating forced convention cooling effect. Also, an agitator made of stainless rod and plate, whose stirring motion was taped from the main shaft with the use of bevel gear converting horizontal motion to vertical motion, was provided for to increase even and fast cooling effect.

2.2.7 Thermal Expansion Calculation

Change in temperature of a metallic object leads to contraction or expansion. The degree of expansion or contraction depends of the type of metal and magnitude of heat subjected to. Coffee roasting can require temperature up to 1000°F (537.77°C). Stainless material was used for the roasting and cooling chamber assembly since coffee bean, being food material, will be in direct contact with said components. It is important to make provision for linear expansion in the drum which is the function coefficient of thermal expansion of stainless-steel using equation 6.

\[
\Delta L = L_0 \alpha (T_f - T_i) \quad (6)
\]

From equation 6, change in length \( \Delta L \) was calculated.

\[
\Delta L = 0.592 \times 103 \times 10^{-7} \times (482 - 73.4)
\]

\[
\Delta L = 0.00249\text{mm} \approx 2.5\text{mm}
\]

Where the Coefficient of thermal expansion of stainless is given as 103x10^{-7}(°F^{-1})

\( \Delta L \) is the change in length of roasting drum due to high temperature (mm), \( L_0 \) is the original length of roasting drum (mm), \( \alpha \) is the coefficient of thermal expansivity of stainless steel (°F^{-1}), \( T_f \) is the final temperature of the drum (mm) and \( T_i \) is the initial temperature of the drum (mm).

3. Result and Discussion
On completion, the 25kg capacity coffee roaster was developed and evaluated in the workshop. It had a weight of 175 Kg and was electrically operated. During evaluation, it was established that the installed elements were able to raise the roasting chamber temperature from room temperature to 200°C in approximately 5 minutes of heating. The control unit was pre-set such that the roasting temperature was maintained at 200°C throughout the roasting period. The roaster was charged with 10kg of green coffee at 12% mc. Roasting was completed after 20 minutes and then discharged into the cooling unit.

![Orthographic view of the coffee roaster showing three views.](image)

**Figure 2.** Orthographic view of the coffee roaster showing three views.

4. Conclusion

A 25kg/batch coffee bean roaster was developed locally and tested. Homogenous roasting was achieved through an instrumented rotating paddle carrying shaft. The shaft has the capacity to paddle both clockwise and anti-clockwise sequentially during roasting and clockwise for discharge. Roasting of 10kg was achieved in 20 minutes and cooling process was achieved as fast as possible ready for packaging. Extensive performance evaluation is recommended for optimization of the locally produce coffee roaster. The roaster attained a temperature of 200°, 250° and 300° C in 5, 7 and 10 minutes respectively.

References

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