JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

FACULTY OF MECHANICAL ENGINEERING

CHAIR OF THERMAL SYSTEMS ENGINEERING

DESIGN AND MODELLING OF DRUM TYPE COFFEE ROASTING MACHINE USING LIQUEFIED PETROLEUM GAS (LPG) AS A SOURCE OF ENERGY:

A Thesis submitted to the School of Graduate Studies of Jimma Institute of Technology as partial fulfillment of the requirements for the award of Master of Science in Mechanical Engineering (Thermal Engineering Stream)

BY: **NASIR FARIS**

Dec, 2019

Jimma, Ethiopia

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DECLARATION

This research paper is my original work and has not been presented for a degree in any other university.

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ABSTRACT

Coffee is one of the world's most popular beverages and its processing involves distinct operations: planting, harvesting,sorting,drying, roasting, grinding and packing. Among these processes the roasting process is extremely crucial for the quality of the final coffee aroma. Roasting presents the key step in coffee processing to develop the characteristic flavor properties for which coffee is appreciated. In addition, roasting induces major physical changes within the coffee beans and determines their behavior in storage, grinding, and brewing. The impact of the roasting parameters roasting time, roasting temperature, moisture content, quenching method, and roaster design, on aroma formation, aroma stability, and grinding properties of roasted coffee were a very important things to investigate for better economical and customer satisfaction. Since the existing roasting machines are not fully capable of obtaining the desired quality and depending on their source of energy, therefore in order to obtain the mentioned merits to fulfil the demands satisfaction it is needed to design the rotating drum type coffee roasting machine to keep in touch the specific desires of this thesis accordingly. The beans are roasted for a period of time ranging from a few minutes to about 30 minutes and the roasted coffee would be packed in order to keep its aroma and quality The general objectives is design and modelling of rotating drum type coffee roasting machine using LPG as a source of energy and the system uses atmospheric burner which is placed outside underneath of rotating drum. The methodology of working is, the drum type coffee roasting machine is typically horizontal rotating drums that tumble the green coffee beans in a current of hot burner flame and very important roaster that it keeps the uniformity and homogeneity of roasting. At the end of the roasting cycle, water sprays, fan and air are used to "quench" the beans. In conclusion, the study would yields economical, easily operated and maintainable roasting machine to obtain the crucial and valuable flavor of coffee aroma with high quality.

Key words: coffee; roaster; aroma

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F.S. = Factor of safety

σ_{ult} = Ultimate stress

σ_y = Yield stress

τ_{all} = Ultimate shear stress

τ_y = Yield shear stress

σ_c = direct compressive stress

σ_o = Static stress

σ_e = Flexural endurance

σ_{es} = Surface endurance limit

l = lead

ρ = density

λ = Lead angle

l_N = Normal lead

p_a = axial pitch

p_c = circular pitch

p_N = normal pitch

m = module

η = Efficiency

M = Moment

PCD = Pitch circle diameter

D_w = pitch circle diameter of the worm

D_G = pitch circle diameter of the gear

N_G = speed of the worm gear

N_w = speed of the worm

Φ = pressure angle

α_W = helix angle of the worm

V.R = velocity ratio

v_w = linear velocity of the worm

v_G = linear velocity of the gear

T = torque

F_t = tangential load

W_N = normal load

W = weight

W_R = resultant load

P = power

d = deddendum

a = addendum

c = clearance

E = modulus of elasticity

Y = tooth form factor

K = factor depending up on the form of teeth

e = Tooth error action

W_w = Wear tooth load

Q = Ratio factor

K = Load stress factor

CHAPTER ONE

1. Introduction

A coffee bean is the seed of the coffee berry, that's the parts inside the red or purple fruit. Even though they are seeds, they are referred to as coffee beans simply because they resemble beans.

The coffee plant fruit, called the coffee cherry or coffee berry, almost always generates two seeds, which grow with their flat sides together. However, in a standard crop some of the coffee berry will generate just a single bean, and this is called a pea berry. Coffee beans consist mostly of endosperm that contain from 0.8 to 2.5% caffeine, which is the main reasons the plant is cultivated.

Three main types of coffee beans dominate world production. These are *the Kona*, *the Arabica*, and *the Robusta Coffee Beans*. But because environmental factors deeply affect the flavor of coffee, the coffee bean types and blends are more usually identified by geographic location rather than coffee bean type.

The Kona

Figure 1: The Kona Coffee Bean

Compared to Robusta and Arabica in the commercial world, Kona is much smaller yet very expensive. This type of coffee bean normally grows in the country of Hawaii. Though Kona is not being patronized as much by most common people in the market, it still has a very high demand worldwide due to its powerful aroma.

The Arabica

The Arabica type of coffee beans covers 60% of the coffee production in the whole world because of the large bush that Arabica plants have. Also Arabica plants are very vulnerable to

Pests, disease and frost. With this reason, the coffee beans of Arabica plants are extremely expensive. Arabica coffee beans can be used on its wholesome form as well as it can be used as a base with Robusta for coffee blends.

Figure 2: The Arabica Coffee Plant

But Arabica coffee beans still vary accordingly to the region where they are grown and used. There are many variations of Arabica coffee beans found in Ethiopia because the country is the first one in the entire world that valued drinking coffee. Three of the topmost variations of Arabica coffee found in Ethiopia are: the Yirgacheffe, Sidamo and Harrar.

The Robusta

Robusta coffee beans are favored more for their robust coffee blends. Robusta coffee is considered a lower grade of coffee, as it is usually grown at lower elevations. It has a more astringent flavor and contains a higher amount of caffeine. Robusta trees are normally easier to grow and simpler to maintain. They are also more resistant to disease and produce a higher yield. The types of coffee beans and/or coffee blends are more usually identified by geographic location rather than primary coffee bean type. These include: the Tanzanian Pea berry, Organic Sumatra Reserve, the Madriz from Nicaragua Klatch, and the Bourbon Santos from Brazil.

Figure 3: The Robusta and Arabica coffee beans

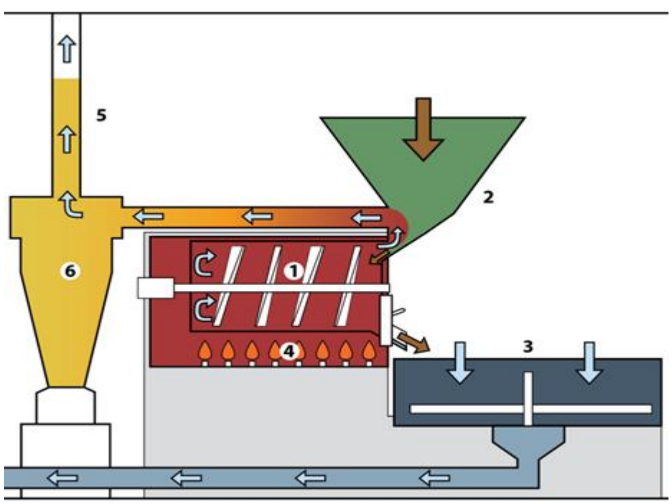
Coffee processing involves basic distinct operations and among these clean coffees, prior to roasting is blended in desired proportions. Among these processes the roasting process is extremely crucial for the quality of the final coffee aroma.

1.1. Roasting machines

To roast green beans, roasters are needed. A coffee roasting machine is a specialized oven that transfers heat to coffee beans in a stream of hot gas while continually mixing the beans to ensure they roast evenly. Several types of roasters are in use today in the specialty coffee industry; drum – type roasters, fluid bed roasters, recirculation roasters and several others.

1.1.2. Drum – type coffee roaster

A drum roaster consists of a solid, rotating, cylindrical steel or iron drum laid horizontally on its axis with an open flame below the drum. The flame heats the drum. A fan draws and exhausts the smoke, steam, and various by – products of roasting through the component called the cyclone. The drum's rotation mixes the beans while they absorb heat by conduction from direct contact with the hot drum and convection from the air flowing through the drum.



Operation or working principles

Beans enter the roasting drum (1) through the loading funnel (2). Heat necessary for roasting is supplied at (4). After roasting, the beans cool in the cooling bin (3). By –products of roasting are exhausted from the roasting drum through the chimney (5) after passing through the cyclone (6) which traps chaff.

Figure 4: Roasting operation in drum – type coffee roasters

At the completion of a roast, the machine operator opens the door to the drum dumping the beans into the cooling tray, which stirs the beans while a fan draws room – air temperature through the bean pile to cool it rapidly.

1.2. Statement of the problem

The demand for roasted ground and packed coffee is directly related with number of coffee serving bars. Literally bar means "coffee shop" or "Buna bet" in Amharic indicating the formation of such a business as directly dependent on roasted and milled coffee. Now a day, it is not surprising to see lots of street coffee shops being opened in Addis Ababa or any other part of the country. Hotels, restaurants and clubs also provide coffee to the public using packed coffee. Out of the three coffee processing operations, i.e. roasting, grinding and packing, roasting process is extremely crucial to attain a high quality aroma – rich coffee. Therefore this paper aims at designing a coffee roasting machine which process and deliver a high quality roasted coffee beans for better benefit as well as satisfaction. Thus, this thesis aims to minimize the habit of using wood for this purpose which leads directly or indirectly affect our forest which also increases the global warming as well as having a great role on air pollution and so to develop the habit of using LPG as a source, since it is cheap, available anywhere, environmental friendly and almost air pollution free.

1.3. Objectives

1.3.1. General Objective

- ✓ To design and modeling of rotating horizontal drum type coffee roasting machine using liquefied petroleum gas (LPG) as a source of energy, which is capable of roasting 25 kg of coffee in one batch within a time of 20 minutes, keeping its natural taste.

1.3.2. Specific Objectives

- ✓ To design the components of the roasting machine
- ✓ To design thermal analysis of the roasting process
- ✓ To collect data of the material available in the local area and evaluate the cost of the overall roaster machine.
- ✓ To show the structural model of the machine and to check the strength of some important components of the machine using engineering Software such as Catia V5, Solid work

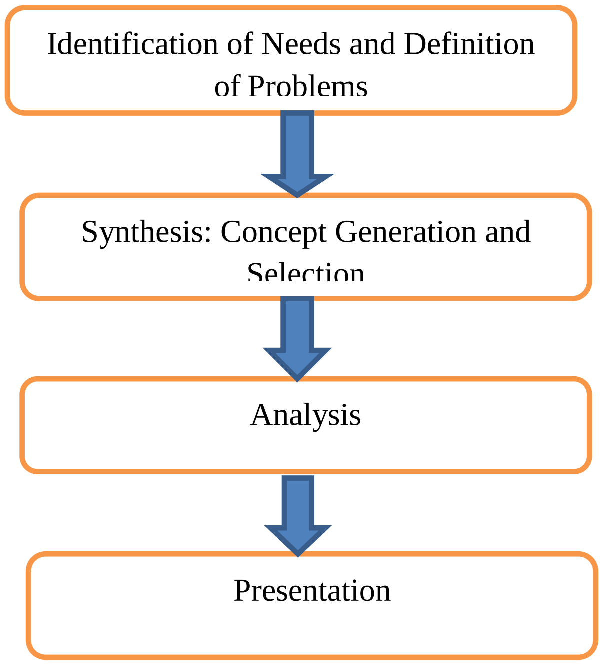
1.4. Scope of the Thesis

The design process of this thesis started with data gathering from the literature review and information obtained through direct observation. This thesis was done based on the scope below:

- ✓ This thesis would focuses on designing and modeling of rotating drum type coffee roasting machine
- ✓ The study would focus only on roasting machine
- ✓ Fabrication and manufacturing of the machine is not the aim of this written work so that it is not included in this study.

1.5. Methodology

In order to achieve the specified objectives the following tasks have been completed. Since most of the task includes the design of a system the general design procedures needs to be followed. This would begin with literature review from internet, books and other relevant academic materials related to the title. After generating idea and refining it, the next step was being started designing the machine based on standards.. The design sketching would be deeply discussed and the general design procedure is shown below.



Therefore, the design sketching was deeply discussed and the best design is selected in order to touch the target of this thesis to fulfil the basic and specified objectives of the study. Here in design of this roasting machine; in deep the tools which were used in large were CATIA V5 for structural modelling and also some basic components are checked whether they were feasible and strong enough to hold and support necessary loads, since it provides a complete set of elements behavior, material models and equation solvers for a wide range of mechanical design problems.

Additionally, the detail design of mathematical parameters would have been done analytically in order to check whether the designs of basic components are safe or not according to Standard set margins.

CHAPTER TWO

LITERATURE REVIEW

2.1 Coffee roasting – a brief history

It wasn’t that long that it was common for people to buy raw coffee beans from the stores and then roast at home for fresh coffee. That was particularly true in rural areas that were removed from the same roasters found in city neighborhoods. At that time, roasting coffee was considered a normal part of everyday life and a part of many peoples’ cultural heritage. There were many types of small hand – cranked roasting devices available, usually heated with wood, coal, or gas. These were either used in the kitchen, the garden, or on the balcony. People look pride in their ability to produce the type of roast that they liked best, and considered it a sort of ceremony, or art. Each morning in these neighborhoods, the sweet smell of roasting coffee lingered in the streets.

With the advent of instant coffee, developed for the soldiers in WWII, and the post – war boom of the convenience – food industry, the art of coffee roasting was all but lost to the masses. The same corporate brands that produced instant soups and washing detergents erected huge coffee roasting facilities to provide people with a ready – made product. What used to be a fine art became a factory product. Today, most consumers buy pre-ground coffee from these factories, unaware of the culinary tradition that once existed.

Abandoning home coffee roasting has come at a price. While green (raw) coffee will easily keep for over a year with little care, it has been shown that roasted whole coffee beans lose a large part of their flavor within two or three weeks after roasting. Once it has been ground, the coffee stales at an even faster rate, and loses its fresh-roasted taste within a matter of hours. Consequently, most cans and vacuum bricks found on the supermarket shelves contain a product that has long since lost its precious, volatile flavors. Even when one finds whole beans in a supermarket or specialty shop, one hardly ever knows whether these beans are fresh-roasted, weeks old, or worse. Roasting coffee is a thermodynamic process in which the application of heat and the resulting uptake of heat by the bean directly affects final flavor. The condition under which heat is applied is affected by environmental factors, including internal volume of the roaster, humidity, barometric pressure, and ambient temperature. The ability of the bean to take on heat and the rate

At which the absorbed heat dissipates throughout the bean is a function of its physical state, including % moisture, density, and bean size. The chemical changes taking place at any instant in the process depend upon the amount of heat already taken on, the amount of heat available in the immediate environment, the ability of the mass of beans to conduct heat, and the reactions that have already taken place or are in the process of taking Place .The roaster technician makes adjustments to the flame based upon knowledge of the roasting process, observations of the processes taking place, and experience. Additional operations associated with processing green coffee beans include decaffeination and instant (soluble) coffee production. Decaffeination is the process of extracting caffeine from green coffee beans prior to roasting. The most common decaffeination process used in the United States is supercritical carbon dioxide (CO_2) extraction. In this process, moistened green coffee beans are contacted with large quantities of supercritical CO_2 (CO_2 maintained at a pressure of about 4,000 pounds per square inch and temperatures between 90° and 100°C [194° and 212°F]), which removes about 97 percent of the caffeine from the beans. The caffeine is then recovered from the CO_2, typically using an activated carbon adsorption system. Another commonly used method is solvent extraction, typically using oil (extracted from roasted coffee) or ethyl acetate as a solvent. In this process, solvent is added to moisten green coffee beans to extract most of the caffeine from the beans. After the beans are removed from the solvent, they are steam-stripped to remove any residual solvent. The caffeine is then recovered from the solvent, and the solvent is re-used. Water extraction is also used for decaffeination, but little information on this process is available. Decaffeinated coffee beans have a residual caffeine content of about 0.1 percent on a dry basis. Not all facilities have decaffeination operations, and decaffeinated green coffee beans are purchased by many facilities that produce decaffeinated coffee. [1]; [30]

2.2 Coffee roasting – terminologies

The following are commonly used terms in coffee roasting process taken from *roast magazine, 2013.*

Acidity: a pleasing piquant or tangy quality characteristic of high – altitude coffees. Citric, malic and lactic acids are three of the most pleasing and predominant of the hundreds of acids found in coffee.

Aroma: the fragrance of brewed coffee.

Air roaster: a roasting apparatus that utilizes force hot air to simultaneously agitate and roast green coffee beans.

Baked: bland, tasteless or flat. Often the result of coffee roasted too slowly at too low temperature.

Batch roaster: apparatus that roasts a given quantity of coffee at a time. Unlike continuous roasters, batch roasters have an identifiable start and stop time to each roast.

Bean temperature: the external temperature of the coffee bean during the roast cycle. Generally used as the control temperature for the roasting process.

Bitter: a harsh, unpleasant taste perceived at the back of the tongue. All coffees have a slight bitterness that is characteristic of the roasting process, and moderated bitterness can be balanced by sweetness. It is commonly found in dark roast or overly extracted coffees.

Blend: a mixture of two or more coffees that differ by growing regions, districts, farms, varietals, processing methods or roasts.

Burnt: a bitter, smoky or tarry flavor characteristic, often found in brewed coffee that has been over – roasted.

Buttery: a full and rich flavor with an oily body or texture.

Caffeine ($C_8H_{10}N_4O_2$): a bitter white alkaloid found in coffee beans and leaves, having certain drug-like properties.

Chaff: flakes of the innermost skin of the coffee fruit that remain on the green bean after processing, and which float free during roasting.

City roast: a traditional term for a light to medium commercial roast.

Coffee oil: the volatile coffee essence developed in a bean during roasting.

Continuous roaster: large commercial coffee roaster that roasts coffee continuously rather than in batches.

Cooling tray: a piece of equipment, usually circular and equipped with stirring arms, which agitates fresh – roasted coffee to cool it to room temperature.

Cyclone: component of roasting machine which is used to discharge the smoke and skin of coffee bean (chaff) separately.

Dark roast: dark roast experience higher temperatures in the roaster. They have absorbed more energy which creates more dry-distillates and Maillard reactions. They have minimal acidity and can taste truly terrible (ash, toast, tobacco, burnt coffee etc.).

First crack: the second stage of coffee roasting. Once the beans reach 190^0c, complex chemical reactions occur which cause an audible cracking sound.

Flat: coffee that has been exposed to oxygen for too long.

Fragrance: the smell of dry ground or whole bean coffee before brewing.

Fresh: a recent roast, often characterized by a distinctly pleasing aroma.

Light roast: light roast experiences lower temperatures in the roaster. They have absorbed less energy absorbed less energy which preserves more acids and aromatics. They have more acidity and complex aromas (fruity, bright, citric, floral etc.)

Medium roast: sits somewhere between dark and light roasts. There are many shades of brown in here; most of them are some kind of compromise between darker and lighter roasts.

Overdevelopment: occurs when the coffee has become soluble and displays no undesirable organic flavors, but the energy and time applied during roasting has left nothing delicious behind. It is empty, lifeless and hollow.

Pyrolysis: during roasting, the chemical breakdown of fats and carbohydrates into the delicate oils that provide the aroma and much of the flavor of coffee.

Second crack: the stage in roasting where the beans become brittle due to dehydration. As a result, the beans crack and begin to carbonize, producing the burnt characteristics of extremely dark roasts.

Silver skin: the thin, innermost skin of the coffee fruit. During roasting, any silver skin left on the bean turns into chaff.

Sour: one of the basic tastes: sweet, sour, salty, bitter and umami.

Specialty coffee: coffee that tastes good. Coffee produced with care and sophistication to achieve recognized quality.

Stale: an unpleasant taste fault found in old and deteriorated roasted coffee. It can also be defined as roasted coffee that has faded in quality after excessive storage or exposure to air.

Thin: coffee that lacks body or flavor.

Underdevelopment: underdeveloped coffee displays those undesirable "green" flavors and is less soluble. [13] &[Roasting Magazine 2013]

2.3 Roasting techniques and machines

The primary objective of roasting is to produce a desired taste and aroma. Furthermore, coffee is roasted to generate a dark color and a dry and brittle texture that makes grinding and extraction possible (Clarke and McRae, 1987, Johannsen, 1992). In industrial practice coffee is normally roasted by means of an hot air flow, therefore, it is possible to distinct systems where conductive heat transfer prevails and systems with prevailing convective heat transfer. For this reason, the ratio between the amount of hot air used during a roasting process and the batch size of coffee beans is an important parameter. Mehlman (1986) defined this value as air – to bean ratio, measured in kg of air per kg of green coffee. This ratio is a characteristic parameter for roasting systems, when it is coupled to a given degree of roast. Mehlman (1986), reported that it can range from 1 in a typical "conventional" process up to 150 in fully fluidized-bed systems. It is also possible to group roaster system considering the mechanical layout. Clarke and McRae (1987) give an illustrated summary of different industrial roasters. Horizontal rotating drum is the most commonly used system, but also the vertical fixed drum with rotating mixing elements, the vertical rotating bowl and the fluidized bed are used by manufacturers. The main task is to mix the beans in order to achieve homogeneous roasting and to prevent scorching of beans.

Bonn lander and others (2005) summarize different modern roasting methods by type and characteristics as follows:

- **Rotating cylinder (drum type):** batch operated, direct heating by convective heating of hot gases, temperatures between 204 – 287^{0}C and roasting times between 8.5 and 20 minutes.
- **Fixed drum:** batch operated, direct heating by convective heating of hot gases, temperatures between 204 – 232^{0}C and roasting times between 3 and 6 minutes.
- **Fluidized bed:** Batch operated, direct heating by fluidizing gas, temperatures between 115 – 132^{0}C and roasting time of 5 minutes. (Nutting et al. 1971, Banner 1978, Clarke and McRae 1987)
- **Spouted bed:** batch operated, direct heating by fluidizing gas, temperatures between 310 – 360^{0}C and roasting times between 1.5 and 6 minutes
- **Swirling bed:** batch operated, direct heat transfer, temperature 174^{0}C and roasting times between 1.5 and 3 minutes.
- **Bowl:** continuously operated, direct heating by convective heating of hot gases, temperatures of hot gases being between 480 – 550^{0}C and roasting times between 3 and 6 minutes

2.3.1 Continuous Coffee Roasters

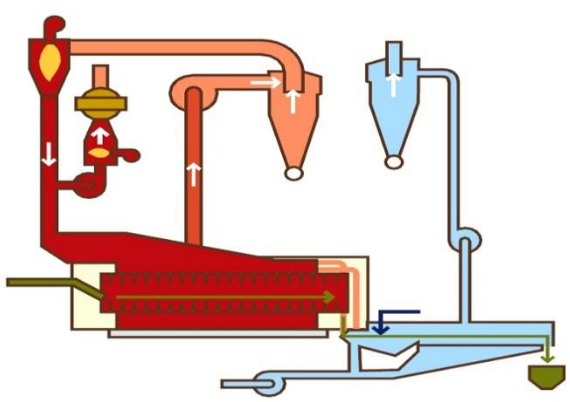


Figure 5: Continuous coffee roaster

Figure 5 shows a horizontal, continuous roaster. Characteristic of roasting section is the horizontally supported drum, made of special perforated sheets. Via a feeding screw conveyor the green coffee is fed into the drum. With every turn of the drum, an auger inside the drum conveys the coffee continuously, slowly, and gently through the roasting section.

The rotation and the static tools cause an efficient intermixing of the coffee beans. The roasting gas flows through the drum and the coffee bed perpendicular to the conveying direction. The coffee is transported through the encapsulated discharge unit at the end of the drum when the desired degree of roasting is obtained.

2.3.2 Rotating Drum Roasters

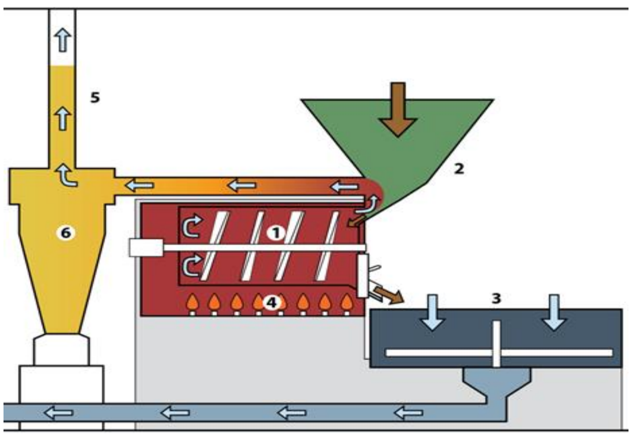


Figure 6: Drum type coffee roaster

While continuous roasting systems are characterized by architectures that are quite similar to the shown case, different layouts of batch roasting drum are constructed. The drum rotation is the fundamental parameter in the roasting process. Too low value can cause an insufficient mixing (the beans sleek on the drum surface).

A too high value can influence negatively the roasting process. Due to the centrifugal force, the beans are slicked to the drum wall and will not be correctly mixed**.**

Drum machines consist of horizontal rotating drums that tumble the green coffee beans in a heated environment. The heat source can be supplied by liquefied petroleum gas (LPG). The most common employed drum roasters are indirectly heated drums where the heat source is under the drum. Direct – fired roasters are roasters in which a flame contacts the beans inside the drum.

2.3.3 Spouted – Bed roasters

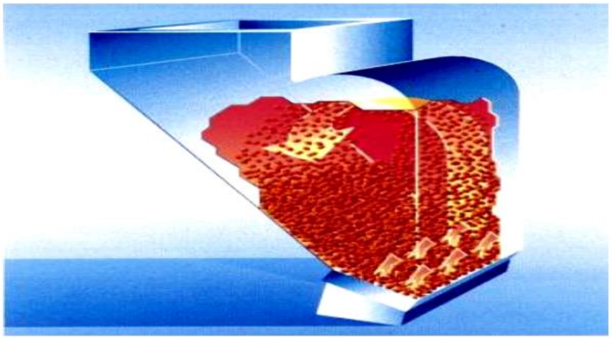


Figure 7: Spouted - Bed roaster

In this roaster the volume, where coffee beans are loaded and hot gas is addressed, has a geometrical configuration optimized in order to ensure a good mixing and enough bean - air contact surface for very rapid roasting. Hot gas passes through the chamber and the fluid – dynamic conditions of the flow causes turbulences that mix beans. Generally, inlet gas at a temperature between 310°C and 360°C is provided. The roasting time is inversely proportional to the gas flow rate; 3 to 6 min roasting is normally used. Very fast roasting can be completed in 1.5 min by using enough gas flow. Lower inlet gas temperatures of 232 to 276°C, and longer roasting times of 10 to 20 min, are used in some spouted – bed roaster

2.3.4 Rotating – Bowl Roaster

In this machine; beans are driven across the surface of a rotating heavy cast-iron bowl by centrifugal force and thrown upward at the rim of the bowl. The beans then strike a stationary circular cover, where blades direct the beans inward. A large central circular duct in the top cover addresses hot gas into the roaster. The beans move across the gas stream exchanging heat. The temperature of the hot gas inlet can vary between 480°C and 550°C and roasting times between 3 and 6 minutes are used.

Fig 8. rotating bowl roaster

2.3.5 Scoop – wheel Roasters

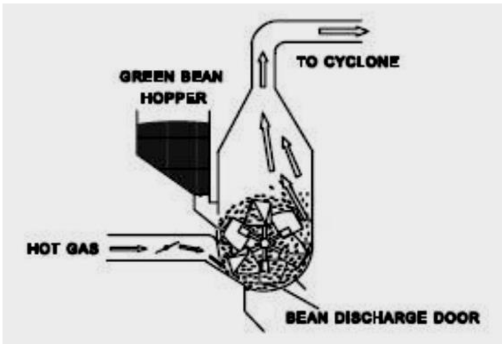


Figure 9: Scoop – wheel roaster

In this type of roaster, scoops mounted on a wheel rotate through the deep bed of beans in the trough. Hot gas flows tangentially downward into the trough through a long axially-oriented slit or perforated metal plate just below the junction of a side wall and the bottom of the trough. Hot gas is addressed by a blower through the beans and towards a metal hood above the trough. The bed of beans is axially mixed by the rotating scoops, that strongly agitates the bed and throws the beans upward into the head space. Temperature of inlet hot gas is close to 420°C. Roasting times between 3 to 6 min are generally employed but very fast roasting cycles can be obtained (1.5 min).

2.3.6 Swirling – Bed Roasters

Figure 10 shows a swirling – bed roaster, that is vertical and circular in cross section with walls that taper slightly outward in the upward direction. Inlet gas from 274 °C to 280 °C is used. Roasting times are inversely proportional to the gas flow rate. Roasts can be completed in 1.5 min but cycles of 3 min are usually used.

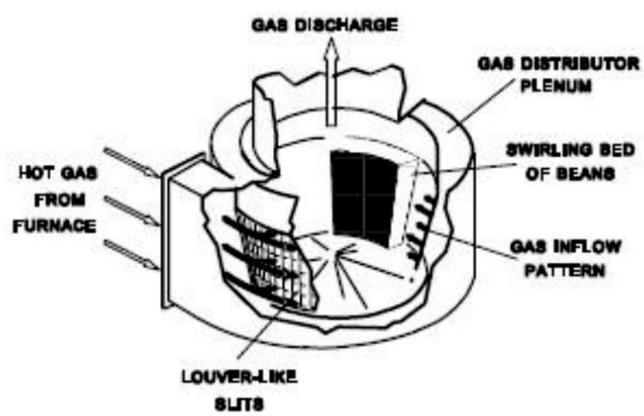


Figure 10: Swirling – Bed roaster

Time, temperature and type of roasting technique will lead to a different degree of roast, which will possess many different characteristics detailed by Coffee Research Organization, 2002d.

2.4 Chemistry of coffee roasting

Coffee processing involves three distinct operations: roasting, grinding and packing. Clean coffee, prior to roasting is blended in desired proportions. Coffee-roasting is a process of pyrolysis which, by increasing the temperature of the coffee from room temperature to 200 - 230^0C, brings about marked physical and chemical changes in the beans that improve the quality of coffee and make it easier to prepare. [21]

Table 1: Coffee roast characteristics

Roast Degree	Characteristics
Light	Light brown to cinnamon color. Low body and light acidity. The beans are dry. This roast is too light and does not allow the coffee to develop to its full potential.
Medium - Light	Medium light brown color. The acidity brightens and body increases slightly. The bean is still dry.
Medium **Figure 11: Coffee roast chart**	Medium brown color. The acidity continues to increase and the body becomes more potent. The bean is mostly dry.
Medium - Dark	Rich brown color. Very small droplets of oil appear on surface. The acidity is slowly diminished and body is most potent. This is the ideal roast for a well-blended espresso.
Dark	Deep brownish/black color. The bean has spots of oil or is completely oily. Subtle nuances are diminished. Flavor decreases, while body dominates.
Very Dark	Black surface covered with oil. All subtle nuances are gone, aroma is minor, and body is thin. This roast is characteristic of American espresso.

Coffee Roast Style Chart

Roast Color	Name of Roast	Bean Surface	Ave. Bean Temp. (at end of roast)	Acidity	Body	Aroma	Sweetness
	Light Brown/ Cinnamon	Dry	380- 400 °F "First crack"	High	Weak	Medium	Low
	Medium light Brown/ American	Dry	400- 415 °F	High	Full	Full	Mild
	Full Medium Brown/ City	Dry	415- 435 °F "second crack"	High	Full	Strong	Mild
	Medium-dark brown/ Full City/ Viennese/ Light French	Slight oily surface	435- 445 °F	Medium	Very full	Strong	Strong
	Dark brown/ French/ Espresso	Shiny surface	445-460 °F	Low	Full	Medium	Full
	Very dark (nearly black)/ Dark French/ Spanish	Very shiny surface	460- 480 °F	very low	Weak	Mild	Low

The changes that the coffee bean goes through during the roasting process are amazing. Those small hard beans, when properly exposed to controlled heat, grow in size and change in color, becoming the source of one of the world's most cherished beverages. [16]

The main physical changes are:

- Loss of weight mainly due to water evaporation and the release of certain heavy gases such as CO_2 which causes the bean to swell
- Increase its volume by about 60%

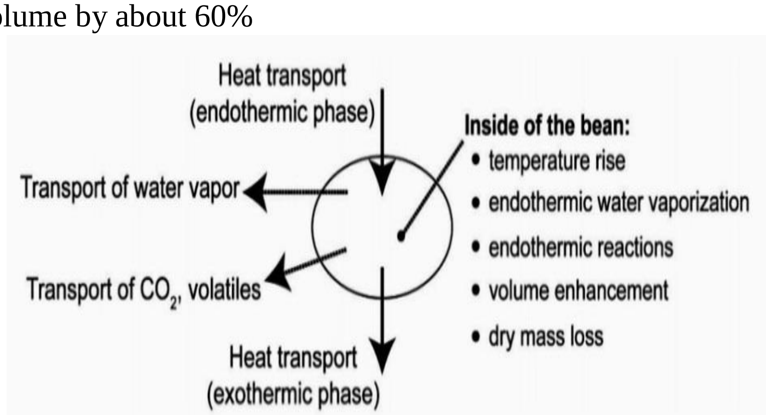


Figure 12: Aspects of coffee roasting

Loss of weight and increased volume are accompanied by a change in the structure of the bean, which becomes more elastic more brittle (which makes it easier to grind). Its color changes from green to brown through the caramelizing of the sugar and other carbohydrates and the formation of certain pigmented substances produced by different chemical reaction.

The aromatic qualities of coffee only become apparent once the beans have been exposed to high temperatures during pyrolysis or roasting.

The aroma of green coffee seeds is quite different from what we imagine when we hear the word coffee. It is only through roasting that the seeds gain the characteristic aroma and flavor of coffee. Although roasting appears to be simple in terms of processing conditions, the chemistry underlying this flavor development is highly complex and not completely understood. The high roasting temperatures cause a series of physical and chemical changes in the seeds. The specific roasting conditions strongly influence these changes and consequently affect the bioactivity and flavor of the beverage. The most common roasters available for home and industrial use are drum roasters, in which the seeds are in direct contact with fire and/or a hot surface.

The temperatures used to roast the seeds depend on the roaster type, but experts place the roasting zone between 180^oC and 250^oC the optimum temperature being between 210^oC and 240^oC. Above this temperature, over-roasting begins. In general, four principal groups of reactions occur during roasting: dehydration (deprive of moisture), hydrolysis (breaking down of water molecules in hydrogen and oxygen elements), desmolysis and catalysis (for aiding the speeding up of chemical process).

In the initial phase of roasting, free water evaporates. When the seed temperature reaches 130^oC, sucrose caramelizes, and the seeds begin to brown and swell. Chemical changes in this initial phase are relatively small compared to those that occur at the end of the roasting process. At temperatures higher than 160^0C, a series of exothermic and endothermic reactions take place; the seeds become light brown, their volume increases considerably, and aroma formation begins. The chemical reactions responsible for the aroma and flavor of roasted coffee are triggered at approximately 190^0C. [16]; [18]

The roasting process normally lasts for between 12 and 15 minutes. In slow roasting techniques, it requires about 25 minutes. While roasting gives coffee its taste and aroma, it also changes the bean in certain ways. [20]

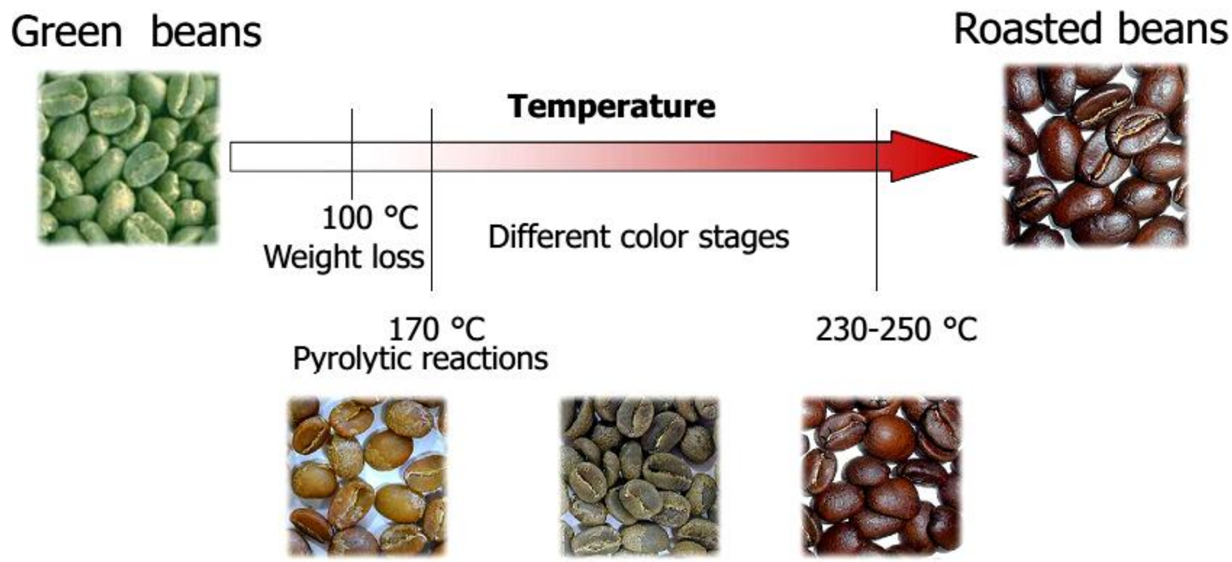


Figure 13: Color change of coffee beans at different temperature

The beans lose weight due to evaporation of water from the green coffee. About 0.2 - 0.4 percent silver skin is also eliminated due to roasting. Roasting induces the endosperm to increasing volume due to the formation and expansion of gas between 180^{o}C and 220^{o}C.This is manifested in a volumetric increase of about 50 to 80 percent, the extremes being between 30 and 100 percent. The bean becomes porous and crumbles when pressure is applied. The minerals in coffee do not change noticeably during roasting, but their relative content increases when the water and volatile organic components disappear. When the desired color is reached, the coffee is discharged into the cooling bin where it is cooled up to room temperature. The color of roasted beans gives a good indication of the taste and flavor. But the color differs at every batch, whereas the aim is to get the same color every time and therefore a consistent taste. [4]; [8]

2.4.1 Chemical changes produced during roasting

As already explained in the introduction part, many physical and chemical transformations and reactions take place during roasting. Bonn lander and others (2205) explain these changes from a microscopic and macroscopic point of view. Table 2 describes the roasting characteristics for Arabica and Robusta coffee. Many physical changes occur during roasting. The color of the beans fades to a light yellow color at the beginning of roasting (20 -130^{0}C) and it darkens with an increase in temperature. Oil sweats to the surface of the bean at high roasting levels causing a brilliant appearance. Beans become more porous with the increase of temperature, releasing water and carbon dioxide generated by Maillard reaction. Density decreases by approximately 30% with roasting. Many organic losses occur like destruction of carbohydrates, chlorogenic acid and trigonelline. The aroma content reaches a maximum at low to medium roasting. The pH increases with the increase in roasting levels. Chemically the beans main constitute are affected in many ways. [22]

Carbohydrates: are broken down. Sucrose is partially hydrolyzed, and the rest caramelized. Maillard reaction takes place producing volatiles or aroma compounds and non-volatiles from the reducing sugars present. Polysaccharides except cellulose are partially solubilized. (Bradbury, 2001; Red well and others, 2002; cited in Bonn lander and others (2005).

Non – volatile lipids: Are only affected slightly upon roasting. The level of trans-fatty acids increases. The linoleic acid content decreases slightly with roasting temperature. Dehydrocafestol, dehydrokahweol, cafestal and kahweal are formed increasingly with high temperatures. Up to 20% of tocopherols and 25-50% of carbonic acid 5-hydroxytryptamides are destroyed. (Wurziger and Harms, 1969; Wurziger, 1972; Speer and Kölling-Speer, 2001; Kurt and Speer, 2002; cited in Bonn lander and others, 2005).

Proteins, peptides and amnoacids: Protein content changes only slightly upon roasting but almost all the proteins present in green coffee are denatured (McRae, 1985; cited in Bonn lander and others, 2005). Some cross-links between amino acid residues of the proteins are formed (Homma, 2001; cited in Bonn lander and others, 2005). The amino acid composition is changed; the stable ones like glutamic acid remain the same but others like cysteine or arginine decrease or are destroyed (McRae, 1985; cited in Bonn lander and others, 2005). Of the free amino acids, only traces are left after roasting. The reaction products are Maillard products which are melanoidins, their precursors and volatiles, and dioxopiperazines, of which proline containing ones are bitter (Ginz, 2001; cited in Bonn lander and others, 2005). [23]

Minerals and Alkaloids: Minerals with the exception of phosphoric acid do not change upon roasting. Alkaloids such as caffeine do not change upon roasting, but a small part is lost by sublimation; others like trigonelline are partially decomposed. [29]

Table 2: Roasting characteristics of Arabica and Robusta coffee beans

Type of roast	Arabica Coffee			Robusta Coffee		
	Roasting Time (min)	Roasting loss (%)[a]	Moisture weight (%)[b]	Roasting Time (min)	Roasting loss (%)[a]	Moisture weight (%)[b]
Light	7	3.8	2.1	5	2.4	2.3
Medium	10	3.7	2.1	7	4	1.9
Dark	13	10	1.8	14	8.3	1.8
Very Dark	19	9.8	1.7	16	7.8	1.3

a. dry matter bases
b. Moisture content of green beans: Arabica 8.4%; Robusta 7.9%. (determined by the vacuum oven method

Source: (Pearson 2009; Trugo and McRae 2011)

2.4.2 Recognizing roast level

To get the taste desired in coffee means knowing when to stop the roast. There are a number of indicators which can be used to judge the roast level. Even in this computer age, they are the same ones that professional roasters have long used to recognize the level of roast. These indicators include *sound*, *color*, *temperature* and *aromas* of the roasting process. [4]; [14]

2.4.2.1 Sound

When first beginning to roast coffee, the sounds the beans make are the easiest roast-level indicator to learn. The beans actually make certain noises during the roasting process and these noises are an accurate indicator of roast level. These sounds are referred to as “cracks” and there are two different cracks that take place at two distinct time periods during the roast. These two different periods, for obvious reasons, are called *“first crack”* and *“second crack”*.

During both these periods, the sounds start slowly at first. It will be initially noticed just an occasional “crack,” followed by another a few seconds later. This increases in frequency as sounds become gradually more rapid. After a while, the progression of sounds slows down again, and eventually subsides altogether.

First crack

“First crack” refers to a specific period of time during which similar sounds will be heard. First crack sounds somewhat like breaking wooden pencils; distinct, easy to hear, sharp snaps. During

this time, the beans in the roaster are already light brown, and the grassy smelling steam changes to a mellow, drier-smelling smoke. It can be heard an occasional snap, then another, then the crackling gradually speeds up, and, after a while, slows down again, then stops.

The actual times at which these periods start and stop again depend a lot on the variety of coffee being roasting. The coffee roasted will affect the differences in sound, volume, and speed of the cracks. In some varieties the two periods also partly overlap, making it difficult to tell when first crack ends, and second crack begins.

Second crack

After first crack ends, there is usually a period of about one minute before second crack begins. By that time, the beans are a delicious-looking, dark shade of brown. Second crack can be a little more difficult to hear as these sounds are lower in volume, but once it is learned to distinguish the sound it is unmistakable. It is a more muffled subtle, subtle sound than first crack. If first can be described as breaking pencils, second sounds like breaking toothpicks. Generally, once second crack really gets going the individual cracks occur with much greater frequency than the sounds during first crack.

The beginning of second crack is an indicator that the coffee is nearly done and it should be ready to end the roast very soon. When second crack begins to diminish, most coffees are near the end of their preferred-flavor profile, and when second crack ceases the beans are on the edge of being ruined and are approaching the ignition point. [14]

Timing of the cracks

There are many factors that can affect the various times at which to expect the following changes. These influencing factors can include:

- **Beans chosen** (different varieties have various roasting characteristics)
- **Actual weight of bean** (250 grams of one variety can take up more space than the same weight of another variety)
- **Size of beans:** some beans are small (pea berry) and some quite a bit larger (Colombian Supremo)
- **Ambient air temperature and humidity**

Moisture level of the beans

The following table shows an averagely accurate guideline for roasting coffee. The times indicated are generalizations from experimenting variety types of coffee.

Table 3: Roast level indicators at different roasting temperature

18:00 Roast (Time Remaining) (mm:ss)	Roast Level Indicators which will be observed
14:00 – 12:00	Beans become green in color; there is some steam which has a pleasant grassy aroma.
11:00 – 10:00	Beans change slowly from green to yellow. The smoke initially smells like pancakes, then become more like baking bread.
9:00 – 8:00	Beans gradually turn from dark yellow to a “cinnamon” brown color. The smoke has a “nutty” odor.
4:00 – 3:00	First crack, sounds like breaking pencils. Beans are medium brown at this stage. The smoke increases and begins to smell like coffee.
2:00	Second crack, sounds like breaking toothpicks. Beans are dark brown and oil spots seen on some beans. Smoke becomes much denser.
1:00	The rapid sounds of the second crack will be heard, and the smoke coming from the roaster will be pungent and quite dense. This is about as dark as dark as most coffees should be roasted.

2.4.2.2 Temperature as a roast indicator

Temperature is an excellent indicator of the state of the roast. For example, when roasting decaffeinated coffee it will be more difficult to see color changes and there will not be as many cracks as “regular” coffee. Temperature can be an important indicator with these beans. The temperatures given below can be used as a general reference during the process. [18]

Table 4: Physical changes on coffee beans at different level temperature

Up to 135^0C	Not much happening
135 – 148^0C	The beans begin to turn more green

165 – 173^{0}C	Turning from green to yellow
173 – 176^{0}C	The yellow has turned to a yellow – tan
182^{0}C	Mostly a light tan
187^{0}C	Medium tan
190^{0}C	Dark tan
196^{0}C	Light brown
196 – 198^{0}C	First crack begins
204 – 207^{0}C	First crack is active, then slows
210 – 215^{0}C	Beans are a beautiful brown
212^{0}C	Second crack begins
216 – 217^{0}C	Second crack quite active. Beans are a dark brown and becoming oily
218^{0}C	Beans are oily and smoke increases and is quite dense
218 – 220^{0}C	Second crack still active and the beans are very oily and getting darker

2.4.2.3 Bean Color as a Roast Indicator

As the roast progress the beans go through series of a subtle, and sometimes not-so-subtle color changes from their original color, to green to beige, then through a whole range of browns – first dull then shiny as they darken, and progressing to brown so dark that it can look black. Although color is important, for someone new to coffee roasting it can be difficult to use color as the sole indicator of roast. As the skill and perception of the roasting operator grow, bean color will increase in importance as an indicator of roast level. [18]

2.4.3 Roasting imperfections

There are four key roasting imperfections to avoid:

Temperatures too low, time too short

Result: underdeveloped flavor characterized by roasted beans which have not fully expanded in volume, exceedingly light roast color, grassy, grainy, raw nut like flavor.

Temperature too high, short roasting time

Result: disparity in roast levels between the outer bean layer and the inner bean. Extreme examples show a burnt outer layer and raw underdeveloped inner layer. This is the classic case of “tipped” coffee. Taste results are a combination of charred, grassy and grainy. It is decidedly unpleasant.

Too high temperature, too long roast

Result: Burnt coffee. The flavor has crossed the line from a coffee flavor with carbony overtones, to a pure charcoal taste.

Too low temperature, too long roast

Result: Visually, this coffee may look just fine, good bean size, surface texture and even roast color all through the bean. Flavor and fragrance, however, are “missing in action”. Very blend, lifeless boring brown liquid. This is the classic “baked” coffee.

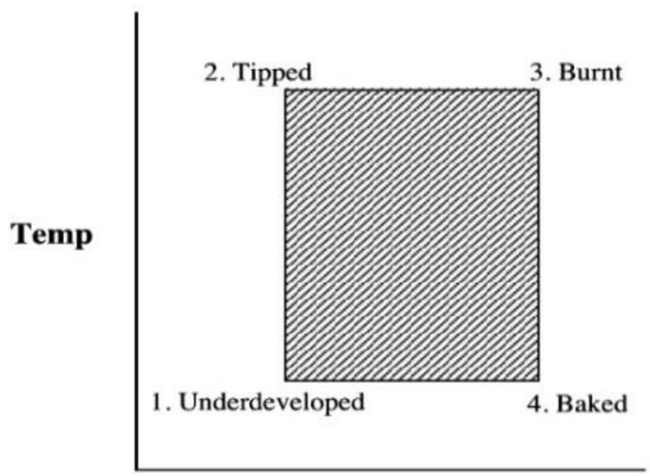


Fig.14: temperature_time requirement of good roasting

Literature Summary

Roasting coffee is a thermodynamic process in which the application of heat and the resulting uptake of heat by the bean directly affects final flavor. The condition under which heat is applied is affected by environmental factors, including internal volume of the roaster, humidity, barometric pressure, and ambient temperature. The ability of the bean to take on heat and the rate at which the absorbed heat dissipates throughout the bean is a function of its physical state, including % moisture, density, and bean size. The chemical changes taking place at any instant in the process depend upon the amount of heat already taken on, the amount of heat available in the immediate environment, the ability of the mass of beans to conduct heat, and the reactions that have already taken place or are in the process of taking Place. The temperatures used to roast the seeds depend on the roaster type, but experts place the roasting zone between 180^{o}C and 250^{o}C the optimum temperature being between 210^{o}C and 240^{o}C. Above this temperature, over-roasting begins. In general, four principal groups of reactions occur during roasting: dehydration (deprive of moisture), hydrolysis (breaking down of water molecules in hydrogen and oxygen elements), desmolysis and catalysis (for aiding the speeding up of chemical process).Since the existing roasting machine has many roasting imperfection having heterogeneous mixing of beans which yields undesired and unwanted outcomes.

Research Gap

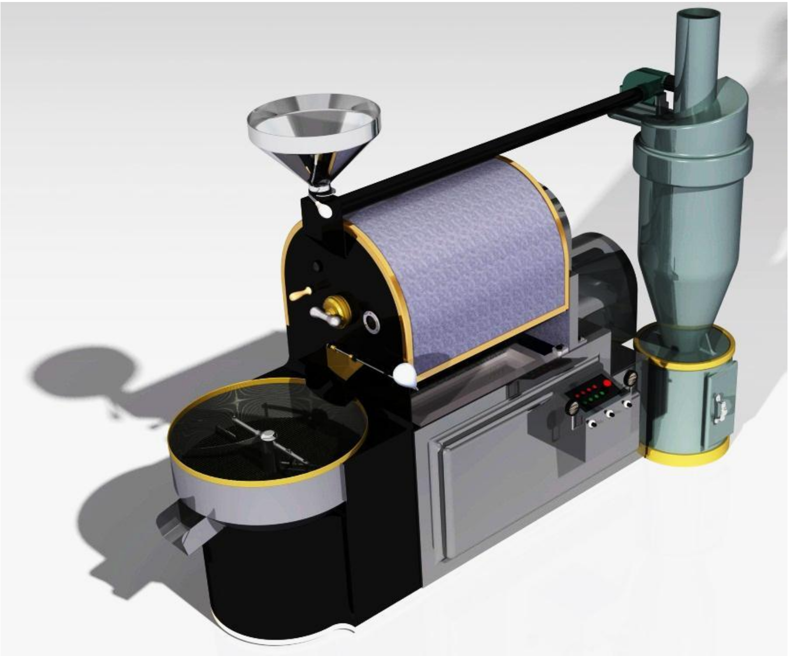
Since the roasted qualified coffee commodity exchange in the World has its own influence on the National economic issues as it is the export standard trademark, in order to compute the World market it is needed to have standard roasting machine which will yields the optimum and desired quality of coffee called aroma. But the existing roasting machine now in use has great cons in that it is impossible to mix the coffee beans uniformly free from roasting imperfections, thus to fulfill this problem or shortage it is needed to design and model rotating horizontal drum type coffee roasting machine using LPG as a source of energy because of its high heating value and burning consistently without stoppage and interruption; in addition to this it is free of ozone depleting potential compared to other energy sources.

CHAPTER THREE

DESIGN OF DRUM – TYPE COFFEE ROASTER

3.1 Mechanical design of the machine

3.1.1 Introduction - Machine specification



Capacity per batch	25kg
Heat source	Liquefied Petroleum Gas (LPG)
Burner type	Atmospheric burner
Roasting time	15 – 20 minutes
Electric power	220V, 60 Hz, single phase
Roaster dimension	60 x 200 x 150
Roster weight	120 kg
Table-5 Machine specification	

Source: Design Assumption

Figure 15: The Roasting Machine

3.1.2 Components of the machine

1. Frame: the frame is the basic component on which all the other components (the drum, cooling tray, gearbox, motor drives, etc.) reside on. It is made from RHS (rectangular hollow steel) structured as shown in the figure.

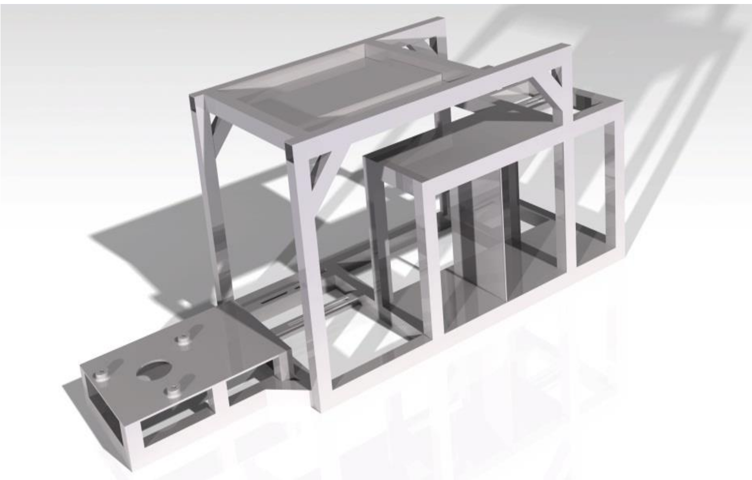


Figure 16: Frame

2. **Hopper**: conical funnel which is used to load coffee beans into the roasting drum.

3. **Hopper lid lever**: is used to close the hopper once the roasting process starts.

4. **Sight glass**: to see – through the roasting process inside of the roasting drum.

5. **Bean release lever**: is used to discharge the coffee once the roasting process ends.

6. Thermostat: is used to sense the temperature of the coffee beans and the air between them so that the process's temperature is maintained near a desired set point.

7. Testing spoon: is used to see the level of roast (when color is used as roast level indicator) while the drum is still in rotation.

8. Drum – wall clearance adjuster: as the name indicates, it is used to adjust the clearance between the drum and the internal wall of the roaster. The shaft has internal thread in which this part is tightened or loosened for proper adjustment.

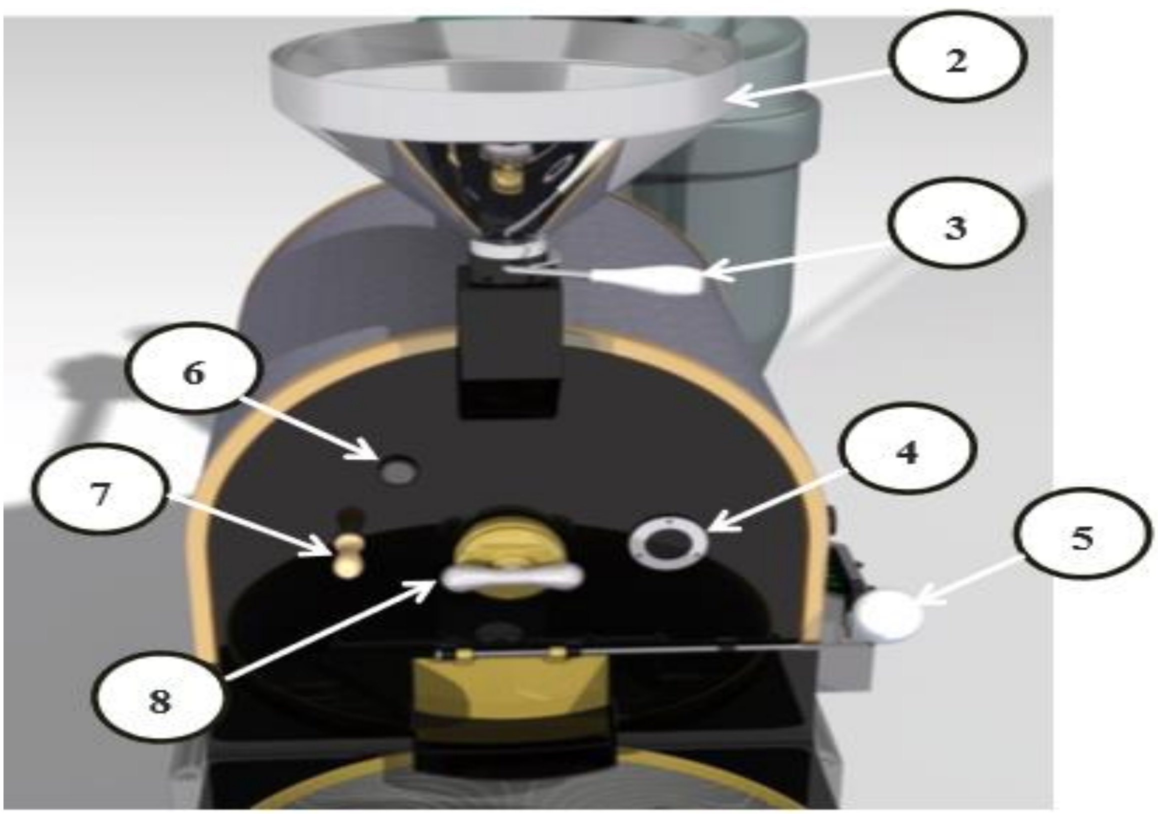


Figure 17: Roasting process controlling components

9. Roasting drum: is a solid, rotating, cylindrical chamber laid horizontally on its axis, with an open flame below it. It is made from mild steel sheet. Paddles of opposite arrangement are provided for evenly mixing the beans and also to push the beans out from the drum during discharge.

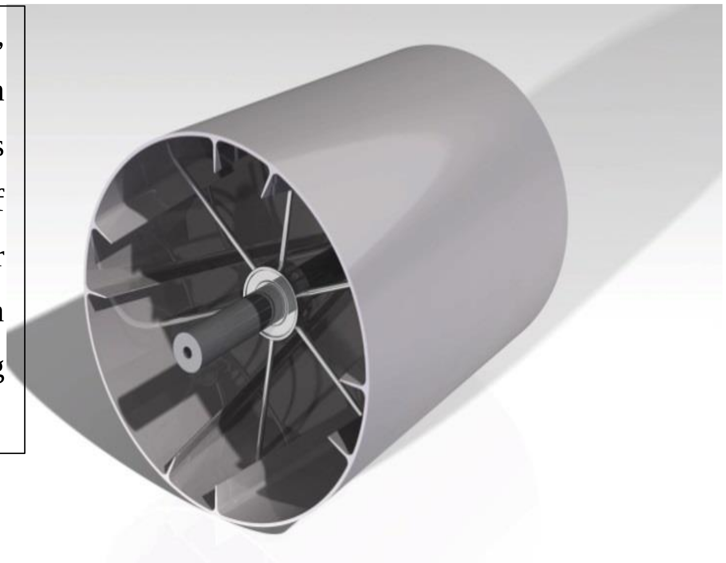


Figure 18: The roasting drum

10. Cooling tray: once the desired level of roast is reached, the coffee is discharged into this part where it is cooled up to room temperature using a rotating paddle and fan.

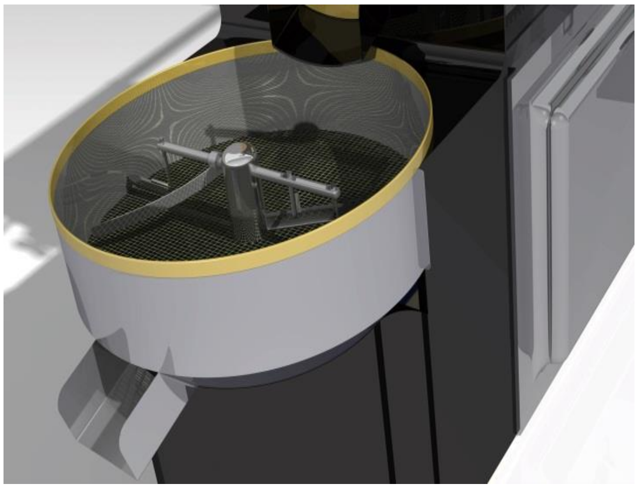


Figure 19: The cooling tray

11. Burner: the heat source for the roasting process is LPG which uses atmospheric burner.

12. Cyclone: is used to discharge the smoke and skin of the coffee bean (chaff) separately.

13. **Electrical control cabin:** consists of different push buttons to start and stop rotation of the drum, cooling bin mixing paddles and fans.

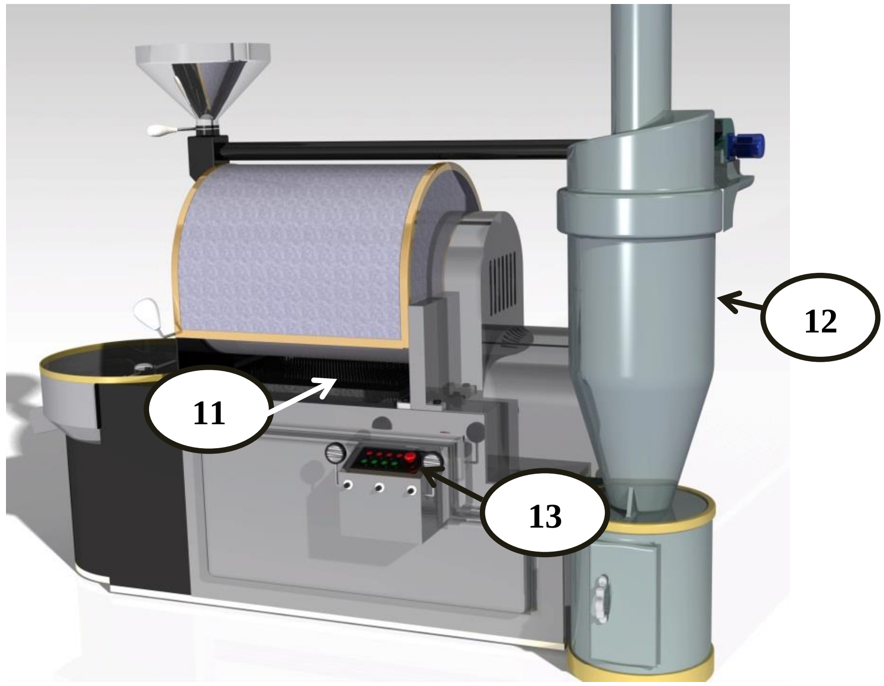


Figure 20: Location of burner, electrical cabin and cyclone

3.1.3 Material selection

The selection of a proper material for the design purpose is a very crucial issue. The best material is one which serves the desired objective at the minimum cost. The following factors should be considered while selecting the material.

- ✓ availability of the materials
- ✓ suitability of the material, for the working condition in service and
- ✓ mechanical and thermal property of the material
- ✓ the cost of the materials

Table 6: materials used in the design of the machine

Component	Material
Sheet metal	Mild steel
Chain	Mild steel
Sprocket	Mild steel
Shaft	Mild steel (C - 30)
Hollow square bar	Mild steel

Bearings	Tin – based alloy
Key	Mild steel
Bolts and nut	Mild steel
Asbestos	---
Solid rods	Mild steel
Worm – spur gearing	Phosphor bronze
Angle iron	Mild steel

As it can be inferred from table 6, most of the components are made from mild steel. This is due to the fact that this material is a good candidate for the selection of material due to its plenty positive attributes compared to other materials. (Based on AISI/SAE previous application 1020)

The most important advantages of mild steel are:

- ✓ it is produced in large quantity and is largely available
- ✓ have high ductility and toughness
- ✓ easily machineable
- ✓ easily weldeable
- ✓ least expensive to produce

Bearing material

The selection of particular type of bearing metals depends upon the condition under which it is to be used. A bearing material should have the following properties:

- ✓ low coefficient of friction
- ✓ ability to withstand bearing pressure
- ✓ high thermal conduction
- ✓ good casting qualities
- ✓ good wearing ability
- ✓ economic in cost

For the design of this machine tin based alloy is selected because this material have many desired attributes such as: low coefficient of friction, non-corrosive property, economic in cost and is most common bearing material used with cast iron boxes.

3.1.4 Design of the rotating drum and cooling tray

The roasting capacity of the drum depends directly on the total volume of the drum. In order to estimate the roaster volume, the area of cross section (of the shaded region) must be first calculated. This area is the area occupied by the coffee in each batch of the process.

The total volume occupied by the coffee beans once it enters the drum is first calculated. To determine this volume the following parameters are used. (FAO, Bulk Density Averages, 2010)

- Mass of coffee to be roasted in each batch = 25kg
- Density of coffee = 401kg/m^3

We know that density, ρ = mass/volume

Volume = mass / density== 25kg / 401kg/ = 0.063m^3

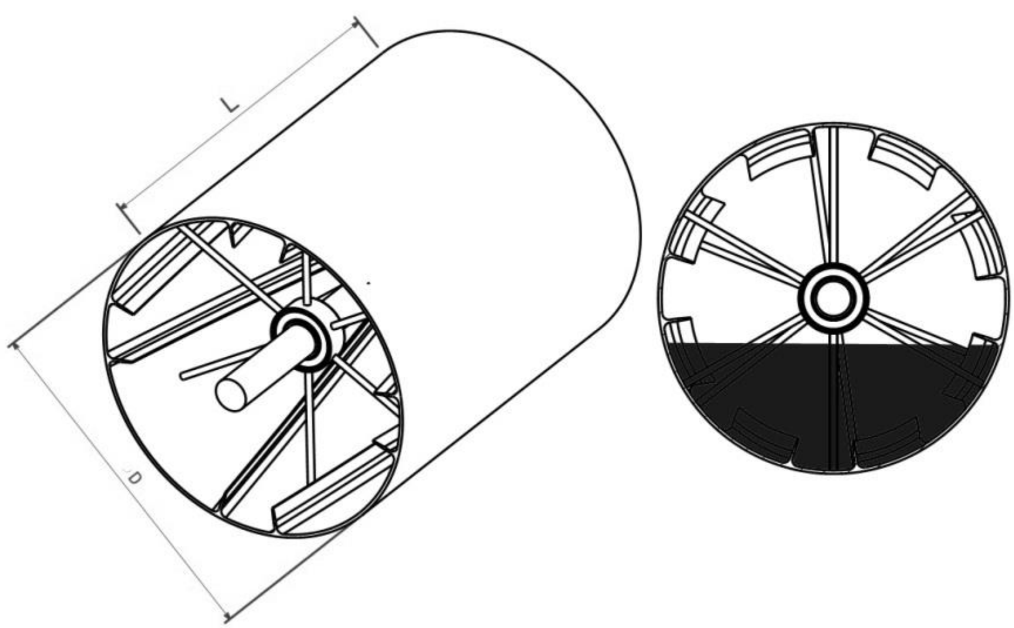


Figure 21: Geometry of the rotating drum

But this volume doesn't include the air gap between each bean. To account for this lets take the volume twice of the one calculated above. i.e. $V_1 = 0.126m^3$

This volume must equal with the volume of the shaded region of the drum.

$$V_2 = \frac{cross\ sectional\ area\ of\ the\ drum}{2} * \text{length of the drum}$$

$$= \frac{\pi r^2}{2} * L$$

Now let's equate these two volumes, i.e. $V_1 = V_2$

$$0.126m^3 = \frac{\pi r^2}{2} * L$$

There are two unknowns: the radius and the length of the drum. By assuming one parameter we can find the other. Let's take r = 25cm = 0.25m

$$0.126m^3 = \frac{\pi r^2}{2} * L$$

$$L = \frac{2\ (0.126)}{\pi r^2} = \frac{2\ (0.126)}{\pi (0.25)^2} = 1.28 \approx 1.3m$$

Following similar steps the size of the drum is determined. We have already calculated the total volume of the coffee bean. But during roasting there is an increase in volume and decrease in density. The increase in volume can reach up to 60%.

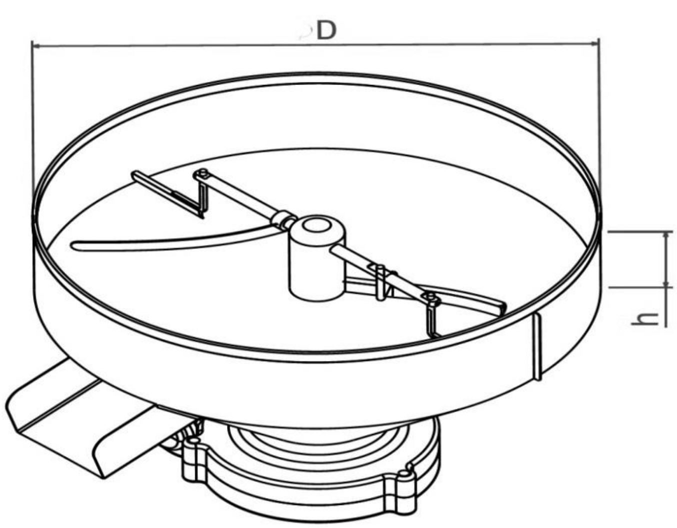


Figure 22: Geometry of the cooling tray

Therefore, the volume of the roasted coffee, $V_3 = V_1 * 1.6 = (0.126m^3) *1.6 = 0.2016\ m^3$

This new volume must be equal with the volume of the cooling tray.

The volume of the cooling tray, V_4 = cross sectional area of the tray * height of the chamber

$$= лr^2 * h$$

Now these volumes have to be equal, i.e. $V_3 = V_{4;}$ $0.2016\ m^3 = лr^2 * h$

The same principle used to determine the size of the roasting drum applies here too. By assuming one parameter we fined the other one. Let's take r = 30cm = 0.3m

$0.2016\ m^3 = лr^2 * h$; $h = \frac{0.2016^3}{лr^2} = \frac{0.2016^3}{л(0.3)^2} = 0.143 \approx 0.2m$

The coffee must be some space once the coffee is discharged for cooling. To account for this lets height of the cooling tray, h = 0.25m = 25cm

3.1.5 Design of chain and sprocket

Power is transmitted to the rotating drum through chain and sprocket. There are some machines which use belt drive. But due to the following main reasons chain transmission is selected.

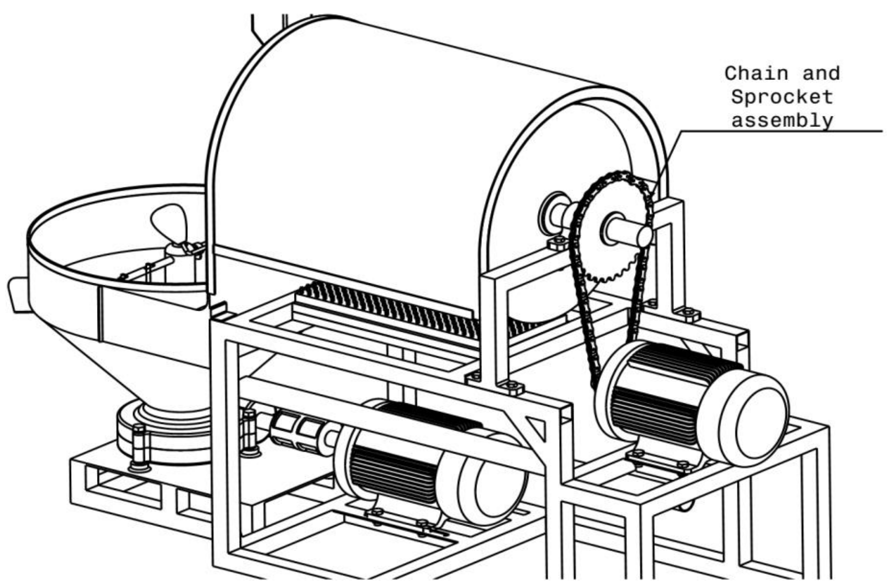
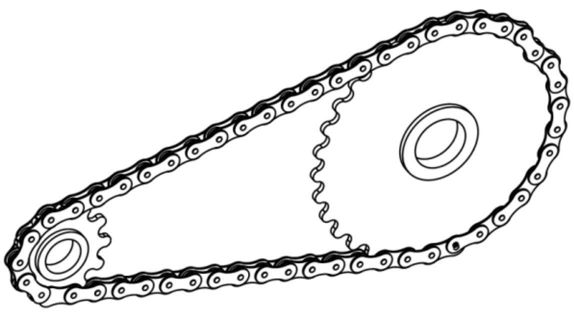


Figure 23: Chain and sprocket assembly

- It can be operated under adverse temperature and atmospheric condition. The heat from the drum won't affect the transmission at all unlike in belt drives as the belt softens easily due to this heat.
- No slip takes place during chain drive, hence perfect velocity ratio is obtained
- It gives high transmission efficiency (up to 98%)
- It gives less load on the shafts
- It transmits more power than belt
- Since the chains are made of metal, therefore they occupy less space in width than belt drive



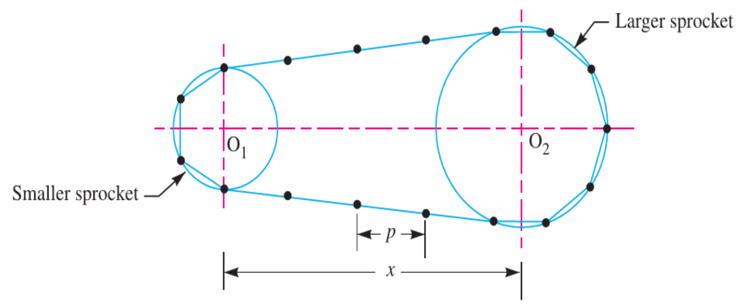


Figure 24: Length of chain and center distance

Let T = number of teeth on the sprocket

p = pitch of the chain

x = center distance

To simplify the design process, the following assumptions are made depending on the desired geometry and shape of the machine.

- Rated power = 5.2 KW
- Rotational speed of the driving sprocket, N_1 = 600 rpm
- Velocity ratio, V.R. = 1 : 6
- Roller type of chain is used

From table 13 (APPENDIX B), we find that for the roller chain, the number of teeth on the smaller sprocket or pinion (T_1) for a velocity ratio of 6 are 17.

From this, the number of teeth on the larger sprocket, $T_2 = 17 * \frac{N_1}{N_2} = 17 * 6 = 102$

We know that the design power = Rated power * Service factor (K_s)

The service factor, K_s is the product of various factors K_1, K_2 and K_3.

The values of these factors are taken as follows:

K_1 = Load factor = 1, for constant load
= 1.25, for variable load with mild shock
= 1.5, for heavy shock loads

K_2 = Lubrication factor = 0.8, for continuous lubrication
= 1, for drop lubrication
= 1.5, for periodic lubrication

K_3 = Rating factor = 1, for 8 hours per day
= 1.25, for 16 hours per day
= 1.5, for continuous service

The transmission is subjected to variable loads as the weight of coffee inside the drum varies from time to time. For this reason the load factor K_1 is taken 1.25. There will be periodic lubrication and the machine is intended to operate 8 hours per day. So $K_2 = 1.5$ and $K_3 = 1$.

$\therefore$ Service factor, $K_s = K_1 * K_2 * K_3 = 1.25 * 1.5 * 1 = 1.875$

Design power = Rated power * Service factor (K_s)

= 5.2 * 1.875 = 9.75 KW

From table 14(APPENDIX B), It was found using interpolating the neighboring values that corresponding to a pinion speed of 600 rpm, the power transmitted for chain number 12B is 10.08KW per strand.

According to Indian Standards (IS: 2403 – 1991), the various characteristics such as pitch, roller diameter, width between inner plates, transverse pitch and breaking load for the roller chains are given in table 15(APPENDIX) ;

Pitch, p = 19.05 mm

Roller diameter, d = 12.07 mm

Minimum width of roller = 11.68 mm

Breaking load, W_B = 28.9 KN

The pitch circle diameter of the smaller sprocket or pinion,

$$d_1 = p \operatorname{cosec}\left(\frac{180}{T_1}\right)$$

$$= 19.05 * \operatorname{cosec}\left(\frac{180}{17}\right) = 74.87 \approx 75 \text{ mm}$$

and pitch circle diameter of the larger sprocket or gear

$$d_2 = p \operatorname{cosec}\left(\frac{180}{T_2}\right)$$

$$= 19.05 * \operatorname{cosec}\left(\frac{180}{102}\right) = 449.52 \approx 450\text{mm}$$

Pitch line velocity of the smaller sprocket,

$$v_1 = \frac{\pi * 0.075 * 600}{60} = 2.36 \text{ m/s}$$

$$\therefore \text{ Load on the chain, } W = \frac{Rated\ power}{Pitch\ line\ veloctiy} = \frac{5.2}{2.36} = 2.2 \text{ KN} = 2200\text{N}$$

And factor of safety = $\frac{W_B}{W} = \frac{28.9}{2.2} = 13.14 \approx 14$

This value is more than the value given in table 16(APPENDIX), which is equal to 10.3

The minimum center distance between the smaller and larger sprockets should be 30 to 50 times the pitch. Let us take it as 30 times the pitch.

$\therefore$ Center distance between the sprockets, x = 30 * 19.05 = 572 mm

In order to accommodate initial sag in the chain, the value of center distance s reduced by 2 to 5 mm. therefore correct center distance, x = 572 - 5 = 567 mm

We know that the number of chain links, k = $\frac{T_1 + T_2}{2} + \frac{2x}{p} + \left[\frac{T_1 - T_2}{2\pi}\right]^2 * \frac{p}{x}$

$$= \frac{17+102}{2} + \frac{2*567}{19.05} + \left[\frac{17-102}{2\pi}\right]^2 \frac{*19.05}{567}$$

$$= 121$$

From this, the length of the chain, L = k * p = 121 * 19.05 = 2305 mm = 2.305m

3.1.6 Design of the main shaft

The main shaft is the one which is subjected to both bending moment (due to the combined weight of both the drum and the coffee in the roasting chamber) and twisting moment (due to the torque from the pulley). Therefore the shaft is designed on the basis of these two moments simultaneously.

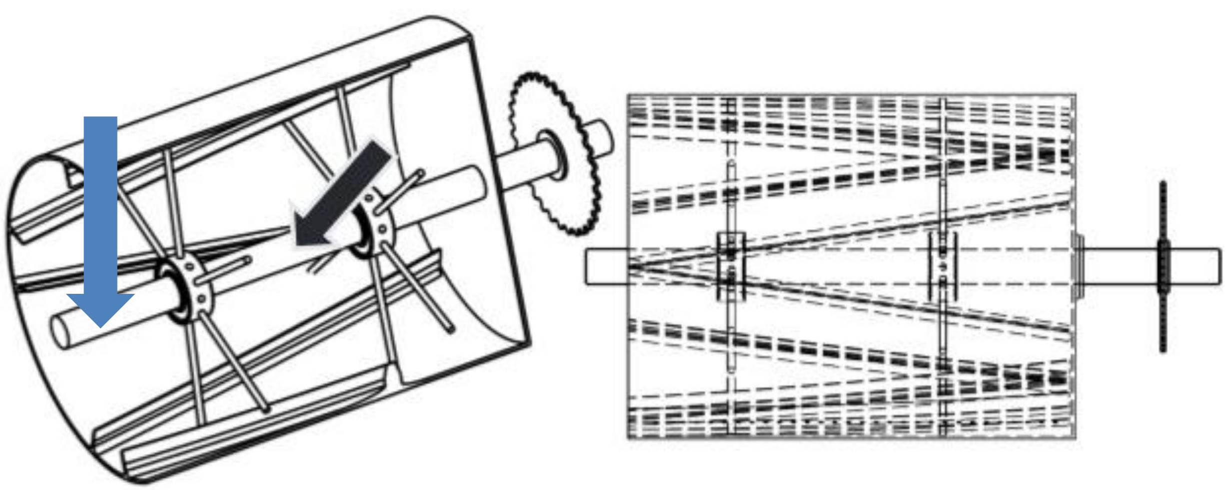


Figure 25: The main shaft – drum assembly

When a shaft is subjected to combined loading, the design is usually based on the maximum shear stress theory, since this theory is used for ductile material such as mild steel. According to this theory, the following relation must be satisfied.

$$\tau_{max} = \frac{1}{2}\sqrt{\left(\frac{32M}{\pi d^3}\right)^2 + 4\left(\frac{16T}{\pi d^3}\right)^2} = \frac{16}{\pi d^3}\left[\sqrt{M^2 + T^2}\right],$$

Or $\frac{л}{16} * \tau_{max} * d^3 = \sqrt{M^2 + T^2}$

the expression $\sqrt{M^2 + T^2}$ is the equivalent twisting moment and is denoted by Te. It is a moment when acting alone, produces the same shear stress, τ as the actual twisting moment.

By limiting the maximum shear stress, τ_{max}, equal to the allowable shear stress for the material, the above equation may be written as:

$$T_e = \sqrt{M^2 + T^2} = \frac{л}{16} * \tau * d^3$$

Now according to maximum normal stress theory, the maximum normal stress in the shaft,

$$\sigma_{b\,(max)} = \frac{1}{2}\sigma_b + \frac{1}{2}\sqrt{(\sigma_b)^2 + 4\tau^2}$$

$$= \frac{1}{2} * \frac{32M}{лd^3} + \frac{1}{2}\sqrt{\left(\frac{32M}{лd^3}\right)^2 + 4\left(\frac{16T}{лd^3}\right)^2}$$

$$= \frac{32}{лd^3}\left[\frac{1}{2}\left(M + \sqrt{M^2 + T^2}\right)\right]$$

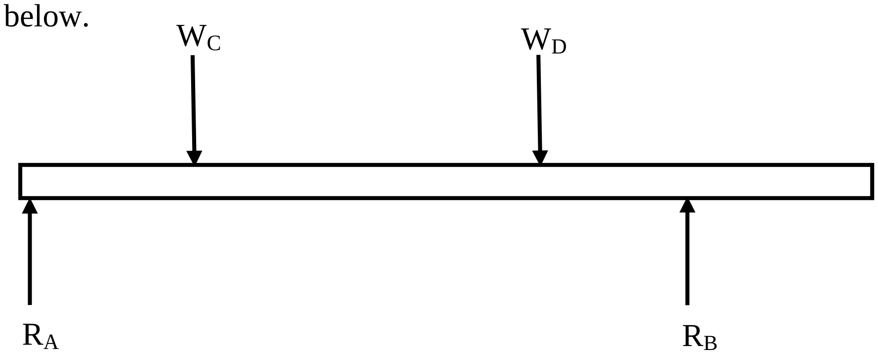
Or $\frac{л}{32} * \sigma_{b\,(max)} * d^3 = \frac{1}{2}\left[M + \sqrt{M^2 + T^2}\right]$

The expression $\frac{1}{2}\left[M + \sqrt{M^2 + T^2}\right]$ is the equivalent bending moment and is denoted by M_e. It is the moment which when acting alone produces the same tensile or compressive stress, σ_b as the actual bending moment

By limiting the maximum normal stress, $\sigma_{b(max)}$ to the allowable bending stress for the material, σ_b, the above equation can be written as,

$$M_e = \frac{1}{2}\left[M + \sqrt{M^2 + T^2}\right] = \frac{л}{32} * \sigma_b * d^3$$

The static load distribution on the shaft due to the weight of the drum and the coffee is shown in the figure below.



Where R_A and R_B are = reaction forces at point A and point B respectively

W = total weight of the coffee and drum

The drum is made from mild steel.

The weight of the drum is calculated below.

We know $\rho = \frac{mass}{volume}$,

Mass = ρ * volume

But the volume for the periphery of the drum, V_1 = A * L, where A = cross sectional area of the sheet metal and L = length of the drum. But A = t * C, t = thickness of the sheet metal

$\rightarrow V_1 = t * C * L = 0.0025 * (\pi * 0.5) * 1.3 = 0.00511\ m^3$

V_2 = volume of the back cover = $A * t = \pi r^2 * t = \pi * 0.25^2 * 0.0025 = 0.000491\ m^3$

Now the total volume, $V = V_1 + V_2 = 0.00511 + 0.000491 = 0.0056\ m^3$

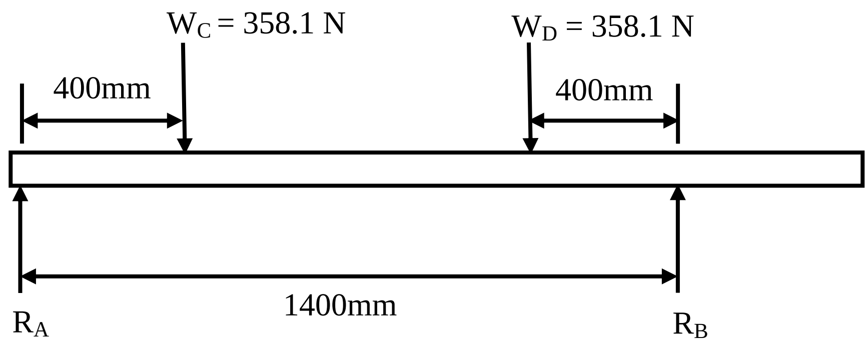
Total mass of the drum = $\rho * V = 7.85 * 10^3\ kg/m^3 * 0.0056\ m^3 = 40$ kg to account for mass of additional drum components (the ring, paddle and rod), let's take m = 48 kg

Mass of coffee to be roasted per batch = 25kg

Total mass of the drum and the coffee beans = 25 kg + 48 kg = 73 kg

From this the weight, W = 73 * 9.81 = 716.1 N

This weight acts on the shaft at points C and D as shown on the figure. Therefore weight at the two points, i.e., $W_C = W_D = W/2 = 716.1/2 = 358.1$ N



The moment produced at the point A will be calculates as;

$\sum M_A = 0$

W_C * 400mm + W_D * 1000mm - R_B * 1400mm = 0

358.1 N * 400mm + 358.1 N * 1000mm - R_B * 1400mm = 0

R_B = 358.1 N

The summation of all forces produced in the vertical direction now can be computed to find the reaction at point A. i.e.

$\sum F_y = 0$

$R_A + R_B - W_C - W_D = 0$

$R_A + R_B$ - (358.1 N + 358.1 N) = 0

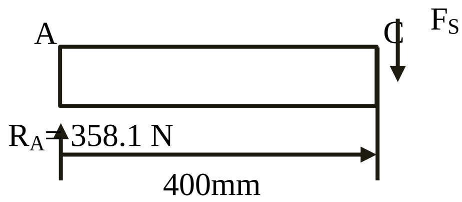
R_A + 358.1 N - (716.2 N) = 0

R_A + 358.1 N = 716.2 N

R_A = 358.1 N

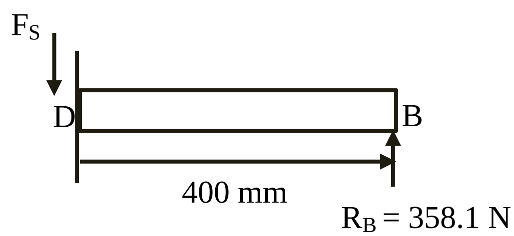
Now the maximum bending moment can be calculated at each section since all the required loads are obtained.

Section AC



$\sum M_b = 0$;$M_b - R_A * 400\ mm = 0$; $M_b - 358.1\ N * 400\ mm = 0$; $M_b = 143240$ Nmm

Section BD



$\sum M_b = 0$

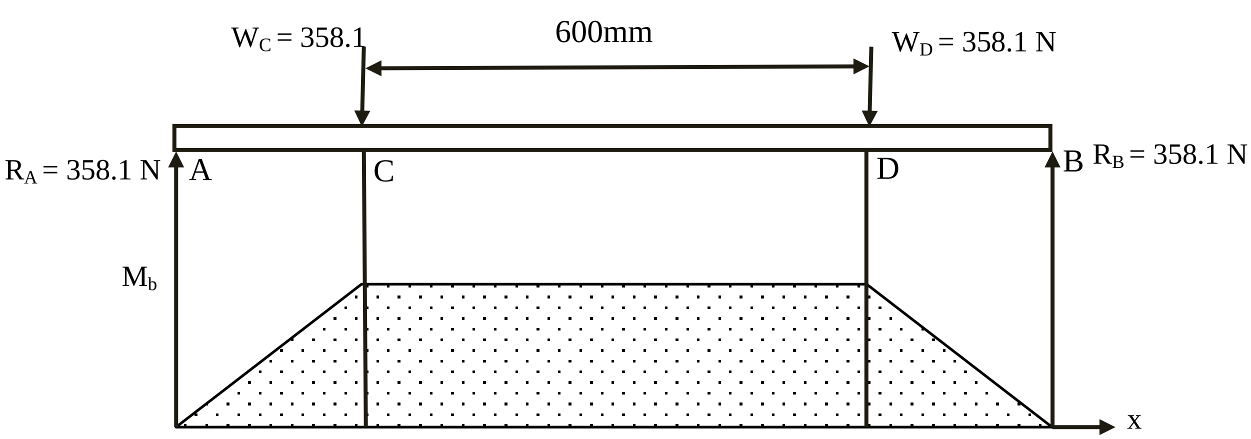
$M_b - R_B * 400\ mm = 0$

$M_b - 358.1N * 400\ mm = 0$

$M_b = 143240$ Nmm

Referring the above results, maximum bending moment is obtained at point C and D. the bending moment at points A and B is equal to zero.

Now we have sufficient information to draw the bending moment diagram of the main shaft.



The torque produced by the sprocket on the main shaft can be calculated as:

T = F * r, where F = force (load) on the chain and r = radius of the sprocket

= 2200N * 225mm = 495000 Nmm

Now the equivalent twisting moment produced is:

$T_{eq} = \sqrt{(143240)^2 + (495000)^2}$ = 515308.4 Nmm

The yield strength for plain carbon steel of C – 30 is σ_y = 300 Mpa = 300 N/mm^2

Now diameter of the shaft, $d = \sqrt[3]{\frac{32\, T_{eq}}{\pi * \sigma_y}} = \sqrt[3]{\frac{32 * 515308.4}{\pi * 300}}$ = 25.96 mm, from commercial shafts available as per IS 3688 – 1977, we take the nearest standard value of d = 28mm

According to maximum normal stress theory, equivalent bending moment,

$$M_e = \frac{1}{2}\left[M_b + \sqrt{{M_b}^2 + T^2}\right] = \frac{\pi}{32} * \sigma_b * d^3$$

The maximum normal (tensile) stress for plain carbon steel of C – 30 is 550N/mm^2

$$M_e = \frac{1}{2}\left[143240 + \sqrt{(143240)^2 + 495000^2}\right] = \frac{\pi}{32} * 550 * d^3$$

d = 20.1 mm

Comparing these two values, we take the larger one, i.e. d = 28 mm

3.1.7 Design of the drum supporting rods

As it can be observed from the figure below, the function of these components is to connect the roasting drum with the shaft and in doing so it prevents deformation of the drum while it is in operation. Due to the combined weight of the drum and the coffee beans, these rods are subjected to compressive stress as the drum rotates.

From section 3.1.6, we have seen the load due to the combined load of the drum and the coffee acts on the shaft at point C and D and has a magnitude of W/2.

i.e. $W_C = W_D = W/2 = 716.1/2 = 358.1$ N

The rod material is mild steel with allowable compressive stress, $\sigma_{c\,(all)} = 155$ Mpa

Now, $\sigma_c = \frac{W_C}{A}$, where A = cross sectional area of the rod = $\frac{\text{л}d^2}{4}$

$$\therefore \quad \sigma_c = \frac{4W_C}{\text{л}d^2}$$

$$155 = \frac{4 * 358.1}{\text{л}d^2}\ ;\ d = \frac{4 * 358.1}{\text{л} * 155} = 15.71\text{m} \approx 16\text{m}$$

From this we get the diameter of the rod, d = 15.71 mm ≈ 16

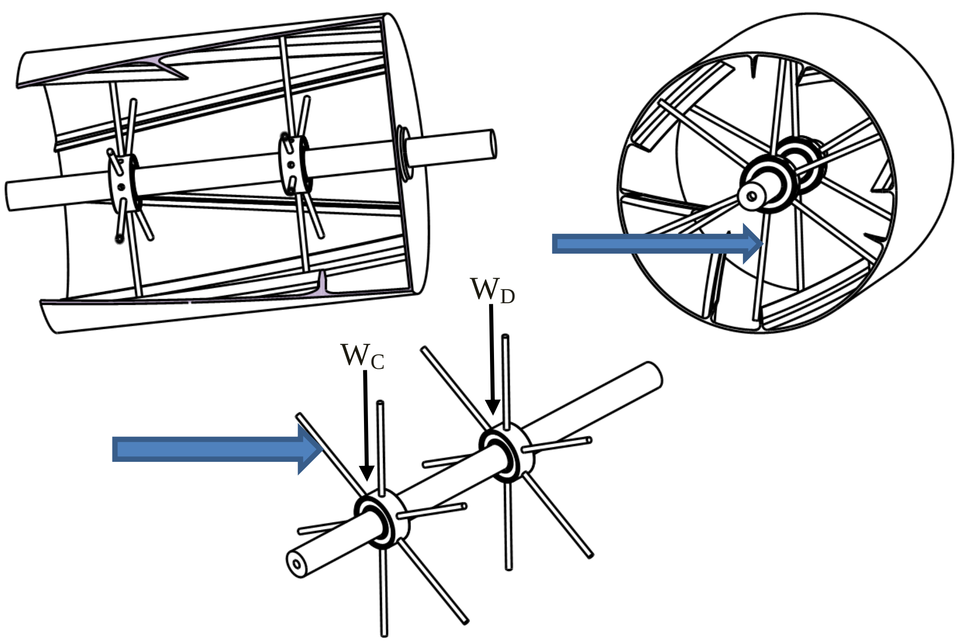


Figure26: Forces acting on the drum – rods

3.1.8 DESIGN OF THE SPEED REDUCER (GEARBOX)

Design input and assumptions

- ✓ 20^0 involute worm and gear
- ✓ Power to be transmitted = 3KW
- ✓ Rotational speed of the worm = 1200 rpm
- ✓ Reduction ratio = 20:1
- ✓ Center distance between shafts = 200mm

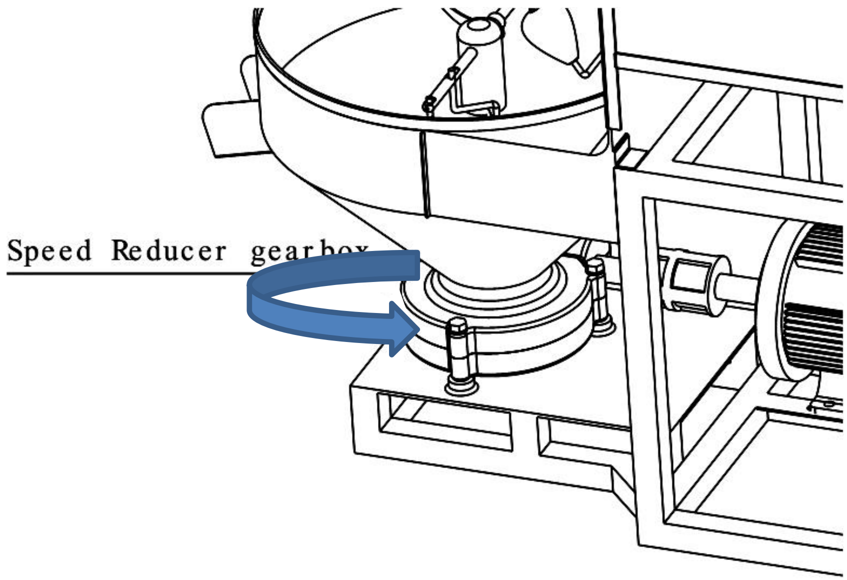


Figure 27: Speed reducer gearbox

3.1.8.1 Worm gearing advantage over other gearings

- ✓ Self-locking characteristics; reverse movement will be restricted
- ✓ Higher speed reduction could be secured; speed reduction could be secured up to 300:1
- ✓ The gearing operates silently
- ✓ Compact design
- ✓ Very good output torque will be secured

Terms used in worm gearing:

The following terms in connection with the worm gearing, are important from the subject point of view:

1. Axial pitch (p_a): is also known as linear pitch of a worm. It is the distance measured axially (i.e. parallel to the axis of worm) from a point on one thread to the corresponding point on the adjacent thread on the worm, as shown in... The axial pitch (p_a) of a worm is equal to the circular pitch (p_c) of the mating worm gear, when the shafts are at right angles.

2. Lead (*l*): It is the linear distance through which a point on a thread moves ahead in one revolution of the worm. For single start threads, lead is equal to the axial pitch, but for multiple start threads, lead is equal to the product of axial pitch and number of starts. Mathematically,

Lead, $l = p_a \cdot n$, Where n = number of starts

3. Lead angle (λ): It is the angle between the tangent to the thread helix on the pitch cylinder and the plane normal to the axis of the worm. A little consideration will show that if one complete turn of a worm thread be imagined to be unwound from the body of the worm, it will form an inclined plane whose base is equal to the pitch circumference of the worm and altitude equal to lead of the worm, as shown in Fig. 29

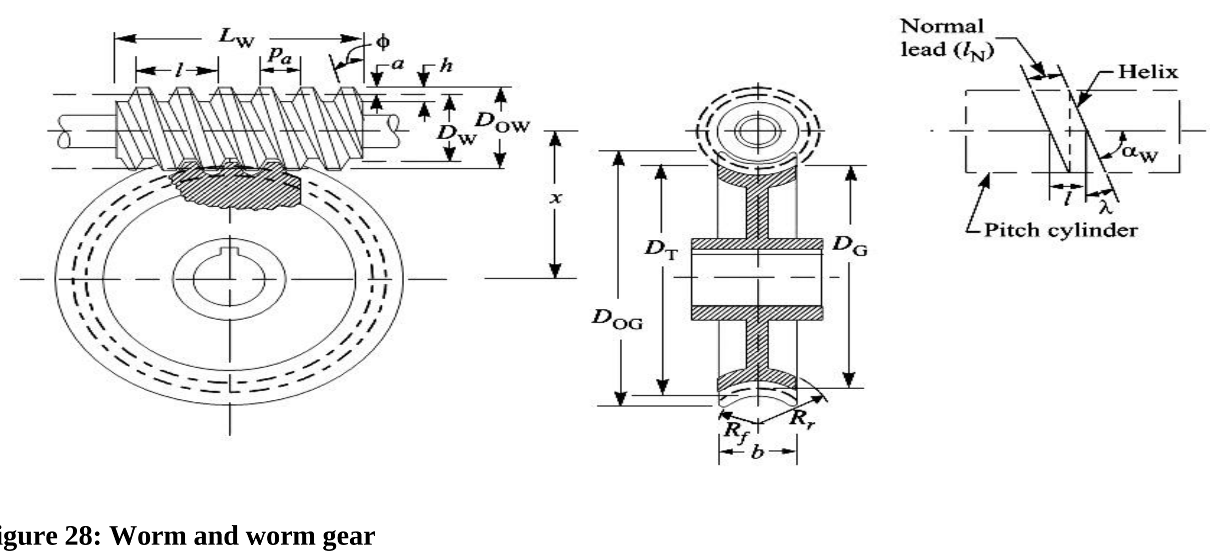


Figure 28: Worm and worm gear

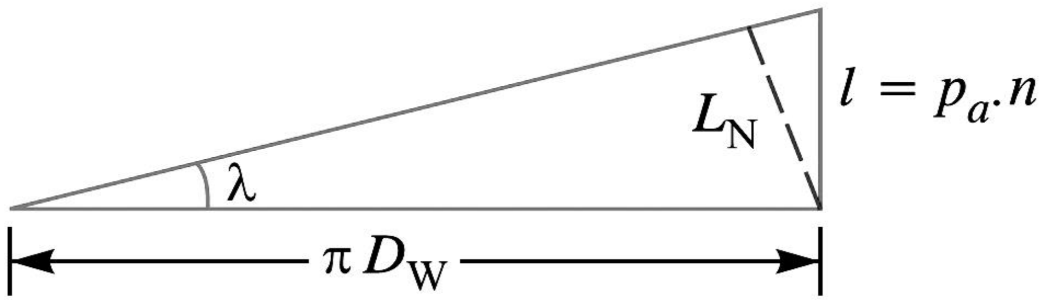


Figure 29: Development of helix thread

From the geometry of the figure, we find that

$$\tan\lambda = \frac{\text{lead of the worm}}{\text{pitch circumference of the worm}}$$

$$= \frac{l}{л\, D_w} = \frac{p_a * n}{л\, D_w}, \text{ since } l = p_a . n$$

$$= \frac{p_c * n}{л\, D_w} = \frac{л * m * n}{л\, D_w} = \frac{m * n}{D_w}, \text{ since } p_a = p_c = л * m$$

Where m = module; D_w = pitch circle diameter of the worm

The lead angle (λ) may vary from 9° to 45°. It has been shown by F.A. Halsey that a lead angle less than 9° results in rapid wear and the safe value of λ is 12½°.

For a compact design the lead angle may be determined by the following relation, i.e.

$\tan\lambda = \left[\frac{N_G}{N_W}\right]^{1/3}$, where N_G is the speed of the worm gear and N_W is the speed of the worm

4. Tooth pressure angle (φ): it is measured in a plane containing the axis of the worm and is equal to one-half the thread profile angle as shown in Fig. 28

Table (appendix)

5. Normal pitch (p_N): it is the distance measured along the normal to the threads between two corresponding points on two adjacent threads of the worm.

Mathematically, $p_N = l * \cos\lambda$

Note: the term normal pitch is used for a worm having single start threads. In case of a worm having multiple start threads, the term normal lead (l_N) is used, such that

$$V.R. = \frac{N_W}{N_G} = \frac{\pi * D_G}{l} = \frac{\pi * m * T_G}{l} = \frac{p_c * T_G}{l} = \frac{p_c * T_G}{p_a * n} = \frac{T_G}{l},$$

Table 7: Recommended value of lead angle and pressure angle

Velocity ratio (V.R.)	36 and above	12 to 36	8 to 12	6 to 12	4 to 10
Number of starts or threads on the worm ($n = T_w$)	Single	Double	Triple	Quadruple	sextuple

8. Center distance: is the distance between the center of the worm gear and the worm. It is calculated as: $x = \frac{D_W + D_G}{2}$

Where D_w = diameter of the worm and D_G = diameter of the worm gear

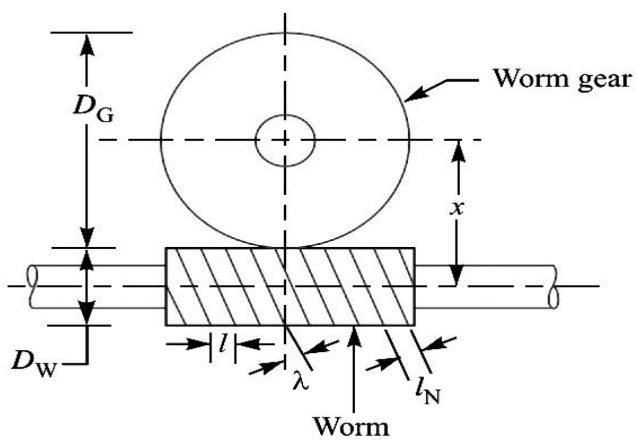


Figure 30: Geometry of worm and worm gear

The center distance may be expressed in terms of the axial lead (l), lead angle (λ) and velocity ratio (V.R.), as follows: $x = \frac{l}{2л}(\cot\lambda + V.R.)$ in terms of normal lead ($l_N = l\cos\lambda$),

the above expression may be written as:

$$x = \frac{l_N}{2л}\left(\frac{1}{sin\lambda} + \frac{V.R.}{cos\lambda}\right) \quad \text{Or} \quad \frac{x}{l_N} = \frac{l}{2л}\left(\frac{1}{sin\lambda} + \frac{V.R.}{cos\lambda}\right)$$

3.1.8.2 Design of worm

Let l_N = Normal lead, λ= Lead angle, x = center distance

We have already discussed that the value of x/l_N will be minimum corresponding to

$\cot^3 \lambda = V.R. = 20$ or $\cot \lambda = 2.71$

$\underline{\lambda = 20.3^0}$

We know that $\frac{x}{l_N} = \frac{1}{2\,л}\left(\frac{1}{sin\,\lambda} + \frac{V.R.}{cos\,\lambda}\right)$

$$\frac{200}{l_N} = \frac{1}{2\,л}\left(\frac{1}{sin\,20.3^0} + \frac{20}{cos\,20.3^0}\right) = \frac{1}{2\,л}(2.9 + 21.3) = 3.9$$

$\rightarrow l_N = 200/3.9 = \underline{51.3mm}$

and axial lead, $l = l_N / \cos\lambda = 51.3 / \cos 20.3^0 = \underline{54.7mm}$

From table 9(APPENDIX B), we find that for a velocity ratio of 20 the number of starts or threads on the worm, $n = T_w = 2$

Therefore the axial pitch of the threads on the worm, $p_a = l / 2 = 54.7 / 2 = 27.35$ mm

and the module, $m = p_a / л = 27.35 / л = 8.71$

We take the nearest standard value of module, $\underline{m = 9mm}$

∴ Axial pitch of the threads on the worm, $p_a = л * m = л * 9 = \underline{28.27mm}$

The axial lead of the threads on the worm, $l = p_a * n = 28.27 *2 = \underline{56.54mm}$

and normal lead of the threads on the worm, $l_N = l \cos\lambda = 56.54 * \cos 20.3^0 = \underline{53mm}$

We know that the center distance,

$$x = \frac{l_N}{2\,л}\left(\frac{1}{\sin\lambda} + \frac{V.R.}{\cos\lambda}\right) = \frac{53}{2\,л}\left(\frac{1}{\sin 20.3^0} + \frac{20}{\cos 20.3^0}\right)$$

= 8.44 (2.88 + 21.32) = 204.3 ≈ 205 mm

Let Dw = pitch circle diameter of the worm

We know that $\tan\lambda = \frac{l}{л\,D_w}$; $D_w = \frac{l}{л\tan\lambda} = \frac{56.54}{л\tan 20.3^0}$ = 48.65 ≈ 50 mm

Since the velocity ratio is 20 and the worm has double threads (i.e. n = T_w = 2), therefore number of teeth on the worm gear, T_G = 20 x 2 = 40

Now from table 10(APPENDIX B); we find that the face length of the worm or the length of threaded portion is, $L_w = p_c\,(4.5 + 0.02\,T_w)$

= 28.27 (4.5 + 0.02 x 2) = 128 mm *(since $p_c = p_a$)*

This length should be increased by 25 to 30 mm for the feed marks produced by the vibrating grinding wheel as it leaves the thread root. Therefore let us take L_w = 155 mm

We know that depth of tooth, $h = 0.623 * p_c$ = 0.623 * 28.27 = 17.6 mm

And addendum, $a = 0.286 * p_c$ = 0.286 * 28.27 = 8.1 mm ≈ 9 mm

∴Outside diameter of worm, $D_{ow} = D_w + 2a$ = 50 + 2 * 9 = 68mm

3.1.8.3 Design of worm gear

It is known that pitch circle diameter of the worm gear,

$D_G = m * T_G$ = 9 x 40 = 360 mm

From table 11(APPENDIX B) the outside diameter of the worm gear,

$D_{OG} = D_G + 0.8903 * p_c$ = 360 + 0.8903 * 28.27 = 385.2 mm

Throat diameter, $D_T = D_G + 0.572 * p_c$ = 360 + 0.572 * 28.27 = 376.2 mm

And face width, $b = 2.15 * p_c$ + 5mm = 2.15 * 28.27 + 5 = 65.8 mm

Let us now check the designed worm gearing from the standpoint of tangential load, dynamic load, static load or endurance strength, wear load and heat dissipation.

Check for the tangential load

Let N_G = speed of the worm gear in rpm

We know that velocity ratio of the drive $V.R. = \frac{N_W}{N_G}$ or $N_G = \frac{N_W}{V.R.} = \frac{1200}{20}$ = 60 rpm

∴Torque transmitted, $T = \frac{P\ x\ 60}{2\ л\ N_G} = \frac{3000 * 60}{2\ л * 60}$ = <u>477.5 N-m</u>

And tangential load acting on the gear, $W_T = \frac{2\ x\ Torque}{D_G} = \frac{2\ x\ 477.5}{0.36}$ = <u>2652.8 N</u>

We know that pitch line or peripheral velocity of the worm gear,

$$v = \frac{л\ D_G\ N_G}{60} = \frac{л * 0.36 * 60}{60}$$ = <u>1.13m/s</u>

∴velocity factor, $C_v = \frac{6}{6 + v} = \frac{6}{6 + 1.13}$ = <u>0.84</u>

And tooth form factor for 20^0 involute teeth, y = 0.154 - $\frac{0.912}{T_G}$ = 0.154 - $\frac{0.912}{40}$ = <u>0.131</u>

Commonly used worm gear material is phosphor bronze, therefore taking the allowable static stress for phosphor bronze, σ_o = 84 MPa or N/mm^2.

We know that the designed tangential load,

W_{Td} = (σ_o * C_v) b * лm * = (84 * 0.84) 65.8 * 3.14 * 9 * 0.1 = <u>17188N</u>

Since this is more than the tangential load acting on the gear (i.e. 2652.8N), therefore the design is safe from the standpoint of tangential load.

Check for dynamic load

We know that the dynamic load, $W_D = W_{Td}/C_v$ = 17188/0.84 = <u>20462N</u>

Since this value is more than the tangential load on the gear (i.e. 20462 > 2652.8), therefore the design is safe from the standpoint of dynamic load.

Check for static load or endurance strength

We know that the flexural endurance limit for phosphor bronze is σ_e = 168 MPa

∴static load or endurance, $W_s = \sigma_e * b * лm * y$ = 168 * 65.8 * 3.14 * 9 * 0.131 = 40924N

Since this is much more than W_T = 2652.8N therefore the design is safe from the standpoint of static load or endurance strength.

Check for wear

Assuming the material for worm as hardened steel, therefore from table 12(APPENDIX B) I find that for hardened steel worm and phosphor bronze worm gear, the value of load stress factor,

K = 0.55 N/mm2

∴Limiting or maximum load for wear, $W_w = D_G * b * K$ = 360 * 65.8 * 0.55 = 13028.4N

Since this is more than W_T = 2652.8N, therefore the design is safe from the standpoint of wear.

Check for heat dissipation

First of all, the efficiency of the worm gearing (η).

We know that rubbing velocity, $V_r = \frac{л * D_W * N_W}{cos\,\lambda} = \frac{л * 0.05 * 1200}{COS\ 20.3^0}$ = 201m/min

∴ coefficient of friction, $\mu = 0.025 + \frac{201}{18000} = 0.025 + 0.0112 = 0.0362$

And angle of friction, $\varphi_1 = \tan^{-1}\mu = \tan^{-1}(0.0362) = 2.1^0$

We know that efficiency $\eta = \frac{tan\,\lambda}{\tan(\lambda+\varphi_1)} = \frac{\tan 20.3^0}{\tan(20.3 + 2.1^0)} = 0.9$

Assuming 25 percent overload, the heat generated,

$Q_g = 1.25\,P\,(1 - \eta) = 1.25 * 3000\,(1 - 0.9) = 375$ W

The projected area of the worm, $A_w = \frac{л}{4}(D_w)^2 = \frac{л}{4}(50)^2 = 1963.5\ mm^2$

And projected area of the worm gear, $A_G = \frac{л}{4}(D_G)^2 = \frac{л}{4}(360)^2 = 101787.6\ mm^2$

∴ Total projected area of the worm and worm gear,

$A = A_w + A_G = 1963.5 + 101787.6 = 103751.1\ mm^2 = 103751.1 * 10^{-6}\ m^2$

The heat dissipating capacity is then calculated as,

$Q_d = A\ (t_2 - t_1)\ K$, K = conductivity of the material = 378 $W/m^2/^0C$

$= 103751.1 * 10^{-6}\ (t_2 - t_1)\ 378 = 39.2\ (t_2 - t_1)$

The heat generated must be dissipated in order to avoid over heating of the drive, therefore equating $Q_g = Q_d$, we have $t_2 - t_1 = 375/39.2 = 9.6^0C$

Since this temperature difference $(t_2 - t_1)$ is within safe limits, therefore the design is safe from the standpoint of heat.

3.1.8.4 Design of worm shaft

Let d_w = Diameter of worm shaft

The torque acting on the worm gear shaft,

$$T_{gear} = \frac{1.25\ P\ x\ 60}{2\ л\ N_G} = \frac{1.25 * 3000 * 60}{2\ л\ 60} = 596.8\ \text{N-m} = 596.8 * 10^3\ \text{N-mm}$$

∴ Torque acting on the worm shaft, $T_{worm} = \frac{T_{gear}}{V.R.\ x\ \eta} = \frac{596.8}{20 * 0.9} = 33.2\ \text{N-m} = 33.2 * 10^3\text{N-mm}$

We know that tangential force on the worm,

W_T = axial force on the worm gear $= \frac{2 * T_{worm}}{D_w} = \frac{2 * 33.2 * 10^3}{50} = 1326.3N$

Axial force on the worm, W_A = Tangential force on the worm gear

$$= \frac{2\ x\ T_{gear}}{D_G} = \frac{2 * 596.8 * 10^3}{360} = 3315.6\ N$$

And radial or separating force on the worm, $W_R = W_A * \tan \varphi = 3315.6 * \tan 20^0 = 1206.8N$

Let us take the distance between the bearings of the worm shaft (x_1) equal to the diameter of the worm gear (D_G), i.e. $x_1 = D_G$ = 360mm

∴ Bending moment due to the radial force (W_R) in the vertical plane

$$= \frac{W_R * x_1}{4} = \frac{1206.8\ x\ 360}{4} = 108540 \text{N-mm}$$

And bending moment due to axial force (W_A) in the vertical plane

$$= \frac{3315.6 * 50}{4} = 41445 \text{ N-mm}$$

Total bending moment in the vertical plane, M_1 = 108540 + 41445 = 149985 N-mm

We know that bending moment due to tangential force (W_T) in the horizontal plane,

$$M_2 = \frac{W_T\ x\ D_G}{4} = \frac{1326.3 * 360}{4} = 119367 \text{ N-mm}$$

∴ Resultant bending moment on the worm shaft,

$$M_{worm} = \sqrt{(M_1)^2 + (M_2)^2} = \sqrt{(149985)^2 + (119367)^2} = 191687.2 \text{ N-mm}$$

We know that equivalent twisting moment on the worm shaft,

$$T_{ew} = \sqrt{(T_{worm})^2 + (M_{worm})^2} = \sqrt{(33.2 * 10^3)^2 + (191687.2)^2} = 194541 \text{ N-mm}$$

We also know that equivalent twisting moment (T_{ew}),

$$194541 = \frac{л}{16} * \tau\ (d_w)^3 = \frac{л}{16} * 50\ (d_w)^3, \text{ taking } \tau = 50 \text{ Mpa}$$

d_w= 27.1mm, referring to commercial shafts available as per IS 3688 - 1977 let's use d_w= 30mm

We can now check the maximum shear stress induced. The actual shear stress,

$$\tau = \frac{16\ T_{ew}}{л\ (d_w)^3} = \frac{16 * 194541}{л\ (30)^3} = 36.7 \text{ N/mm}^2$$

And direct compressive stress on the shaft due to the axial force,

$$\sigma_c = \frac{W_A}{\frac{\pi}{4}(d_w)^2} = \frac{3315.6}{\frac{\pi}{4}(30)^2} = 4.7 \text{ N/mm}^2$$

$\therefore$ Maximum shear stress, $\tau_{max} = \frac{1}{2}\sqrt{(\sigma_c)^2 + 4\,\tau^2} = \frac{1}{2}\sqrt{(4.7)^2 + 4\,(36.7)^2} = 36.8$ Mpa

Since the maximum shear stress induced is less than 50MPa (assumed), therefore the design of worm shaft is satisfactory.

3.1.8.5 Design of worm gear shaft

Let d_G = diameter of worm gear shaft.

We have calculated above that the axial force on the worm gear = 1326.3N

Tangential force on the worm gear = 3315.6N

Radial or separating force on the worm gear = 1206.8

The bending moment due to the axial force on the worm gear = $\frac{Axial\ force\ x\ D_G}{4}$

$= \frac{1326.3 * 360}{4} = 119367$ N-mm

The bending moment due to the axial force will be in the vertical plane. Let us take the distance between the bearings of the worm gear shaft (x_2) as 200mm.

$\therefore$ Bending moment due to the radial force on the worm gear = $\frac{Radial\ force * x_2}{4}$

$= \frac{1206.8 * 200}{4} = 60340$ N-mm

The bending moment due to the radial force will also be in the vertical plane.

$\therefore$ Total bending moment in the vertical plane M_3 = 119367 + 60340 = 179707 N-mm

We know that the bending moment due to the tangential force in the horizontal plane,

$M_4 = \frac{Tangential\ force * x_2}{4} = \frac{3315.6 * 200}{4}$ = 165780 N-mm

∴ Resultant bending moment on the worm gear shaft,

$M_{gear} = \sqrt{(179707)^2 + (165780)^2} = 244.5 * 10^3$ N-mm

We have already calculated the torque acting on the worm gear shaft, $T_{gear} = 596.8 * 10^3$ N-mm

Equivalent twisting moment on the worm gear shaft,

$T_{eq} = \sqrt{(T_{gear})^2 + (M_{gear})^2} = \sqrt{(596.8 * 10^3)^2 + (244.5 * 10^3)^2}$

$= 0.64 * 10^6$ N-mm

We know that the equivalent twisting moment (T_{eq}),

$0.64 * 10^6 = \frac{л}{16} * \tau\ (d_G)^3 = \frac{л}{16} * 50\ (d_G)^3$

∴ d_G = 39.35 mm, referring to commercial shafts available as per IS 3688 - 1977 let's use d_w = 40mm

We can now check the maximum shear induced. The actual shear stress,

$\tau = \frac{16\ T_{eq}}{л\ (d_G)^3} = \frac{16 * 0.64 * 10^6}{л\ (45)^3}$ = 36 Mpa

And direct compressive stress on the shaft due to the axial force,

$\sigma_c = \frac{Axial\ force}{\frac{л}{4}(d_G)^2} = \frac{1326.3}{\frac{л}{4}(45)^2}$ = 0.83 Mpa

∴ Maximum shear stress, $\tau_{max} = \frac{1}{2}\sqrt{(\sigma_c)^2 + 4\ \tau^2} = \frac{1}{2}\sqrt{(0.83)^2 + 4\ (36)^2}$

= 36.1 Mpa, Since the maximum shear stress induced is less than 50MPa (assumed), therefore the design for worm gear shaft is satisfactory.

3.1.9 Design of box or muff or sleeve coupling

The speed reducer gearbox is connected to the driving motor through muff coupling. Box or muff or sleeve coupling is a simple coupling which is used to connect the worm shaft with the motor shaft rigidly. It has a hollow cylindrical piece which is fitted over both shaft ends connected by means of either keys, taper pins or set screws. The torque is transmitted from one shaft to the sleeve and then to the other shaft.

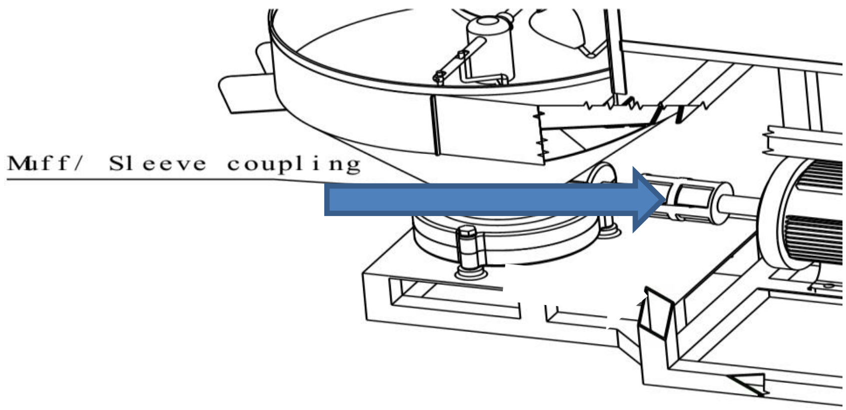


Figure 31: Sleeve / Muff coupling

As it has no projecting parts, its interior is perfectly smooth which is good from safety point of view. From design point of view, the depth of keyway in each of the shafts to be connected should be exactly the same and the diameters should also be the same.

1. The sleeve is designed as a hollow shaft transmitting the entire torque of the shaft
2. The width and thickness of the key are obtained from the PSGDB 5.16 according to the shaft diameter. The length of the key is at least equal to the length of the sleeve. The key will be checked for crushing and shearing strength.

Design input and assumptions

- ✓ Power to be transmitted, P = 3 KW
- ✓ Rotational speed, N = 1200
- ✓ Allowable shear stress for cast iron muff, τ_M = 14 Mpa
- ✓ Allowable shear stress for key, τ_k = 37 Mpa
- ✓ Allowable crushing stress for key, σ_c = 96 Mpa

3.1.9.1 Design of the sleeve

The sleeve is designed by considering it as a hollow shaft. Hence the torque to be transmitted by the sleeve is given by: $M_t = \frac{л}{16} \tau \left(\frac{D^4 - d^4}{D}\right)$

Where τ = shear strength of the sleeve material = 14N/mm2 for cast iron, D = outer diameter of the sleeve, d = inner diameter of the sleeve

The inner diameter of the sleeve can be fairly taken as the outside diameter of the two shafts. i.e. d = 40 mm

The usual proportions for the sleeve are:

Outside diameter of the sleeve, D = 2d + 13mm

Length of the sleeve, L = 3.5d

∴ D = 2 (40) + 13 = <u>93 mm</u>

L = 3.5 * 40 = <u>140 mm</u>

The power transmitted by a torque T (Nm) applied to a shaft rotating at N (rpm) is given by

$P = \frac{2лNM_t}{60}$; $3000 = \frac{2л * 1200 * M_t}{60}$

M_t = 23.9 Nm = 23900Nmm

Check for the induced shear stress in muff

Torque, $M_t = \frac{л}{16} \tau_M \left(\frac{D^4 - d^4}{D}\right)$

$23900 = \frac{л}{16} \tau_M \left(\frac{93^4 - 40^4}{93}\right)$

τ_M = 4.9 N/mm^2 = 5 Mpa

The induce torque is less than the permissible value (14MPa). Hence, the design is safe.

3.1.9.2 Design for keys

We can take the length of the key is equal to the half-length of the sleeve.

∴ Length of the key, $l = \frac{L}{2} = \frac{140\ mm}{2}$ = 70mm

Check for shear strength:

$M_t = l * b * \tau_k * \frac{d}{2}$, where b = width of the key

From PSGDB 5.16, for the shaft diameter, d = 45mm, the width of the key (b) = 12mm, and the height of the key (h) = 7mm

∴ $M_t = l * b * \tau_k * \frac{d}{2}$; $23900 = 70 * 12 * \tau_k * \frac{40}{2}$

$\tau_k = 1.5 N/mm^2$, which is much less than the allowable shear value (37 Mpa). Hence the design is safe.

Check for crushing stress

∴ $M_t = \sigma_c * l * \frac{h}{2} * \frac{d}{2}$

$23900 = \sigma_c * 70 * \frac{7}{2} * \frac{40}{2}$

$\sigma_c = 4.87\ N/mm^2$, which is much lower than the allowable crushing stress (96 Mpa). Hence the design is safe.

3.1.10 Design of the stirring shaft

The steering shaft is the shaft which connects the gearbox with the mixing paddle. The power obtained from the gearbox is directly transmitted through this component. It is obvious the shaft is subjected to twisting moment or torque from the gearbox only.

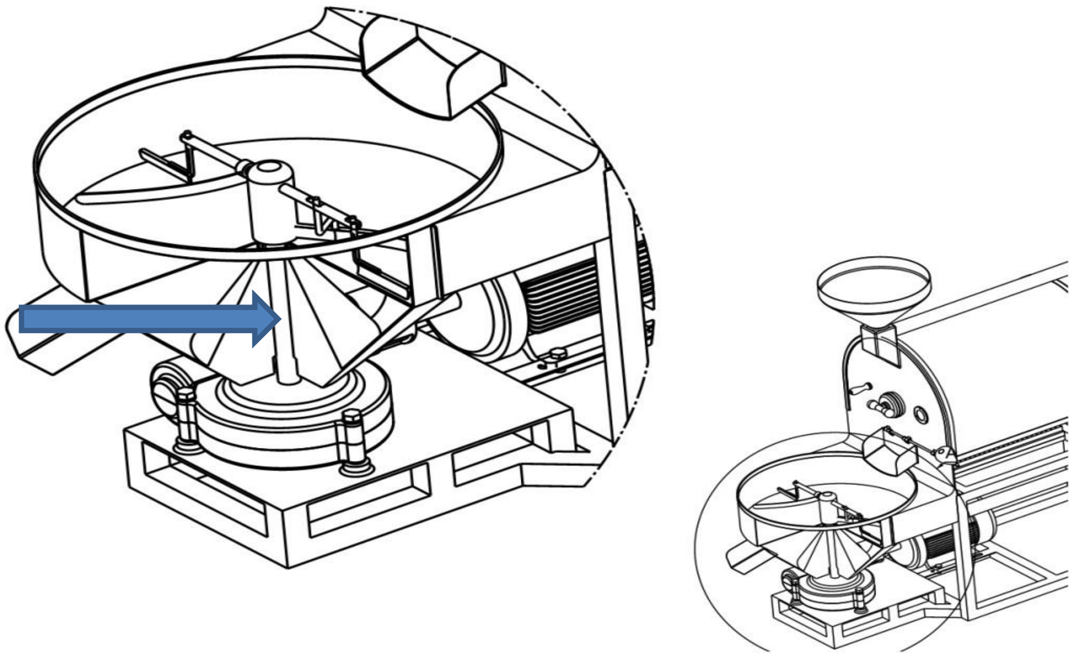


Figure 32: Stirring shaft

When the shaft is subjected to a twisting moment or torque only, the diameter is obtained by using the torsion equation. i.e.

$$\frac{T}{J} = \frac{\tau}{r}$$

Where T = twisting moment (torque) acting upon the shaft

J = polar moment of inertia of the shaft about the axis of rotation

τ = torsional shear stress and

r = distance from neutral axis to the outer most fiber = d/2;

where d is the diameter of the shaft.

For round solid shaft, polar moment of inertia, $J = \frac{л}{32} * d^4$

Substituting the above equation into the torsion equation,

$$\frac{T}{\frac{л}{32} * d^4} = \frac{\tau}{d/2}$$

Rearranging this equation yields, T = $\frac{л}{16} * \tau * d^3$

But T = T_{gear} = 596.8 N-m = 596.8 * 10^3 N-mm (already calculated)

$$596.8 * 10^3 = \frac{л}{16} * \tau * d^3$$

$$d^3 = \frac{596.8 * 10^3 * 16}{л * 300}$$

d = 22.6 mm, from commercial shafts available as per IS 3688 – 1977, we take the nearest standard value of d = 25 mm

3.1.11 Finite Element Analysis of critical components

Check for deformation of cooling blade 1

Entity	Size
Nodes	6103
Elements	3390

Material	Steel
Young's modulus	2e+011N_m2
Poisson's ratio	0.266
Density	7860kg_m3
Coefficient of thermal expansion	1.17e-005_Kdeg
Yield strength	2.5e+008N_m2

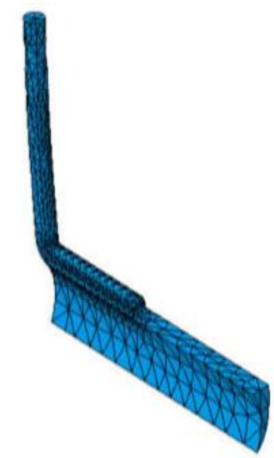


Figure 33: Deformation of cooling blade 1

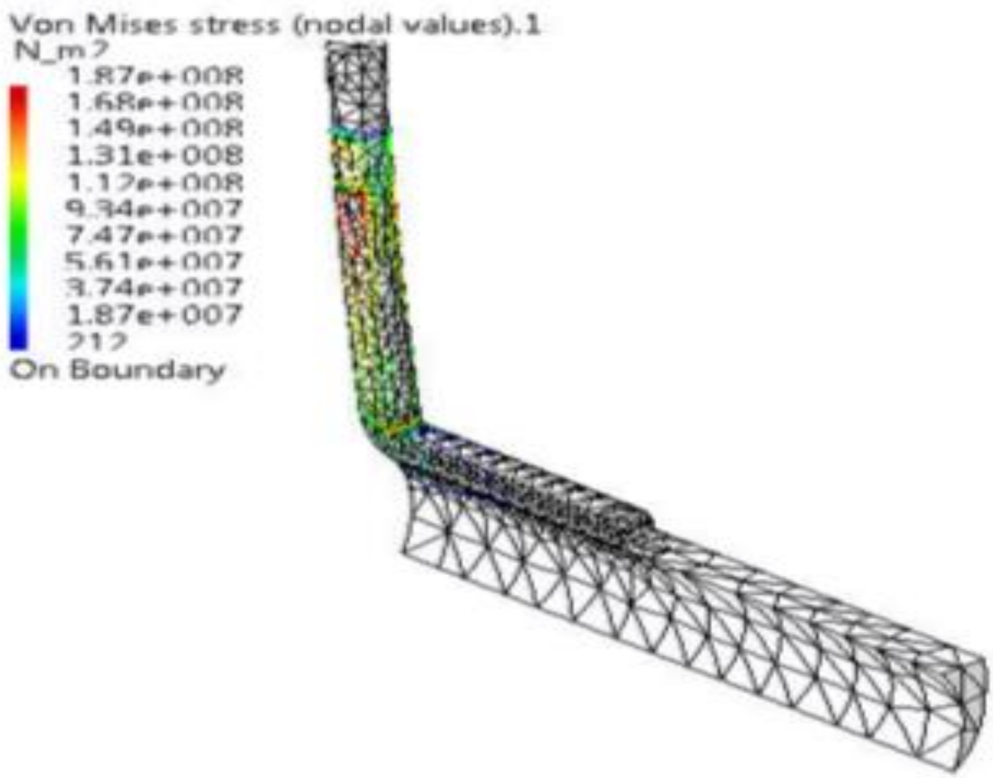


Figure 34: Von Mises stress on cooling blade 1

Force vector Fx = -125N; Fy = 0N; Fz = 0N; Temperature = 523 deg K

- From the Von Mises stress figure, the maximum stress is **1.87e + 008N_m^2** which is below the yield strength of the material, i.e. **2.5e + 008N_m^2**.

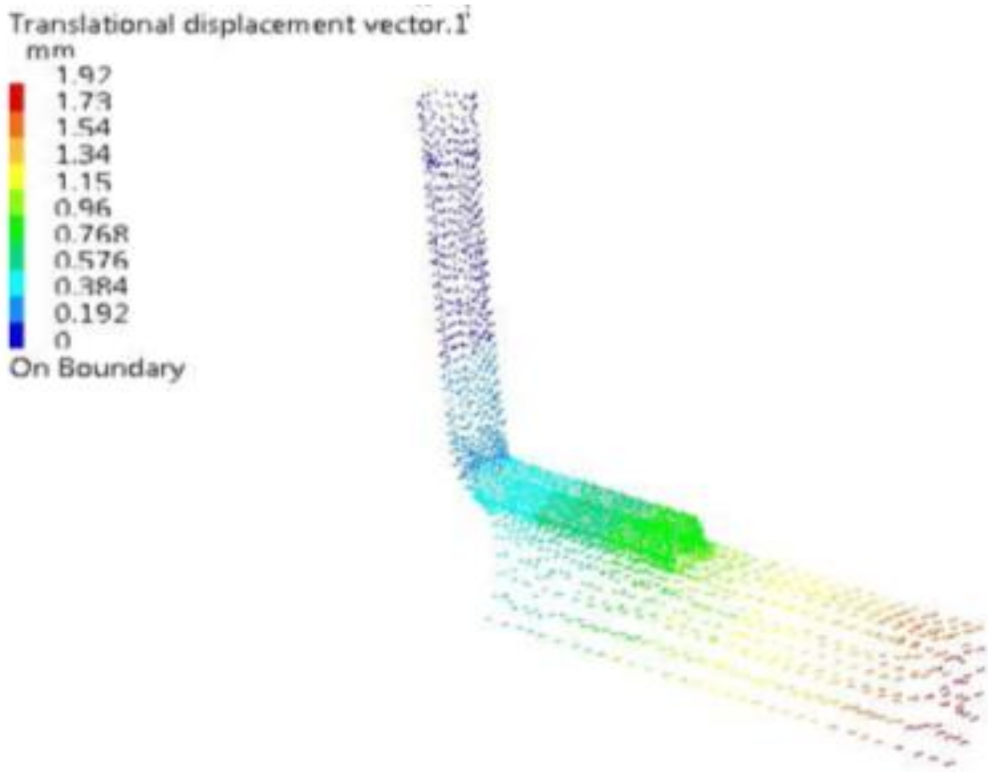


Figure 35: Displacement vector for cooling blade 1

- From the displacement vector figure the color and length of arrows represents the size of displacement. The color legend indicates a maximum displacement of **1.92 mm** at the tip of the blade which is almost unnoticeable.
- ✓ Hence the part designed is satisfactory.

Checking for deformation of drum supporting rods

Entity	Size
Nodes	817
Elements	382

Material	Steel
Young's modulus	2e+011N_m2
Poisson's ratio	0.266
Density	7860kg_m3
Coefficient of thermal expansion	1.17e-005_Kdeg
Yield strength	2.5e+008N_m2

Figure 36: Deformation of Drum supporting rods

Force vector Fx = 0N ; Fy = 180N; Fz = -360N ; Temperature = 523 deg K

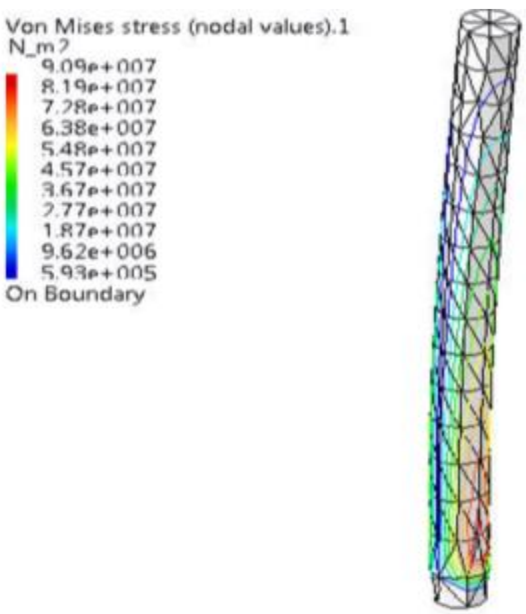


Figure 37: Von Mises stress on drum supporting rod

- From the Von Mises stress figure, the maximum stress is **9.09e + 007N_ m^2** which is below the yield strength of the material, i.e**. 2.5e + 008N_m^2**.

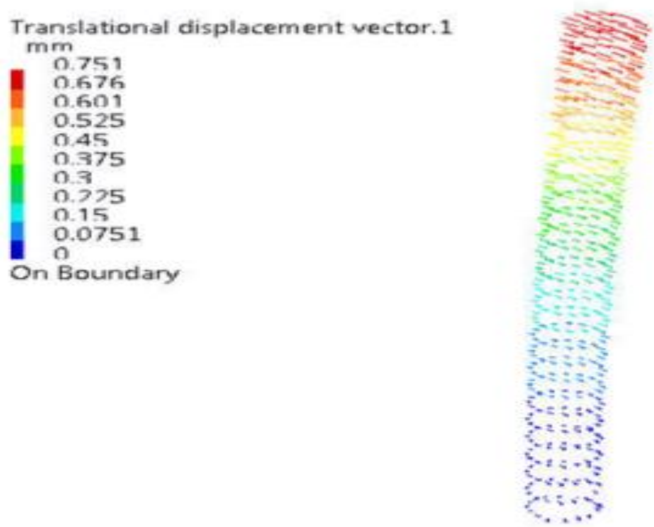


Figure 38: Displacement vector for drum supporting rod

- ❖ The color legend indicates a maximum displacement of **0.751** mm at the tip of the rod which is almost unnoticeable.
- ✓ Hence the part designed is satisfactory.

Check for deformation of frame

Entity	Size
Nodes	6065
Elements	2926

Material	Steel
Young's modulus	2e+011N_m2
Poisson's ratio	0.266
Density	7860kg_m3
Coefficient of thermal expansion	1.17e-005_Kdeg
Yield strength	2.5e+008N_m2

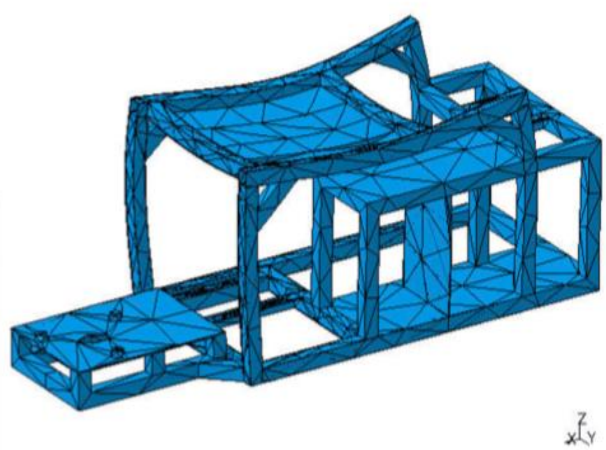


Figure 39: Deformation of the frame

Force vector Fx = 0N; Fy = 0N; Fz = -650N ;Temperature = 523 deg K

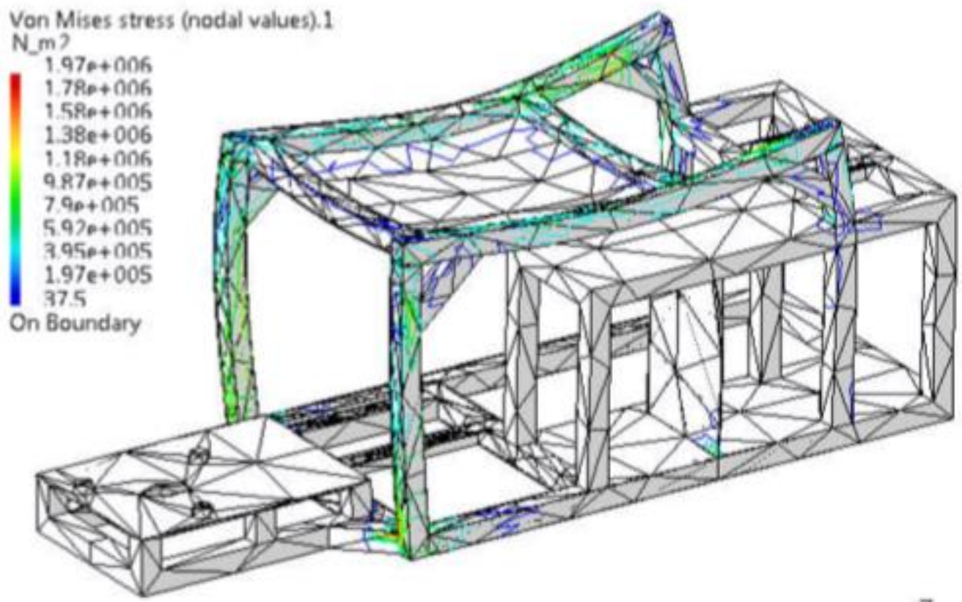


Figure 40: Von Mises stress on the frame

- ❖ From the Von Mises stress figure, the maximum stress is **1.97e + 006N_ m²** which is below the yield strength of the material, i.e. **2.5e + 008N_m²**.

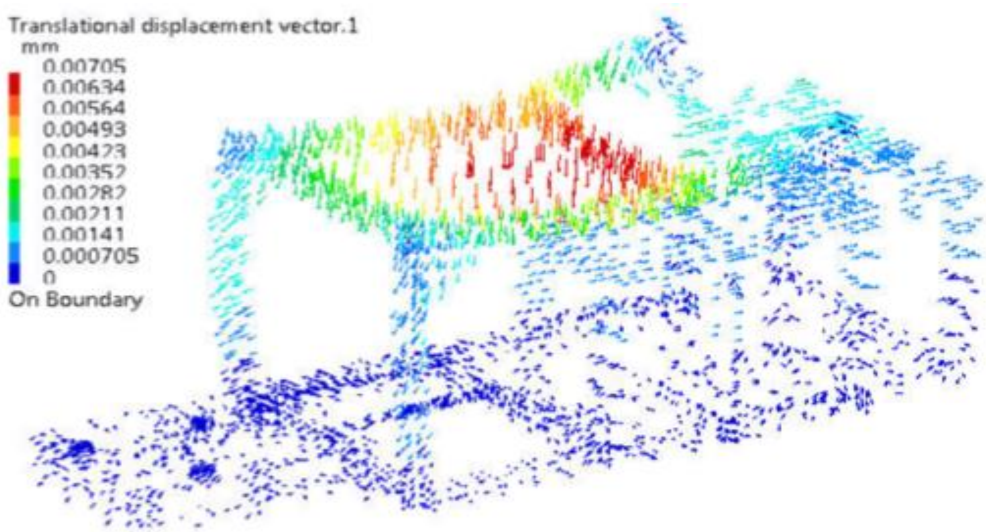


Figure 41: Displacement vector for the drum

- ❖ The color legend indicates a maximum displacement of **0.00705 mm** at the tip of the rod which is almost unnoticeable.
- ✓ Hence the part designed is satisfactory.

3.1.12 COST ANALYSIS

The following table shows the cost analysis of the overall cost (approximate) of the machine design based on the current market condition.

Table 8: Cost analysis of the machine

Component	Dimension	Material	Quantity	Price
Motor	4hp 7hp	--- ---	1 1	4500 9000
Sheet metal	2 x 1 x 0.0008 m 2 x 1 x 0.0025 m	Mild steel Mild steel	6 1	6 x 500 1 x 750
Chain	2.5 m	Mild steel	1	1 x 250
Sprocket	Dia. 0.075 m Dia. 0.45 m	Mild steel	1 1	1x100 1x250
Shaft	Dia. 0.028 x 1.7m Dia. 0.025 x 1m	Mild steel	1 1	1 x 450 1 x 430
Hollow square bar	0.04 x 0.04 x 9 m	Mild steel	5	5 x 550
Angle iron	0.03 x 0.03 x 6 m	Mild steel	2	2 x 375
Bearing	205	Tin based alloy	4	4 x 265
Key	0.007 x 0.012 x 0.070 m	Mild steel	6	6x45
Cost of insulation	---	Fiber glass	4kg	4 x 150
Bolt with nut	M22 M17 M10	Mild steel	15 10 20	15x8 10 x 5 20 x 3
Steel rods	2m x 1m x 0.016 m	Mild steel	1	1 x 200
Hollow pipe	2 x 1 x 0.050 m	Mild steel	1	1 x 450
PVC	2 x 1 x 0.050 m	---	1	200
Thermostat	---	---	1	9500
Switches	---	---	9	9 * 35
Electric cable	---	copper	---	60
Electric fan	---	---	2	500
Atmospheric burner	---	---	1	300
			Total cost	34,000 ETB

3.2 THERMAL ANALYSIS OF HEAT TRANSFER IN COFFEE ROASTING

Roasting coffee is a thermodynamic process in which the application of heat and the resulting uptake of heat by the bean directly affects final flavor. The condition under which heat is applied is affected by environmental factors, including internal volume of the roaster, humidity, barometric pressure, and ambient temperature. The ability of the bean to take on heat and the rate At which the absorbed heat dissipates throughout the bean is a function of its physical state, including % moisture, density, and bean size. The chemical changes taking place at any instant in the process depend upon the amount of heat already taken on, the amount of heat available in the immediate environment, the ability of the mass of beans to conduct heat, and the reactions that have already taken place or are in the process of taking Place .The roaster technician makes adjustments to the flame based upon knowledge of the roasting process, observations of the processes taking place, and experience. In developing an understanding of coffee roasting, it is us it is useful to examine the process from thermodynamic perspective

(where the main issues are where the main issues are heat and mass transfer) and from a flavor perspective (the chemical changes that take place as a result of heat application) and main the main task is to mix the beans in order to achieve homogeneous roasting and to prevent scorching of beans [4]; [30].

Coffee roasting machines transfer heat to beans by convection, conduction, and radiation. Each roasting machine transfers heat by a different mix of these mechanisms.

Drum roasters, which apply heat directly to the drum, cook beans primarily by convection and secondarily by conduction. Radiant heating from hot roasting machine surfaces and between neighboring beans make a small contribution to heat transfer as well. Different studies have shown heat transfer in drum roasters to be 70% by convection and 30% by conduction.

At the beginning of a roast path, charging the beans introduce a large volume of room temperature beans and air into the hot roaster, sending the environmental temperature in the roaster plummeting. During the first few minutes of a batch in a drum roaster, conduction from the hot drum plays a significant role in transferring heat to the beans. As the air temperature in the roaster rebounds after its initial plunge, convection comes to dominate heat transfer. In such a machine the drum acts as a "heat-storage" device that jump-starts development early in a batch. Convection-oriented machines call for the use of hotter charge temperatures to provide adequate heat transfer early in a roast and compensate for lack of a heat-storing drum.

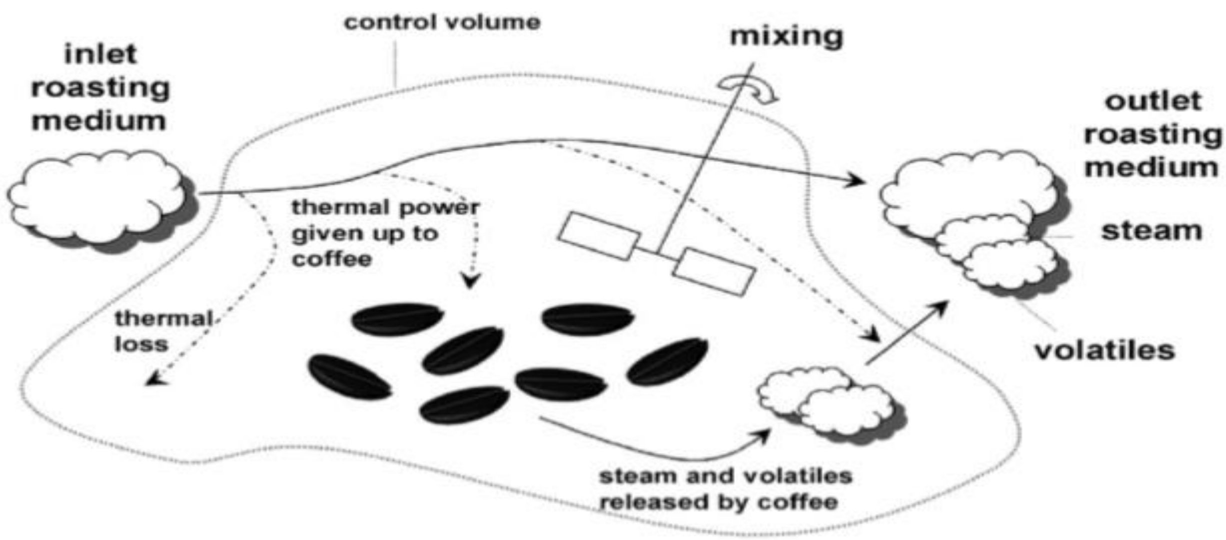


Figure 42: Heat and mass fluxes during coffee roasting

Initial assumptions

- The grains are mixed and have the same temperature profile
- The roasting medium is mixed within the roaster
- The contact area between the coffee beans and the metal parts of the roaster is negligible
- The heat transfer coefficient between the roasting medium and the beans also takes into account the heat transfer from bean to bean.

First let's determine the heat transfer rate from the heater to the roaster made of 2.5mm thick mild steel with radius, r = 250mm and length, L = 1300mm. Mild steel has a thermal conductivity, k_A= 58 W/mk. The heat transfer coefficient, h, of the coffee bean is 2.87W/m^2k.

Let

r_i = inner most radius of roasting zone = 0.0878m

r_1= cylinder bore = 0.25m

x_1= thickness of the roasting drum through which heat is transferred = 0.0025m

r_2 = outer diameter of the drum = 0.2525m, cylinder bore + thickness

R_c = Thermal Resistance due to conduction

Q = rate of heat flow through a block of material, W or J/s

$T_3 = T_d$= desired temperature of coffee bean = 250^{o}C =523K

T_2 = Inner surface temperature, where T2 > T3

T_1=temperature of the outside surface of the roasting drum. Assuming it is 350^{o}C=623K

T_4 = surface temperature of the machine

T_a = atmospheric temperature = 24^{o}C = 297K (the mean temperature for four days sample in Jimma)

K_w = thermal conductivity of mild steel = 48 – 58W/mK

K_b = thermal conductivity of coffee bean = 0.173w/mK

L = length of a roaster chamber containing 25kg of coffee bean = 1.3m

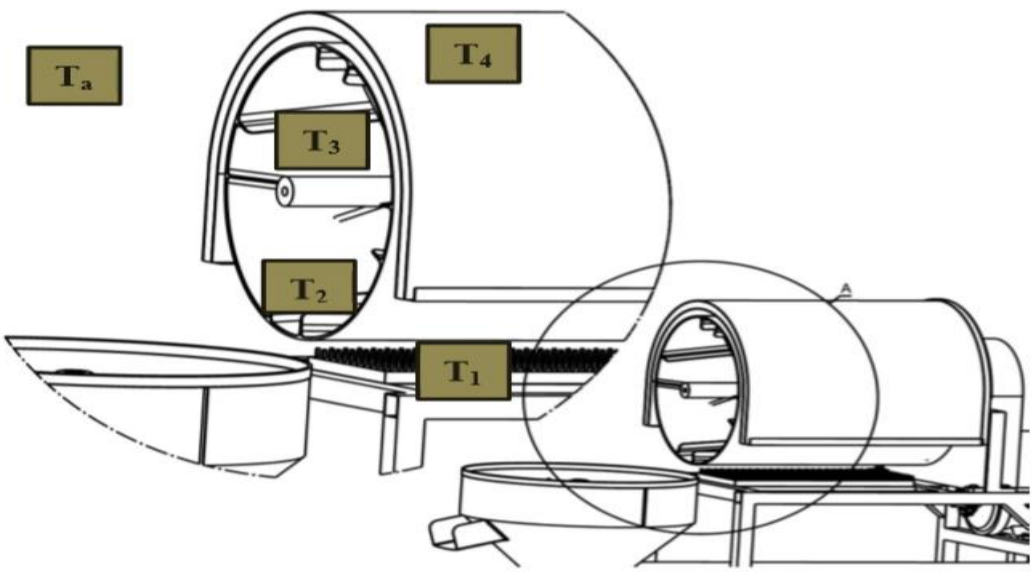


Figure 43: working temperature types of the roaster

3.2.1 Conduction heat transfer

The heat generated is transferred to the coffee bean inside the rotating drum by conduction through the cylindrical wall of the rotating drum. The heat conduction here obeys the Fourier law (Osore, 1997) expressed mathematically below.

$$Q_{Cond} = -KA\frac{dT}{dx}$$

Where k is the thermal conductivity of the material, which is a measure of the ability of the material to conduct heat, and dT/dx, is the temperature gradient

Heat flow by conduction in a cylinder,

$$Q_{cond} = -KA\frac{dT}{dr}, \quad \text{where } A = 2\pi r$$

$$Q_{cond} * dr = -2K\pi r dT$$

$$Q\frac{dr}{r} = -2\pi K\, dT$$

$$Q\int_{r1}^{r2}\frac{dT}{r} = -2\pi L K\int_{T1}^{T2} dT$$

$$Q*\ln\frac{r2}{r1} = -2\pi L K\,(T_2-T_1)$$

$$Q = \frac{-2\pi L K\,(T2-T1)}{\ln\frac{r2}{r1}}$$

$$Q = \frac{\frac{(T2-T1)}{\ln\frac{r2}{r1}}}{-2\pi L K}$$

For continuity of flow, the heat transfer through each layer must be the same, hence

$$Q = 2\pi KwL\,(T_1-T_2/\ln\frac{r2}{r1}) = 2\pi L Kb\,(T_2-T/\ln\frac{r2}{r1}) + hA_s\,(T_2-T_3)$$

$$R_w = \ln\frac{r2}{r1}\Big/2\pi KwL = \ln\frac{252.5}{250}\Big/2\pi * 1300 * 58 = 2.1003214*10^{-8}\,W/K$$

$$R_b = \ln\frac{r3}{r2}\Big/2\pi KwL = \ln\frac{254}{878}\Big/2\pi * 1300 * .287 = 4.53185*10^{-4}\,W/K$$

$$R_{conv} = 1/2\pi L r1$$

Hence for continuity, $(T1 - T2)/Rw = (T2 - T3)/Rb + 1/2\pi r1hL$

$$R_c = Rw + R_b$$

R_c = 2.1003214*10^{-8} + 40531385*10^{-4} = 4.552388*10^{-4}W/K

$R_{conv} = {}^{1}/_{2\pi Lr1} = {}^{1}/_{2\pi * 1.3 * .25 * 2.87}$ = 0.10763W/K

Therefore, ${}^{(T1 - T2)}/_{Rw} = {}^{(T2 - T3)}/_{Rb} + {}^{1}/_{2\pi r 1hL}$

${}^{(623 - T2)}/_{2.1003214 * 10 - 8} = {}^{(T2 - 523)}/_{4.53188 * 10 - 4} +$ 0.10763(T_2-523), Solving these equations we get temperature of the inner wall of the drum,

T_2 = 349.98^{0}c

3.2.2 Heat transfer by convection

The heat generated in the heating chamber of this roasting machine is distributed in this chamber and around the wall of the rotating drum by free movement of air called natural convection.

Treating the coffee flow as a fluid flow over a solid surface and considering the heat transfer from the roaster to the coffee by convection, Newton's Law of Cooling (Osore, 1997)

$Q = h A_s (T_s - T_\infty)$

Where h = convective heat transfer coefficient, W/m2 A_s = area of heat transfer

$A_s = 2\pi r_1 L = 2×0.2475 ×1.3 = 2.0216m^2$

$(T_\infty) = T_3$ = fluid temperature $T_s = T_2$ = solid surface temperature

∴ Q = 2.87*2.021(662.298-523) = 15158.9W= 15.2KW

Therefore 15.6kW heat energy must be transferred from the burner to the coffee bean in the roaster.

3.2.3 LIQUEFIED PETROLEUM GAS (LPG)

Before going to describe the details under this topic it is better to explains why Liquefied Petroleum Gas (LPG) is used as a source of the energy to run the system: Many people are not aware of the option of using LPG or they have heard of LPG and they aren't sure what it is.

There are a number of choices available when it comes to heating homes and businesses and one of these options is LPG. There are advantages to home and business owners who choose LPG over other fuels.

ADVANTAGES OF LPG OVER OTHER ENERGY SOURCES

- LPG is very easy to transport
- It has a higher heating value, allowing you to heat your home at a lower price
- LPG doesn't contains Sulphur, so it burns a lot cleaner than energy sources like oil
- LPG burns consistently, making it more reliable than other forms of energy
- LPG is also perfect for those who don't have access to natural gas lines. Since it is easily transported and even able to be stored underground with little danger
- LPG is a clean fuel
- If LPG was used, the wood consumption can be substantially reduced, 45kg of LPG is sufficient to produce the thermic energy of about half a ton of wood.
- Finally, you will find that LPG is more environmentally friendly than other sources of energy. Though all energy sources will release carbon dioxide, when compared to oil, coal etc. except electricity, LPG release very much less amount of carbon dioxide.

DISADVANTAGES OF LPG

- In case of worn out equipment or incorrect use, LPG bears the risk of explosion
- Accessibility in rural areas due to unreliable or missing distribution network
- LPG is a finite resource
- The heat generated is absorbed by the roasting medium and its surfaces, causing a temperature rise above the ambient temperature. This temperature difference drives the heat transfer from the hot medium to the ambient, and insulation reduces the amount of heat loss and thus saves fuel and money.

3.2.4 Thermal insulation of the machine

Thermal insulations are materials or combinations of materials that are used primarily to provide resistance to heat flow. Temperature difference is the driving force for heat flow, and the greater the temperature difference, the larger the rate of heat transfer. We can slow down the heat flow between two mediums at different temperatures by putting “barriers” on the path of heat flow. Thermal insulations serve as such “barriers” on the path of heat flow.

In this roasting machine, heat is generated in the gas burner by burning fuel (LPG). To sum up, the following are good reasons to insulate the machine

- Energy conservation
- Personnel protection and comfort: a surface that is too hot poses a danger to people who are working in that area of accidentally touching the hot surface and burning themselves. To prevent this danger and to comply with the OSHA (Occupational Safety and Health Administration) standards, the temperatures of hot surfaces should not be reduced to below 60^0C by insulating them.
- To maintain the roasting process temperature: it is necessary to insulate the roasting section to maintain the same temperature throughout.
- Fire protection

Now we know the outside surface temperature of the drum $T_1 = T_i = 350^0$C

The surface temperature of the machine should be below 60^0C. Hence let’s take $T_o = 50^0$C

The atmospheric temperature of the environment can be taken as $T_a = 24^0$C

There is air gap between the inner surface and the drum. Heat transfer in this case is convective type. From that layer towards the outer most layers, convective heat transfer dominates

Initial assumptions

- Steady state heat transfer
- Heat transfer in one dimensional
- Thermal conductivities are constant
- The thermal contact resistance at the interface is negligible

The thermal resistance network involves three resistances in series.

Let

r_1 = outside radius of the roasting drum

r_2 = radius of inner surface of the machine = 30 cm

r_3 = radius of inner surface of the insulating material = 30 cm + 0.08 cm = 30.08cm

r_4 = outside radius of the insulating material

L = length of the drum = 1.3 m

The thermal conductivities for the materials are given to be K = K_1 = 15 W/m^{0}C for the mild steel cover and K = K_2 = 0.038 W/m ^{0}C for fiber glass insulation. The heat transfer coefficient of air, h_a = 50 W/m^2 ^{0}C (for moderate speed, 28m/s, forced convection low speed flow of air over the surface)

A_2 = (2лr2L)/2 = (2 * л * 0.3 m * 1.3 m)/2 =1.225 m^2

The individual thermal resistances can now be determined.

$R_1 = R_{conv} = \frac{1}{haA2} = \frac{1}{50*1.225} = 0.0163\ ^oC/W$

$R_2 = R_{cond} = (\ln\frac{r3}{r2} \Big/ 2\pi K1L) = \ln\frac{0.3008}{0.3} \Big/ 2\pi * 15 * 1.3 = 0.000021^0C/W$

$R_3 = R_{insulation} = \ln\frac{r4}{r3} \Big/ 2\pi K2L = \ln\frac{r4}{0.3008} \Big/ 2\pi * 0.038 * 1.3 = 3.221(\ln\frac{r4}{0.3008})°C/W$

Nothing that all resistances are in series, the total resistance is determined to be: $R_{total} = R_1 + R_2 + R_3$. Then the steady rate of heat transfer from the surface of the drum to the outside surface of the insulation becomes,

$Q = \frac{Ti - To}{Rtot} = \frac{350 - 50}{0.0163 + 0.00021 + 3.22 \ln \frac{r4}{0.3008}}$ …..###

The outer surface temperature of the insulation is specified to be 50^0C. Hence the rate of heat loss can be expressed as: $Q = \frac{Ta - Ts}{Ro}$, where R_o is the thermal resistance of the atmospheric air

$R_O = \frac{1}{haa * Ao}$, h_{aa} = thermal conductivity of the free air at atmospheric condition = 15 $W/m^{2\,0}C$

$R_O = \frac{1}{15 * 2\pi r4 * 1.3/2} = \frac{1}{61.261r4}$ $^oC/W$

Hence, $Q = \frac{50 - 24}{\frac{1}{61.261r4}}$ ………###

Nothing that these two heat transfer rates must be the same. i.e.

$$\frac{50 - 24}{\frac{1}{61.261r4}} = \frac{350 - 50}{0.0163 + 0.00021 + 3.22 \ln \frac{r4}{0.3008}}$$

Solving for r_4, we get $\mathbf{r_4 = 0.6492\ m}$ then the minimum thickness of fiberglass insulation required is: **t = 0.3252 – 0.3008 = 0.0244 m ≈ 2.5 cm**

Adding more insulation to the wall decreases the heat transfer. The thicker the insulation, the lower the heat transfer rate. But the additional insulation increases the conduction resistance of the insulation layer but decreases the convection resistance of the surface due to the increase in the outer surface area for convection. So the heat transfer may increase or decrease, depending on which effect dominates. The critical radius of insulation for a cylindrical body is $r_{cr,\,cyl} = \frac{k}{h}$

Where k = the thermal conductivity of the insulation and h = convection heat transfer coefficient

$r_{cr,\,cyl} = \frac{0.038}{15}$ = 0.002533m = 2.53mm

CHAPTER FOUR

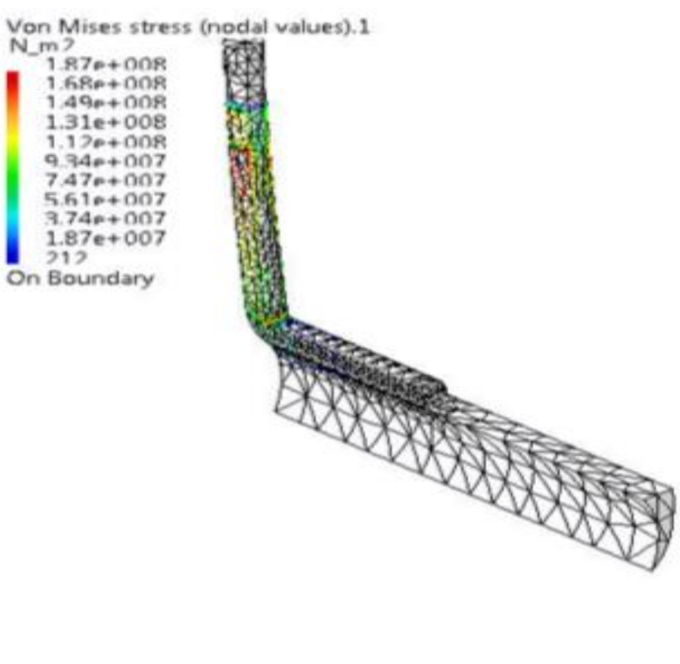
RESULTS AND DISCUSSION

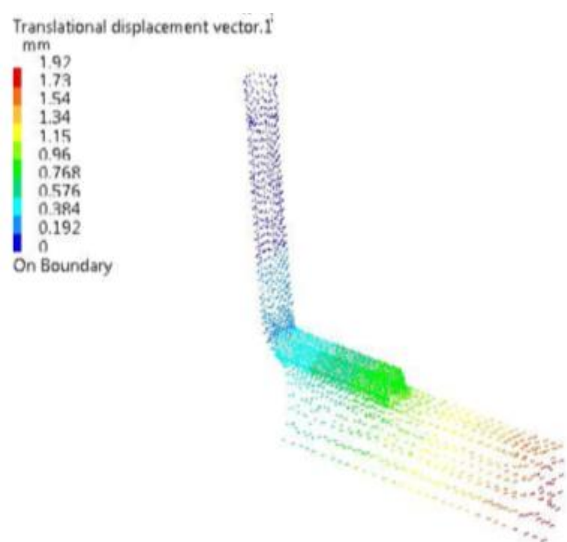
4.1 RESULTS

There are many results obtained during the design analysis of this machine. Among these result, improvement of roasting process in terms of quality, reduced roasting time, simplification of operation and control system, some roasting machine components are also checked whether the design was under failure or not, thus as per IS (Indian Standard and other design standard) it is in safe condition and other related functions that satisfy the customer needs are the major ones. The result is obtained after we identified the weakness and hardship of roasting with traditional roasting method. The literature review is also used to get the basic idea of the existing solution concept. The proposed concepts are then generated according to the problem and establishment of customer needs and specification.

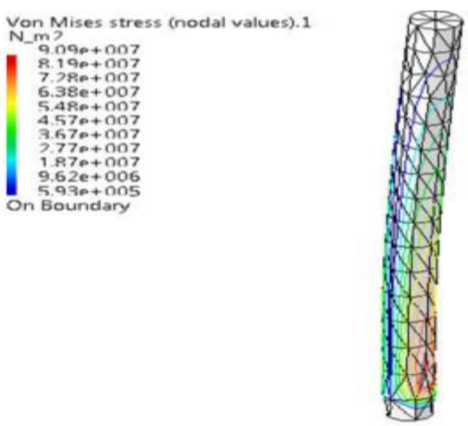
From the perspective of basic components:

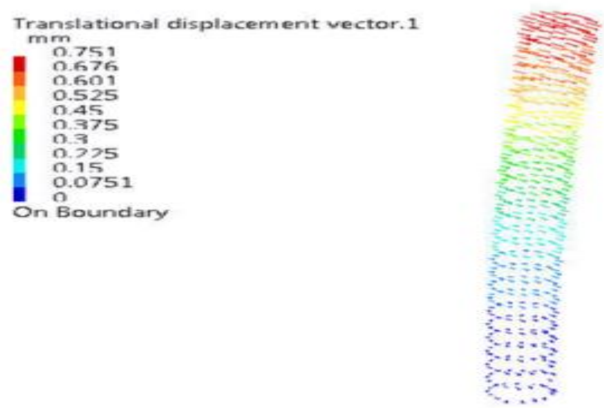
From the Von Mises stress figure, the maximum stress is **1.87e + 008N_m^2** which is below the yield strength of the material, i.e. **2.5e + 008N_m^2** , therefore the component part design(cooling blade) is safe and it is satisfactory to use this material.



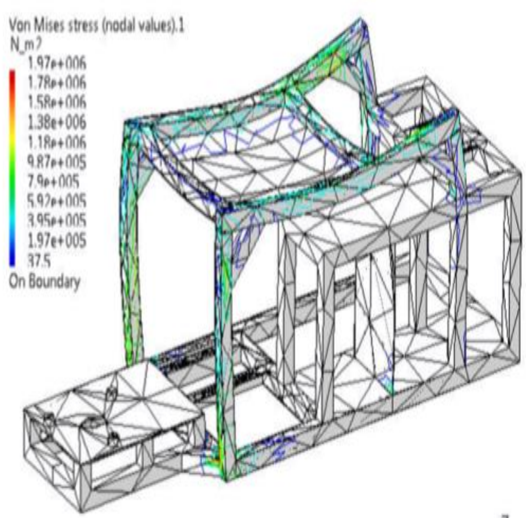


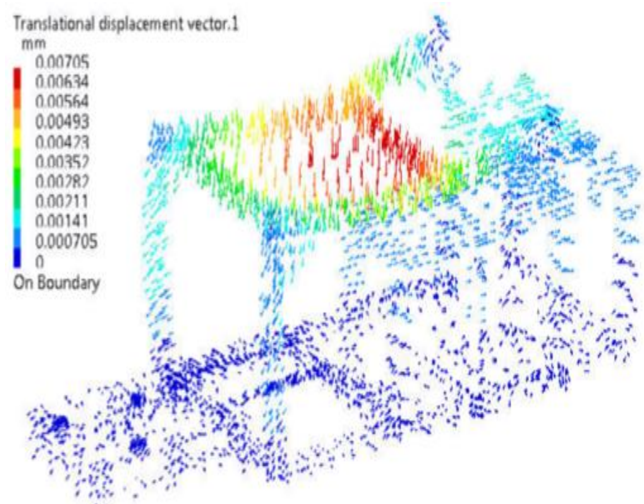
- From the Von Mises stress figure, the maximum stress is **9.09e + 007N_ m²** which is below the yield strength of the material, i.e**. 2.5e + 008N_m²**. Thus, this is also safe design since this component (supporting rods) also supports and holds its duties.





- From the Von Mises stress figure, the maximum stress is **1.97e + 006N_ m²** which is below the yield strength of the material, i.e. **2.5e + 008N_m²**. Also this frame is safe and satisfactory to hold and carry all components or carry the whole machine.





To sum up, the major results obtained are listed below:

- Very simple operation principle
- Easily accessed for maintenance
- Economic operation

- Reduced roasting time and operator effort
- Marketable and other related functions that satisfy customer needs

4.2 DISCUSSION

The design of this machine involves efforts to improve every necessary functions of operation of the roasting process. The machine construction concept is generated identifying set of customer needs and establishing targets product specification.

In concept selection, the concepts are evaluated with respect to customer needs and other criteria, comparing the relative strength and weakness of the concepts, for further investigation. The current machine design used has been chosen to become reference concept, against which all other concepts are rated. Since the existing roasting machine is fixed cylindrical type; so it is very exposed to burn of coffee and yields with non-uniformity mixing process and also it is experienced with use of electricity as a source of energy and this by itself doesn’t bring qualified roasted coffee with desired aroma, because the roasting time is being wether very fast or short and its temperature is too high, thus aroma quality is get low. Since the source of energy is LPG which is unusual before, as per the merits of LPG it is very necessary to use it and in perspective of operation, it is very easy to operate with any kind of operator whether educated or not and also the cost analysis of the machine shows, the overall cost of manufacturing is very much cheaper than the one imported. Hence it can be concluded the manufacturing of this machine is economically sound.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The design of this machine mainly focuses on increasing the operational advantage of this drum – type coffee roasting machine. This paper work encompasses all the procedural processes followed in the thesis. One can observe that every design can be manufactured from cheaper materials available around and it is possible to modify the existing design by certain parameters for its feasibility. The paper has contributed much for design and manufacturing knowledge starting from material selection to the assembly of the machine. The paper has tried to make the machine very simple in construction and also hope that the machine can be further improved.

5.2 RECOMMENDATION

For efficient operation and longer life of the machine system designed, the assembly, maintenance and operation tips are recommended to be noticed well. In addition to this the following points should be strictly adhered to:

- The durability of the machine mainly depends on the type of materials selected. So, best materials should be selected and checked for their property before use.
- The overall roasting process can further be improved by adding some extra computer controlled digital components to the machine
- All the analytical methods followed in the design of the components can be justified using different computer software for better result.

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APPENDIX B

Table 9: Number of starts to be used on the worm for different velocity ratio

Velocity ratio (*V.R.*)	36 and above	12 to 36	8 to 12	6 to 12	4 to 10
Number of starts or threads on the worm ($n = T_w$)	Single	Double	Triple	Quadruple	Sextuple

Table 10: Proportions for worm

S. No.	*Particulars*	*Single and double threaded worms*	*Triple and quadruple threaded worms*
1.	Normal pressure angle (ϕ)	14½°	20°
2.	Pitch circle diameter for worms integral with the shaft	$2.35\ p_c + 10$ mm	$2.35\ p_c + 10$ mm
3.	Pitch circle diameter for worms bored to fit over the shaft	$2.4\ p_c + 28$ mm	$2.4\ p_c + 28$ mm
4.	Maximum bore for shaft	$p_c + 13.5$ mm	$p_c + 13.5$ mm
5.	Hub diameter	$1.66\ p_c + 25$ mm	$1.726\ p_c + 25$ mm
6.	Face length (L_W)	$p_c\ (4.5 + 0.02\ T_W)$	$p_c\ (4.5 + 0.02\ T_W)$
7.	Depth of tooth (h)	$0.686\ p_c$	$0.623\ p_c$
8.	Addendum (a)	$0.318\ p_c$	$0.286\ p_c$

Table 11: Proportions for the worm gear

S. No.	*Particulars*	*Single and double threads*	*Triple and quadruple threads*
1.	Normal pressure angle (ϕ)	14½°	20°
2.	Outside diameter (D_{OG})	$D_G + 1.0135\ p_c$	$D_G + 0.8903\ p_c$
3.	Throat diameter (D_T)	$D_G + 0.636\ p_c$	$D_G + 0.572\ p_c$
4.	Face width (b)	$2.38\ p_c + 6.5$ mm	$2.15\ p_c + 5$ mm
5.	Radius of gear face (R_f)	$0.882\ p_c + 14$ mm	$0.914\ p_c + 14$ mm
6.	Radius of gear rim (R_r)	$2.2\ p_c + 14$ mm	$2.1\ p_c + 14$ mm

Table 12: Values of load stress factor (K)

S.No.	Material		Load stress factor (K) N/mm^2
	Worm	Worm gear	
1.	Steel (B.H.N. 250)	Phosphor bronze	0.415
2.	Hardened steel	Cast iron	0.345
3.	Hardened steel	Phosphor bronze	0.550
4.	Hardened steel	Chilled phosphor bronze	0.830
5.	Hardened steel	Antimony bronze	0.830
6.	Cast iron	Phosphor bronze	1.035

Table 13: Number of teeth on the smallest sprocket

Type of chain	Number of teeth at velocity ratio					
	1	2	3	4	5	6
Roller	31	27	25	23	21	17
Silent	40	35	31	27	23	19

Table 14: Power rating (in KW) of simple roller chain

Speed of smaller sprocket or pinion (r.p.m.)	Power (kW)				
	06 B	08 B	10 B	12 B	16 B
100	0.25	0.64	1.18	2.01	4.83
200	0.47	1.18	2.19	3.75	8.94
300	0.61	1.70	3.15	5.43	13.06
500	1.09	2.72	5.01	8.53	20.57
700	1.48	3.66	6.71	11.63	27.73
1000	2.03	5.09	8.97	15.65	34.89
1400	2.73	6.81	11.67	18.15	38.47
1800	3.44	8.10	13.03	19.85	–
2000	3.80	8.67	13.49	20.57	–

Table 15: Characteristics of roller chains according to IS: 2403 – 1991

ISO Chain number	Pitch (p) mm	Roller diameter (d_1) mm Maximum	Width between inner plates (b_1) mm Maximum	Transverse pitch (p_1) mm	Breaking load (kN) Minimum		
					Simple	Duplex	Triplex
05 B	8.00	5.00	3.00	5.64	4.4	7.8	11.1
06 B	9.525	6.35	5.72	10.24	8.9	16.9	24.9
08 B	12.70	8.51	7.75	13.92	17.8	31.1	44.5
10 B	15.875	10.16	9.65	16.59	22.2	44.5	66.7
12 B	19.05	12.07	11.68	19.46	28.9	57.8	86.7
16 B	25.4	15.88	17.02	31.88	42.3	84.5	126.8
20 B	31.75	19.05	19.56	36.45	64.5	129	193.5
24 B	38.10	25.40	25.40	48.36	97.9	195.7	293.6
28 B	44.45	27.94	30.99	59.56	129	258	387
32 B	50.80	29.21	30.99	68.55	169	338	507.10
40 B	63.50	39.37	38.10	72.29	262.4	524.9	787.3
48 B	76.20	48.26	45.72	91.21	400.3	800.7	1201

Table 16: Factor of safety (n) for bush roller and silent chains

Type of chain	Pitch of chain (mm)	Speed of the sprocket pinion in r.p.m.								
		50	200	400	600	800	1000	1200	1600	2000
Bush roller chain	12 – 15	7	7.8	8.55	9.35	10.2	11	11.7	13.2	14.8
	20 – 25	7	8.2	9.35	10.3	11.7	12.9	14	16.3	–
	30 – 35	7	8.55	10.2	13.2	14.8	16.3	19.5	–	–
Silent chain	12.7 – 15.87	20	22.2	24.4	28.7	29.0	31.0	33.4	37.8	42.0
	19.05 – 25.4	20	23.4	26.7	30.0	33.4	36.8	40.0	46.5	53.5