ANALYSIS OF A COFFEE HUSK FIRED COGENERATION PLANT FOR SHEKA ZONE COFFEE PROCESSING INDUSTRIES

M.Sc. THESIS

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DECLARATION

I hereby declare that this M.Sc. Thesis entitled 'Analysis of a Coffee Husk Fired Cogeneration Plant for Sheka Zone Coffee Processing Industries' Submitted in partial fulfillment of the requirements of the degree of masters of science in thermal engineering is an authentic record of my own work carried out from September 2017 to September 2018 under the supervision of Dr. Suresh G. Assistant Professor of Thermal Engineering program, Adama Science and Technology University.

The matter embodied in this thesis has not been submitted by me for the award of any other degree or diploma. All relevant resources of information used in this thesis have been duly acknowledged.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief. This thesis has been submitted for examination with our approval.

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APPROVAL BY BOARD OF EXAMINERS

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ABSTRACT

Nowadays our energy needs have grown exponentially corresponding with human population growth and technological advancement. Energy consumption linked to non-renewable resources contributes to greenhouse gas emissions and enhances resource depletion. Therefore, in this work the thermal analysis of a coffee husk fired cogeneration plant for Sheka zone coffee processing industries has been presented. In this context the use of coffee husk has been widely studied as an alternative energy source in order to cover the heat and power demand of the coffee processing industries in the zone. The analysis use combustion of coffee husk and solid fuel fired boiler technologies to transform coffee husks into electrical and heat energy (CHP) considering its physical and chemical properties based on the selected design parameters operating steam pressure of 10 bar with the average fuel consumption rate of 1000 kg/h which is calculated from the collected data of the Zone and combustion chamber which utilizes fluidized combustion system. The plant is analyzed for thermal utilization of coffee husk in coffee processing industries in Sheka zone. The average generation of the husk per 100 kg of dry coffee cherry was considered in order to assess the availability of the husk. The data were collected from Sheka Zone Agricultural and Natural Resource Development Department, Yeki Woreda Agricultural and Natural Resource Development Office and from the coffee processing industries. Calculation of calorific value of the husk to determine the heat contents was carried out using Bomb calorimeter in the laboratory of Geological Survey of Ethiopian. The calorific values obtained from this analysis were 18.98 MJ/kg. The maximum temperature of the furnace attained from the energy balance based on this value inside the combustion chamber was 1489 ℃ and the amount of air required per kg of coffee husk was 5.45 kg. The paper also included the design calculation of the steam generator which provides steam with a maximum temperature of 518 ℃ to the steam turbine. In addition, the thesis discussed the selected rotary type dryer design based on the collected and literature data and the calculation of the cogeneration plant energy analysis using the Rankin thermodynamic cycle.

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NOMENCLATURE

ABBREVIATIONS

C	Carbon
H	Hydrogen
O	Oxygen
S	Sulphur
m	Mass
CH	Coffee husk
CHP	Combined heat and power
GCV	Gross calorific value
c_p	Specific heat capacity
$\dot{m}$	Mass flow rate
T	Temperature
A	Area
R	Capacity ratio
P	Temperature ratio
h	Heat transfer coefficient
L	Total length
Q	Heat
E	Energy
M	Present moisture
Nu	Nusselt number
Re	Reynolds number
k	Thermal conductivity
FCR	Fluid capacity rate
H	Thermal energy

SUBSCRIPTS

in	Input
out	Output
FG	Flue gases
UF	Unburnt fuel
FW	Feed water
CW	Cooling water
Eco	Economizer
Eva	Evaporator
SH	Super heater
St	Steam
AS	Actual mass air supplied
BA	Bottom ash
FA	Fly ash
APH	Air preheater
EA	Excess air
WV	Water vapour
Moi	Moisture
Los	Loss
s	Surface
TU	Transfer unit
Tur	Turbine
Con	Condenser
FP	Feed pump
d	Dry basis

Fc	Correction factor
N	Speed (RPM)
D	Dryer diameter
RT	Retention time

GREEK LETTERS

μ	Kinamatics viscosity
η	Efficiency
ρ	Density
ε	Effectiveness

c	Cross section
lm	Logarithmic mean
min	Minimum
max	Maximum
i	Inside
o	Outside
w	Water

CHAPTER ONE

INTRODUCTION

Cogeneration or Combined Heat and Power (CHP) is the production of two different form of useful energy from a single primary energy source, typically mechanical energy and thermal energy. The Mechanical energy may be used either to drive an alternator for producing electricity or rotating equipment such as motor, compressor, pump or fan for delivering various services. Thermal energy can be used either for direct process applications or for indirectly producing steam, hot water, hot air for dryer or chilled water for process cooling. According to the Second Law of Thermodynamics, the plant gives back heat to a cold sink before rejecting the remaining heat to the environment at the reference temperature (T_o). A cogeneration plant system can operate at efficiencies greater than those achieved when heat and power are produced in separate or distinct processes [1].

Cogeneration plant may use different form of primary energy sources (renewable or non-renewable), among these energy sources biomass is the one. It is the third largest renewable primary energy resource in the world, after coal and oil [2]. In all its forms, biomass currently provides about 1250 million TOE (Tons of Oil Equivalence) which is about 14% of the world's annual energy consumption. Biomass is a major source of energy in developing countries, where it provides 35% of all the energy requirements [3]. The worldwide concern about CO_2 emissions and the reduction in use of coal fuels have increased the interest in using biomass fuel for electricity production, because there is no net increase in CO_2 emissions from biomass combustion [4]. Biomass materials with high energy potential include agricultural residues such as straw, bagasse, **coffee husk**, rice husks, as well as residues from forest related activities such as wood chips, sawdust, bark and so forth [5].

Coffee is a major commodity export earner for Ethiopia, accounting for 61% (by value) of the country's annual commodity exports. It is estimated that the total area covered by coffee is approximately 400,000 hectares, with a total production of 200,000 tons of clean coffee per year [6].

In addition, approximately 15 million people (20% of the population) directly make a living from the coffee industries [7]. Industrial coffee production uses either a dry or a wet processing method for the removal of the shell and mucilaginous parts from the cherries resulting in the production of green coffee and large amount of **coffee husk** which is the byproduct of the processes [8, 9].

There are essentially two ways of processing coffee beans from the freshly picked red cherries of the coffee plant: wet and dry processing. Each process produces a different quality of "green coffee" and residues with very different characteristics.

Coffee processing which results washed and dry green coffee as a product and parchment and husk as by-products includes planting, harvesting and processing of cherry coffee (dry or wet) in the factories.

Coffee is usually cultivated between latitudes 25^{O} N and 25^{O} S at altitudes of 3,500 to 6,000 feet above sea level and it requires an average annual temperature range between 20^{O} and 25^{O}C [10].

Coffee bushes normally take three to five years to develop from seedling to full producing shrub. The shrub bears fruit for forty or more years, but productivity is greatest between five and fifteen years of age. Mature fruits (cherries) are produced some six to nine months after flowering. Flowering may occur at one time, but there are often four or more successive flowerings triggered mainly by rainfall. The fruit on any one tree and in any one area does not necessarily ripen at the same time; the cherries stay in their prime for about a week.

Harvesting

The harvesting of coffee is normally by hand and therefore labor intensive. The type of picking practiced depends on local conditions and the type of processing to be used: either 'strip picking' used with dry processing or 'selective picking' with wet processing. Strip picking involves removal of all the fruit from a tree after most of the fruit has matured. A large proportion of the harvested fruit may be over-ripe, immature, or even green. This results in an uneven end-product and reduced liquor quality. Such cherries of mixed maturity are dry-processed. Wet processing requires soft fruit that can be pulped. This process must be accompanied by selective picking as only fruit that is ripe or slightly under- or over-ripe can be used. Over ripe cherries have started to dry and harden making pulping difficult [10].

The coffee cherry comprises three layers around the bean. The outer layer consists of the mesocarp, which is also known as the pulp of the cherry. The color of this outer layer depends on the plant variety and ranges from burgundy red to deep red and yellow for ripe cherries. Below the mesocarp is the endocarp, consisting of the parchment and the mucilage, which is a jelly-like slightly sticky layer rich in pectins. Finally, there is the ‘silver skin’, a thin paper-like fibrous tissue surrounding the bean. By weight, ripe cherries contain about 20% of green coffee beans [6].

Processing of cherries

In Ethiopia, coffee cherries are processed using both dry and wet processing methods. The object of coffee processing in the industries is to separate the beans from the skin and pulp of the cherry. The

basic operations of the dry method are harvesting, drying and hulling, and of the wet method are harvesting, pulping, fermentation and washing, drying, peeling and polishing.

The two systems differ principally in the bean separation stage. The dry process involves drying of the whole cherry until the green bean inside separates from the outer layers. The outer layers are then removed by hulling. Wet processing involves removal of the pulp and mucilage followed by drying then the parchment and silver skin are later removed by hulling [11].

Wet Processing

Wet processing does not require drying of the cherries and during this method of processing three main operations are involved, they are: pulping, fermentation and washing. The end product is wet parchment coffee.

Pulping removes the skin and pulp from the bean. Disc or drum pulpers operate by squeezing and tearing the flesh away from the beans. It is important that the cherries be pulped as soon after picking as possible. Classification by size before pulping and adjustment of the pulper to the cherry size minimizes damage to the beans and water used in flushing must be free of external contaminants. Pulping machines are use little power.

Fermentation starts after pulping is completed, after pulping the beans remain coated with slippery mucilage which is insoluble in water. Fermentation breaks down the mucilage so that it can be readily separated from the parchment. Most of in this specific study area the fermentation process takes 3-4 days but there are also some wet processing factories which use different techniques to reduce the fermentation time.

After fermentation the coffee is repeatedly washed in clean water until the mucilage is removed completely. Washing soon after fermentation prevents microorganism damage to the bean itself. However, if fermented beans dried immediately without repeated washing may be because of scarcity of water, problems may create with initial handling of the sticky beans and lengthens the drying process by about one day.

In the wet (washed coffee processing) process the fresh cherries are milled using wet pulping machines to remove the outer skin and some of the mucilage. The processed cherry is then left to ferment in tanks for a specified period of time and the removal of the remaining mucilage is effected while the parchment is left intact.

As a result of the washed processing method, two distinct types of residue are generated. The first is the wet coffee pulp, which consists of the epicarp that is removed at the washing plants in the coffee

growing regions. For 100 kg of ripe cherries delivered to a washing plant, 60% by mass ends up as washed coffee pulp with the remaining 40% consisting of the green bean and endocarp (parchment). Of this 60% washed coffee pulp, only 20 kg remains after sun-drying of the bean and parchment. This is then shipped to the washed coffee processing facility in Addis Ababa where the parchment is removed. The result is 16 kg of washed coffee beans ready for export and 4 kg of parchment as residues.

The average residue production per ton of wet red cherry is about 600 kg or, based on green coffee bean production, the residue potential would be 1.4 times the mass of green beans produced [12].

Dry processing

Dry processing is the simplest technique for processing coffee cherries. After harvesting, the fresh coffee cherries are dried to about 10–12% moisture content [13]. After the cherries are dry, they are put through a dry mechanical pulping (or decorticating) process in which the green coffee bean is separated from the outer residue material (outer skin, pulp, parchment and silver skin) of the cherry. The dry process removes the upper hard cover (the husk) and the inner skin (parchment) in the milling process. This residue material is generally blown out of the rear of the processing plant

A mass of 100 kg of red cherries picked at 65% moisture content will result in approximately 40 kg of sun-dried coffee cherries delivered to the processing plant. Of this mass, about 17 kg will become sun-dried coffee beans while the remaining 23 kg will end up as residue at the processing plant [12].

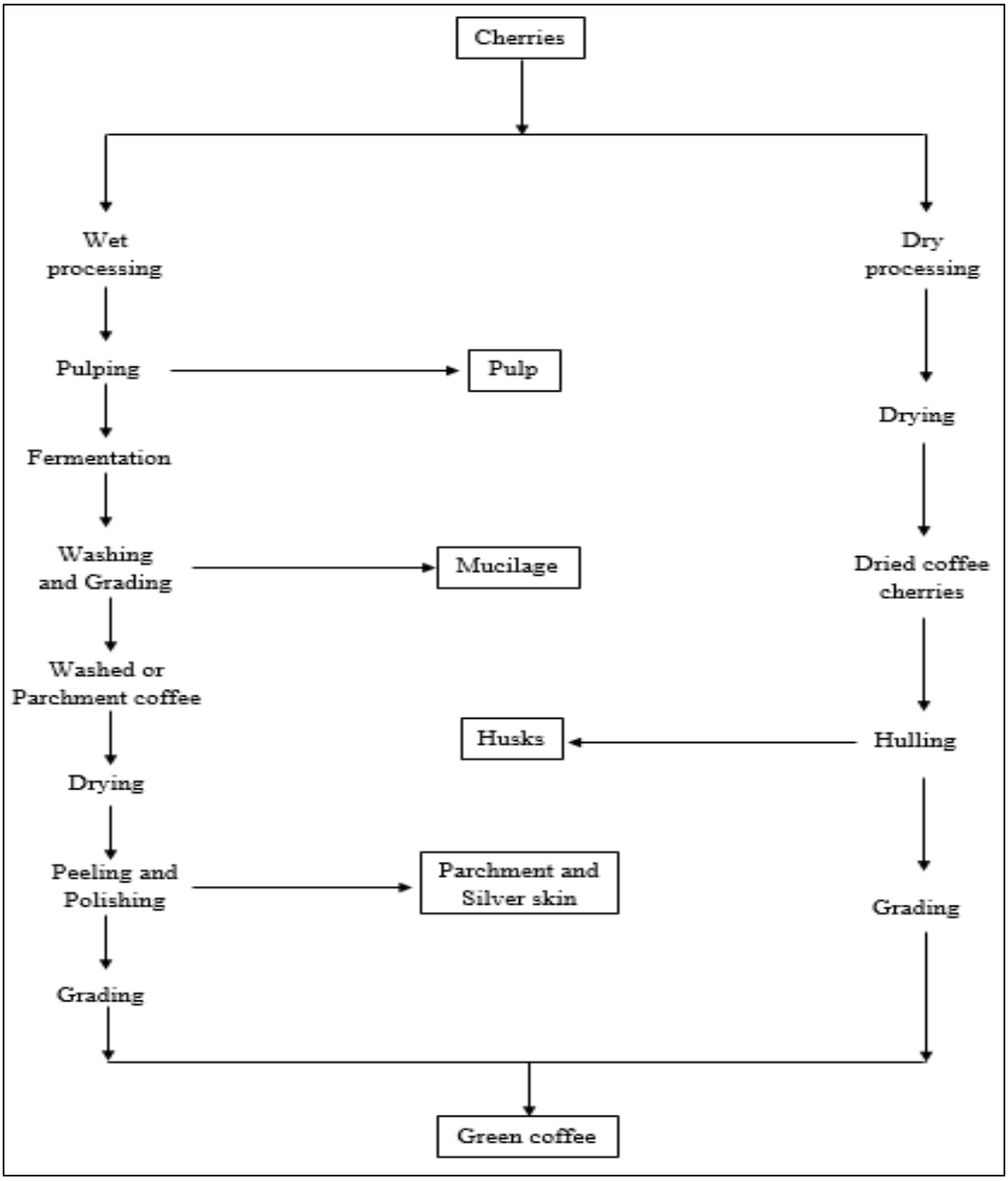

Figure 1.1 Flowchart of Coffee Processing

In Ethiopia 29% of coffee is processed by wet (washed) method to produce green parchment coffee and 71% by dry (natural sundried) method to obtain cherry coffee. Musebe et al. (2007) reported that coffee quality is determined by 40% in the field, 40% at postharvest primary processing and 20% at secondary processing and handling practices [14].

Currently, the wet pulp is discharged into local streams and rivers where it tends to clog, forming a putrescent mass and producing a highly acidic effluent which pollutes the water, destroying aquatic life and generating an offensive odour. Recovery of this pulp for industrial fuel use would require

collecting the residues as they are discharged from the pulping machine and processing them to greatly reduce the moisture content.

Husks represent over 90% of the coffee residues produced. However, the extremely low bulk density (approximately 50-80 kg/m3) of the husks produced precludes their economic transport to cement factories 300-500 km distant. Densifying or pelleting this material to a density of 500-600 kg/m3 would greatly reduce transport, handling and storage costs and facilitate its use as industrial fuel [15].

Most of the coffee production areas and processing plants in Ethiopia are found in the southern and eastern parts of the country, notably in the Southern Nations, Nationalities and People's Region (SNNPR) and in Oromia, which each host more than 500 coffee processing plants.

Sheka Zone is one of coffee growing zone in the Southern Nations, Nationalities and People's Region and lies nearly 594 km southwest of the Ethiopian capital of Addis Ababa.

Despite the favorable climatic conditions coffee is the major cash crop of the Zone, which is produced in the three woredas. Which serves as a major means of cash income for the livelihood of coffee farming families. According to the report (2009 E.C) from Sheka Zone Agricultural and Natural Resource Development Department more than 70% of the people in Sheka Zone are directly or indirectly benefited from the coffee industry [15].

In Ethiopia, coffee cherries are mostly processed using the dry method, thereby leading to an annual release of more than 240,000 tons of coffee husk into the environment [16]. This represents a serious environmental problem mainly due to the high content of tannins and phenolic compounds contained in this product. Their direct release into the environment could inhibit plant root growth and lead to an increase in greenhouse gas emissions through anaerobic decomposition [17].

Waste-to-energy facilities are part of the solution of the worldwide solid waste disposal problem. These facilities, when combined with recycling of critical material, composting, and landfilling, will be a long term economic solution as long as they are designed and operated in an environmentally acceptable manner.

A large variety of technologies has been developed over the past decades to deal with this problem. Among the proposed technologies, those oriented towards energy recovery, including combustion and gasification of biomasses has attracted much interest [18].

Studies suggest that one of the reasons for the low level of usage of coffee husks as fuel for direct combustion is the lack of sufficient information concerning the combustion and emission characteristics of these residues. Such information would be useful for the design and efficient

operation of combustion systems for coffee husks. Like other agricultural residues, some physical and chemical properties of coffee husks, such as the bulk density, ash and moisture content, contents of volatile matter, etc would decide how effectively the combustion process can be carried out [19 – 21].

In my thesis the investigation of the possible use of coffee husk fired cogeneration plant system that generates steam for electric power and drying proses of cherries, washed and parchment coffee in both dry and wet coffee processing industries will be conducted for coffee processing factories found in **Sheka zone**. In the thesis, the performance and economic visibility of the coffee husk fired cogeneration plant will be analyzed.

1.1 The research problem

Coffee processing generates significant amounts of agricultural waste ranging from 30% to 50% of the weight of the total coffee produced, depending on the type of processing. In Ethiopia natural drying or sun drying is the method commonly used because it requires no equipment investments and energy costs [1].

There are 71 coffee processing factories in **SHEKA ZONE**, which are generating over 10,135.96 Ton of coffee husk per annum, of which almost all are burned in open air or discharged into rivers in order to dispose of them. Coffee husk requires treatment or an adequate recovery to minimize environment impacts and increase the economic value of these wastes.

During coffee processing in both methods (dry and wet) drying is a major step which is accomplished by natural (Sun drying) methods in all coffee processing industries of the zone. However, it requires large drying areas (usually concrete surfaces). The process is slow, ranging from 3 to 4 weeks, the berries are usually spread out in a thin layer to avoid fermentation. Frequent raking is required to avoid mold and provide homogeneous drying conditions.

Several solutions and alternative uses of the coffee husk have been attempted. These include as fertilizers, livestock feed, compost, etc. However, these applications utilize only a fraction of available quantity and are not technically very efficient. If an efficient method is available, the coffee husk can be converted to useful energy to meet the thermal and mechanical energy requirements of the coffee processing industries and the electrical power requirements in the rural area.

Thus using direct combustion technologies and analyzing the coffee husk fired steam boiler system with an efficient drying technic the thesis will attempt to transform the coffee husks into useful heat and power energy considering proximate and ultimate analysis of the husk.

1.2 Objectives of the study

1.2.1 General objective

The general objective of the thesis is to analyze a cogeneration plant which uses coffee husk generated from coffee processing industries as direct energy source and that converts efficiently the available coffee husk to useful energy to meet the heat and electrical energy requirements of the coffee processing industries in Sheka zone.

1.2.2 Specific objectives

The specific objectives of this thesis are:

- ✓ To assess the available amount of coffee husk coming out from coffee processing industries in Sheka Zone.
- ✓ Electricity and thermal energy demand assessment of coffee processing industries in the Zone.
- ✓ Experimental characterization of the coffee husk.
- ✓ Combustion analysis of the coffee husk.
- ✓ To design the main parts of the cogeneration plant (Steam generators, Dryer and Condenser).
- ✓ Theoretical analysis of the thermodynamics cycle of coffee husk fired cogeneration plant.

1.3 Methodology

In this thesis direct combustion of coffee husk in combustion chamber which utilizes mass burn incineration is the best selected method for the conversion of energy. The average daily generation of the husk must be considered so in order to assess the availability of the material the data were collected and to determine the heat contents and for understanding of the husk combustion analysis, the ultimate and proximate analysis of the coffee husk were studied in the laboratory. The design analysis was based on the selected design parameters and using different mathematical relations found from literatures and design books the main parts of the cogeneration plat calculation is done. The plant energy analysis using Rankin cycle will be the final step of the project.

1.4 Data sources and collection techniques

The various design parameters are gathered from experimental data which was conducted in two different laboratories to know the chemical and physical properties of the husks.

The average daily generation of coffee husk was considered in order to assess the availability of the material. The data were collected from Sheka Zone Agricultural and Natural Resource Development Department in South Nation, Nationality and People Regional Government and from the coffee processing industries which is found in Tepi town Yeki Wereda. A few datum which are difficult to know are taken from different literatures.

- ✓ Company observations
- ✓ Interview with key persons
- ✓ Relative work papers (like on coal fired, bagasse fired steam power plants)
- ✓ Internet

The above sources used to understand the general combustion properties of the husk and mechanisms of solid fuel fired cogeneration plant system.

1.5 Scope, Significances and Limitations of the Study

The project's intension is to analyze a coffee husk fired cogeneration plant using a Rankin energy cycle and designing its main parts such like the coffee dryer, the condenser and the steam generators that generate stem which used for electric power generation and drying process of coffee (cherries, parchment and washed) during coffee processing in the coffee processing industries. My target community areas are the coffee processing industries in Tepi town as well as for the future it will propagate and adapt to the other parts of the country. This will enable for our country to get economical advantage from agricultural solid residues such like coffee husks.

Coffee husks are abundantly available in Ethiopia especially in the selected area in the form of waste of coffee processing factories but are normally underutilized. For an efficient utilization of these resources, adequate design of coffee husk- fired steam boiler is necessary in order to extract heat produced in the combustion of the husks, considering its high calorific value and the availability of this material around the selected site of the thesis.

The thesis will also enables the coffee processing factories to cover their power and thermal (for drying) demand by its own and provide power to the national grid. It also insure the independency of the industries on Ethiopian Electric Power and it will serve as technology transfer to coffee processing industries that can create job opportunity for the people. In addition, it provides insurance against energy price increases. The project enables to avoid requires of large drying areas for drying processes, minimize drying time and human power.

Besides its many advantages, the use of coffee husks as a direct solid fuel in water tube boiler system has some limitations which are:

If there is no a careful analysis of the melting properties of the ash, combustion of coffee husks may pose serious design and operation problems include agglomeration, fouling, slagging and corrosion. And also if the designer unable to adopt a suitable furnace design, high concentrations of the unburnt pollutants may be expected in the flue gas.

Collecting data was somewhat challenging due to the sake of security of the country and different conflicts raised here and there, moving place to place for data collection was too hard to get relevant information at the right time. The absence of internet connection and being low speed when it works were also a big challenge throughout this work. Lack of necessary data because of unavailability of record such as amount of coffee husk, solar data, etc.

1.6 The thesis outline

A brief introduction on the contents of the thesis is outlined as follows. Literature review of coffee husk fired cogeneration plant is discussed in chapter two. Chapter three focuses on site background and data analysis. The proximate and ultimate experimental result of the coffee husk are also presented in chapter four. Conceptual frame work given to husk fired cogeneration plant, the working principle of the system, system arrangement and key components are discussed in chapter five followed by the combustion analysis and design of steam generator, determination of necessary formulas for boiler calculation in chapter six. Chapter seven discussed about the dryer in details. Energy analysis of the plant using Rankin cycle is presented in chapter eight. In chapter ten the summary of results and discussion of the whole paper are done. The economic analysis of the cogeneration plant is included in the eleventh chapter, while the last chapter is discussed about conclusions and recommendations for future work.

CHAPTER TWO

LITERATURE REVIEW

Coffee husks are the solid residues obtained after hulling the coffee cherries during dry or wet processing. They are probably the major residues from the processing of coffee, for which there are no profitable uses, and their adequate disposal constitutes a major environmental problem. Furthermore, in compliance with the concept of sustainable development, innovative techniques and products for the valorization, reuse, and recycle of this type of residue should be sought. Several research works presenting proposals for such endeavors have been published in the literature and are reviewed below.

The use of husk as a supplement in animal feed was reviewed by Franca and Oliveira [18]; their major conclusions are that CHs as a supplement in cow diets was considered feasible, with the upper limits for feed substitution varying from 30% to 40%; in the case of pigs, use of CH was deemed to be technically and economically feasible at inclusion levels ranging from 5% to 10% for CHs and up to 16% in the case of sticky coffee. For sheep, CHs could be used as a corn substitute up to 25%, and in the case of fish, conclusions varied depending on the fish and on the way in which the husks were incorporated into the fish feed was done. Neither fresh nor ensiled coffee parchment (CP) was considered a suitable foodstuff for Nile tilapia, but CP showed potential as a feed ingredient in fish diets if fish are reared in earthen ponds or pens instead of concrete tanks or raceways.

Using CHs as a diet supplement is significantly restricted by the presence of anti-nutritional compounds such as caffeine, tannins, and others. Some studies with the purpose of removing these anti-nutritional substances from CHs have been successful, but they all involve processing steps that will add to the costs of producing a material that has no significant value added to it.

CHs and CP are rich in potassium and other mineral nutrients, which has resulted in studies of their application as organic fertilizers without any treatment or after composting. The use of CHs directly as soil coverage is deemed a good option for potassium-depleted soils and can be used for different types of crops, including coffee [1]

Composting can be defined as a solid-waste management system that accelerates the process of decomposition of biomass. Decomposition occurs spontaneously for CP and, if not controlled, can result in severe problems, including the proliferation of flies and foul odors, soil infiltration, and others. Controlled composting, however, provides a product that can be easily handled, stored, and

applied to the land without the above mentioned adverse effects. Composting of CP was described in early studies [13].

Matos [1] reported that CHs have low values for the carbon-to-nitrogen ratio (C:N), indicating that residues with high C:N should be mixed with CHs to guarantee a good quality product. The compost produced using CHs should be viewed more as a soil conditioner rather than as a fertilizer. Furthermore, it has the physical effect of increasing soil's water retention and should improve the long term quality of the soil [13].

Production of compost although deemed a feasible solution for the adequate disposal of CHs and present problems: the market demand is not able to keep up with the voluminous supply of husks and pulp, and the composting processes currently used do not guarantee the destruction of the coffee borer that may be infecting some of the CH.

Other studies of the pyrolysis of CHs [22, 23] indicated that the pyrolysis of this residue gives rise to the yield of a larger gas fraction compared to other fractions, even at relatively low temperatures. The gas fraction increased with an increase in pyrolysis temperature. A comparison of microwave assisted pyrolysis and conventional pyrolysis showed that microwave treatment produced more gas and less oil than conventional pyrolysis. In addition, the gas from the microwave had much larger amounts of hydrogen and syngas than those obtained by conventional pyrolysis in an electrical furnace, of which carbon dioxide (CO_2) is the main product.

Wilson [24] studied the high-temperature air/steam gasification of CHs to harness the potential of this biomass energy in a sustainable way. High temperatures enhanced the gasification process. Furthermore, increased gasification temperatures led to a linear increment of carbon monoxide concentration in the syngas. When gasification temperature was increased from 700 to 900 °C, the carbon monoxide yield for the 2% oxygen concentration increased six times.

Even though solid coffee residues have been reported to perform better in terms of biogas production in comparison to other agricultural residues, recent studies related to bio methanation of coffee processing residues indicated that this alternative use still does not seem to be viable because of either technical or economic setbacks. The production of bioethanol by fermentation of CHs constitutes a promising alternative for their adequate use, but there still is a need for significant research to make it both technically and economically viable.

Today's steam plants are a complex and highly sophisticated combination of engineered elements. Heat is obtained either from primary fossil fuels like coal, oil or natural gas, or from nuclear fuel in

the form of uranium. Other sources of heat-producing energy include waste heat and exhaust gases, bagasse and biomass, spent chemicals and municipal waste, and geothermal and solar energy.

Each fuel contains potential energy, or a heating value measured in Btu/lb (J/kg). The goal is to release this energy, most often by a controlled combustion process or, with uranium, through fission. The heat is then transferred to water through tube walls and other components or liquids. The heated water then changes form, turning into steam. The steam is normally heated further to specific temperatures and pressures [4].

Worldwide, the dry coffee processing industry has the potential to be a major generator of electric power for the electricity grid through the use of the by-product of coffee processing, husk as a fuel source. The installation of a high-pressure boiler, condensate steam turbine together with a double extraction turbo-generator is the optimum combination for implementing cogeneration in coffee processing factories. There is no single formula that applies to all cases. Detailed engineering analysis should be done on a case by case basis.

For understanding of solid fuel fired boiler, the following is essential to understand:

- ✓ Steam Generation Fundamentals
- ✓ Components and their arrangement in the Boiler
- ✓ Thermodynamic of Steam.

2.1 Overview of steam generation

The central job of the boiler designer is to combine fundamental science, technology, empirical data, and practical experience to produce a steam generating system that meets the steam supply requirements in the most economical package. Other factors in the design process include [3].

- ✓ Fuel characteristics
- ✓ Environmental protection
- ✓ Thermal efficiency
- ✓ Operations, maintenance and operating costs
- ✓ Regulatory requirements

2.2 Boiling fundamentals

A steam generating system should provide a continuous process of phase change from a liquid to a gaseous state for this conversion. Technical and economic factors indicate that the most effective way to produce high pressure steam is to heat relatively small diameter tubes containing a continuous flow of water. The boiling system used to accomplish this task include a steam drum. The steam drum

system is the most common and simplest to control. In this system, the drum serves as the point of separation of steam from water throughout its boiler's load range [3].

The total circulation rate in a natural circulation system depends primarily upon four factors:

1) The height of the boiler,

2) The operating pressure,

3) The heat input rate, and

4) The free flow areas of the components.

2.3 Cogeneration Power Plant

The primary function of the cogeneration power plant is to produce steam in sufficient quantities to generate electrical and thermal energy. In order to do this, the boiler requires fuel, air and water at all the times during operation. The heat released during the combustion of the fuel produces steam from the water. In most cases the steam is heated further before leaving the boiler. This process is continuous for the entire period that the plant is in operation.

2.3.1 General Working principle of the cogeneration

The coffee husk and combustion air enter in to the furnace and form a combustion flame. The combustion flame releases heat to the water tubes before it achieves its highest flame temperature. In the same time, the flame will release heat in the form of radiation. Similar heat transfer processes exist after the flame achieves its highest temperature.

A steam drum receives feed water from the economizer outlet that mixes with the saturated water in the drum. The steam is separated from the water and dried by the drum internals. The saturated steam flows out of the drum to the evaporator in which latent heat of vaporization is added after which the steam leaving the evaporator inters in to the super heater where it reaches at its maximum temperature.

Heat absorption decrease in the order of super heater, evaporator, economizer and air heater, due to the decrease of flue gas temperature when it travels past the bundles.

The main flow systems in power plant system are water flow, air flow, flue gas flow, steam flow and fuel flow. These all processes illustrated below in figure 2.1.

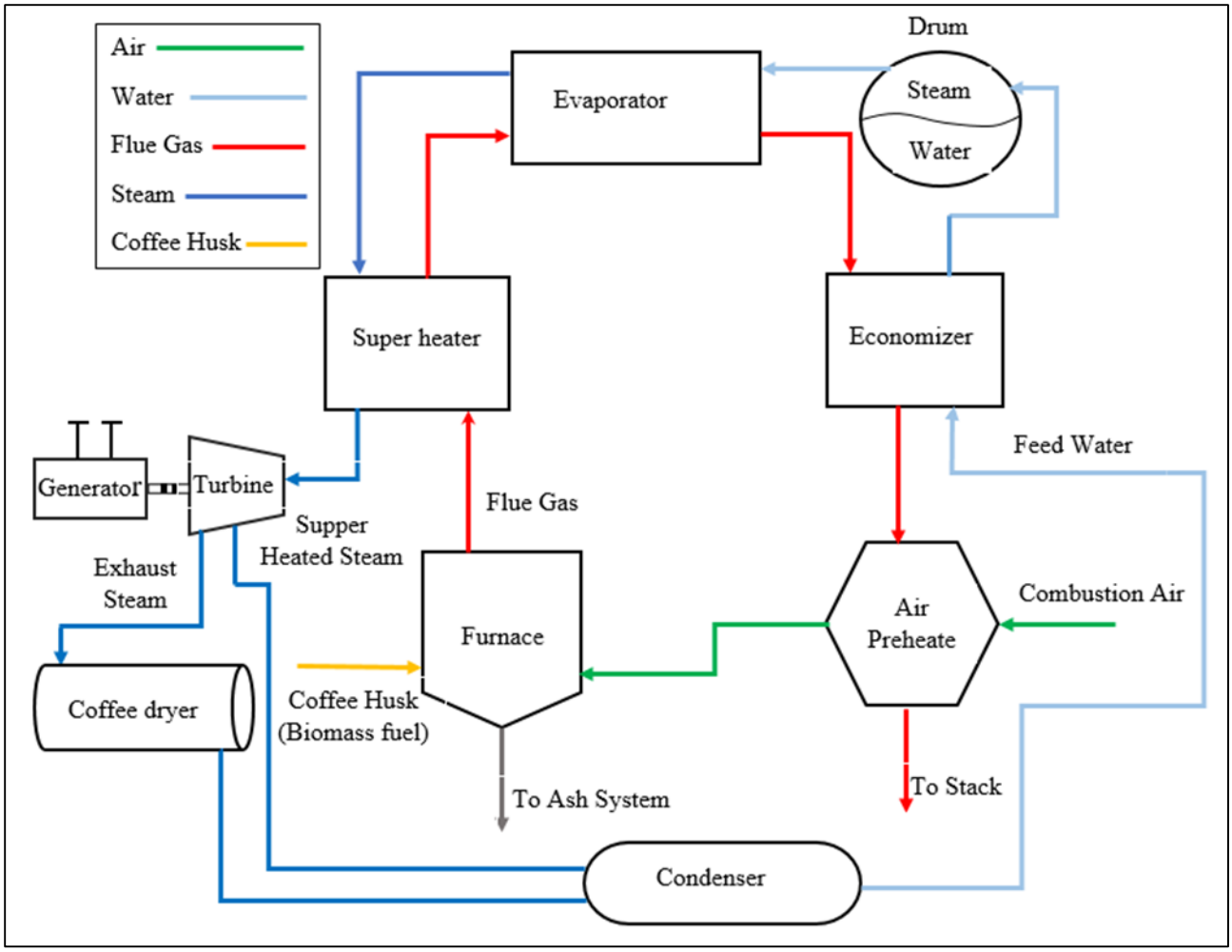

Figure 2.1 Schematic of a coffee husk fired boiler system

Entropy can be considered to be an indication of the intensity of the energy associated with fluid at a given temperature. It is a fluid property given by the fluid's heat content divided by its absolute temperature. As the fluid temperature is raised at a fixed pressure the entropy increases until the fluid starts to boil. The temperature then stays constant while the entropy continues to rise until the fluid becomes saturated steam. At this point, the temperature begins to rise again with increasing entropy [1].

The amount of steam varying according to the load changes. In order to change the steam output, the boiler must change the rate of the air and fuel combustion and rate of water flow proportionately. In order to respond to these changes accurately and efficiently, various control systems are used on the boiler.

2.3.2 Cogeneration Power Plant Main Components

The applications of steam generators involve the production of steam for supply of generation of electricity and drying process. The steam generator is a major part of the cogeneration plant system that has many subsystems and components. Key subsystems include fuel system, steam generation, and combustion, water supply, turbine, generator, and heat rejection.

In the coffee husk fired cogeneration system, the coffee husk (a heat source) is used to heat water in a water tube boiler to generate steam at pressure which then expands through and turns a steam turbine. The low pressure steam exhausted from the turbine is then goes to the drying process to provide heat energy to the drying system then after it condensed back into a liquid through the condenser and returned to the heat source by using feed water pump. In this way, the fluid passes around a cyclic process within the system, ultimately returning to its earlier state. In simple terms, the process can be broken down into four stages: heat addition, expansion, heat rejection and compression as it expressed in the diagram below.

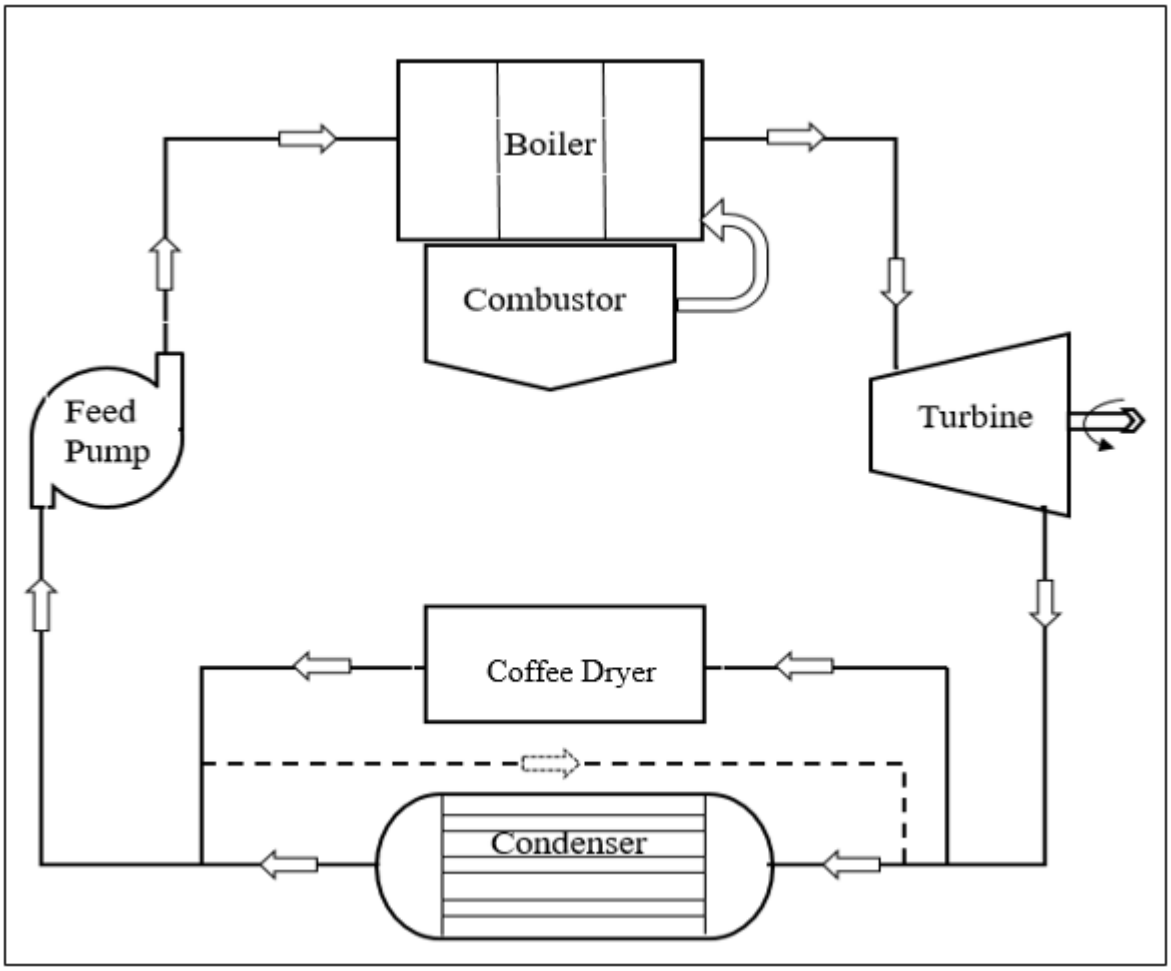

Figure 2.2 Schematic of main System arrangement of the CHP plant and flow of working fluid.

The main components of a modern boiler are: the grate, fuel feeders, combustion chamber or furnace, water or mud drum, steam drum, main bank, superheater, economizer, air preheater, scrubber, induced draught (ID) fan, forced draught (FD) fan, secondary air (SA) fan, boiler feed water pumps, mechanical separators and some auxiliary equipment.

Water and steam drum: separate the steam water mixture in to saturated steam, which is sent the steam in the boiler & saturated liquid for recirculation to furnace circuit.

Super-Heater: The function of a super heater is to increase the temperature of the steam above its saturation point. The super heater is very important accessory of a boiler and can be used both on fire tube and water-tube boilers. Super heaters are located in the path of the furnace gases so that heat is recovered by the superheated from the hot gases. It is used to reduce steam consumption of the turbine and increase the efficiency of steam plant.

Economizer: Economizer is a heat recovery system, usually installed near and at the back side of boiler. In boilers, economizers are heat exchange devices that heat fluids, usually water, up to but not normally beyond the boiling point of that fluid.

Air Pre-Heater: An air preheater or air heater is a general term to describe any device designed to heat air before another process (for example, combustion in a boiler) with the primary objective of increasing the thermal efficiency of the process.

Induced Draught (ID) fan: In this system a fan or blower is located at or near the base of the chimney. The pressure over the fuel bed is reduced below that of the atmosphere. By creating a partial vacuum in the furnace and flues, the products of combustion are drawn from the main flue and they pass up the chimney.

Forced Draught (FD) fan: In a mechanical draught system, the draught is produced by a fan. In a forced draught system, a blower or a fan is installed near or at the base of the boiler to force the air through the boiler combustion bed and other passages through the furnace, flues, air reheated, economizer etc.

Secondary Air (SA) fan: It is secondary air fan. In this system a fan is located at or near the sides of the Furnaces. The discharge of this fan is connected to the body of the boiler with multiple nozzles that direct air to the inside combustion chamber to create turbulence in the flue gas. This insures perfect mixing of fuels which makes the combustion under suspension.

Boiler feed water pumps: A Boiler Feed Pump is a multistage centrifugal pump of higher head and reasonable discharge capacity. As this pump is mainly designed to supply water to the boiler during

steam generating, its discharge head should be sufficient enough to feed the boiler by overcoming the boiler internal pressure.

Mechanical Separators: Mechanical ash handling equipment and separators in solid fuel fired steam boilers are working with one or combined system of the following ash/air pollutant separators. Gravity settlers using force of gravity, Cyclone using force of centrifugal, ESP (Electro Static Separator)

2.4 Feed Water Treatment

There are three phases of water treatment in a boiler system:

• **Blow down,** which maintains the TDS (total dissolved solids) in the system

• **External Treatment,** which removes hard salts, minerals and oxygen before the water enters the boiler

• **Internal Treatment,** which maintains proper water chemistry by adding chemical additives to the boiler water the primary goal of boiler water treatment is to control solids that cause deposits in the boiler and control gases that cause corrosion.

Specifications of boiler feed water

Hardness < 0.2 ppm, 0.15 ppm < Caustic alkalinity < 0.45 ppm, 0.45 ppm < Soda alkalinity < 1 ppm

Should be free from Turbidity, Sediments, Organic matter, Oil and Grease [25].

2.5 Fuel feeding systems

Fuel feed systems play a critical role in the performance of low-emission boilers. Their primary functions include (1) transferring the fuel into the boiler and (2) distributing the fuel within the boiler to promote uniform and complete combustion. The type of fuel and whether the fuel is a solid, liquid, or gas influences the operational features of a fuel feed system.

Mechanical devices such as conveyors, augers, hoppers, slide gates, vibrators, and blowers are often used for this purpose. The method selected depends primarily on the size of the individual fuel particles and the properties and characteristics of the fuel. Stokers are commonly used to feed solid fuel particles such as crushed coal, municipal west, wood chips, and other forms of biomass into boilers. Mechanical stokers evolved from the hand-fired boiler era and now include sophisticated electromechanical components that respond rapidly to changes in steam demand. The design of these components provides good turndown and fuel-handling capability. In this context, turndown is defined as the ratio of maximum fuel flow to minimum fuel flow.

2.6 Combustion in water tube boilers

The various types of fuels (like liquid, solid and gaseous fuels) that are available depend on various factors such as costs, availability, storage, handling, pollution and landed boilers, furnaces and other combustion equipment.

Since biomass fuels are primarily composed of carbon, hydrogen and oxygen, the main products from burning biomass are carbon dioxide and water. Flame temperatures can exceed 2000°C, depending on the heating value and moisture content of the fuel, the amount of air used to burn the fuel and the construction of the furnace [26].

The product of a stoichiometric combustion of biomass in air will include carbon dioxide, water vapor and nitrogen. This reaction will generate heat. The stoichiometric equation for the combustion of biomass is given as follows:

Biomass + Air ⟶ Carbon Dioxide + Water Vapor + Nitrogen + Heat

Calorific value is the measurement of heat or energy produced, and is measured either as gross calorific value or net calorific value. The difference is determined by the latent heat of condensation of the water vapour produced during the combustion process.

There are two ways of Fuel Analysis: Ultimate and Proximate Analysis

The proximate analysis indicates the percentage by weight of fixed carbon, volatiles, ash, and moisture content in the fuel. Fixed carbon is the solid fuel left in the furnace after volatile matter is distilled off. Volatile matters are the methane, hydrocarbons, hydrogen and carbon monoxide, and incombustible gases like carbon dioxide and nitrogen found in solid fuel [4]. Ash is an impurity that will not burn, Moisture content is decreases the heat content per kg of fuel. Increases heat loss, due to evaporation and superheating of vapour.

The ultimate analysis indicates the various elemental chemical constituents such as carbon, hydrogen, oxygen, sulphur, etc. It is useful in determining the quantity of air required for combustion and the volume and composition of the combustion gases.

If the moisture content is too high, the furnace temperature will be too low for combustion, such that auxiliary fuel is needed to raise the furnace temperature and to ensure normal combustion. Lower moisture content give rise to higher furnace temperatures and larger high-temperature zones during combustion so in my case since coffee husks have lower moisture content no need of treatment before use it.

The temperature in the furnace is closely related to Husk (fuel)/air ratio. The influence of excess air on the combustion in furnace will be, with the increase of excess air, the temperature of the furnace tends to decrease. To ensure adequate heating and burnout of wastes, a relatively high temperature level in the furnace should be maintained with a corresponding O_2 content.

CHAPTER THREE

SITE BACKGROUND AND DATA ANALYSIS

3.1 Background

The study areas of this thesis are coffee processing industries located at **Tepi town** in **Sheka Zone** found in S/N/N/P Regional State. In this Zone Coffee husk is abundantly available that is why I have selected this area for my thesis work.

Sheka Zone divided in three Woredas (Yeki, Andracha and Masha) and two city administrations (Tepi and Masha) it also has 57 Kebele farmer associations and covers total area 238,750 hectares out of this 67,986 hectares covered by coffee. The Zone's total population (males + females) is 247,815 out of this above 70% of people directly or indirectly benefits from the coffee [15].

The basic datum for this thesis are collected from Sheka Zone Agricultural and Natural Resource Development Department and Yeki woreda Agricultural and Natural Resource Development Office in addition to site observation and interview with the workers and owner of the industries.

3.2 Data analysis

3.2.1 Annual collected coffee

The data tabulated in table 3.1 is found from Sheka Zone Agricultural and Natural Resource Development Department. It is eight successive years' data which expresses the amount of coffee collected in the zone throughout these years in wet and dry form.

Table 3.1 Coffee collected and generated from the factories from 2003-2010 (E.C) [in Ton]

Year / Kind	2003	2004	2005	2006	2007	2008	2009	2010
Washed coffee	2225.55	2369..28	1941..09	2870.33	1600.33	2714.56	2649.64	3637.36
Unwashed coffee	5970.74	5100.03	7127.17	10742.58	6167.00	8760.59	5728.03	4380.75
Collected wet	11127.50	11846.45	9705.45	14351.65	6401.32	15978.00	20298.09	23740.63
Collected dry	17912.22	7102.84	14454..34	24290.00	10579.76	13764.31	11739.20	7055.23

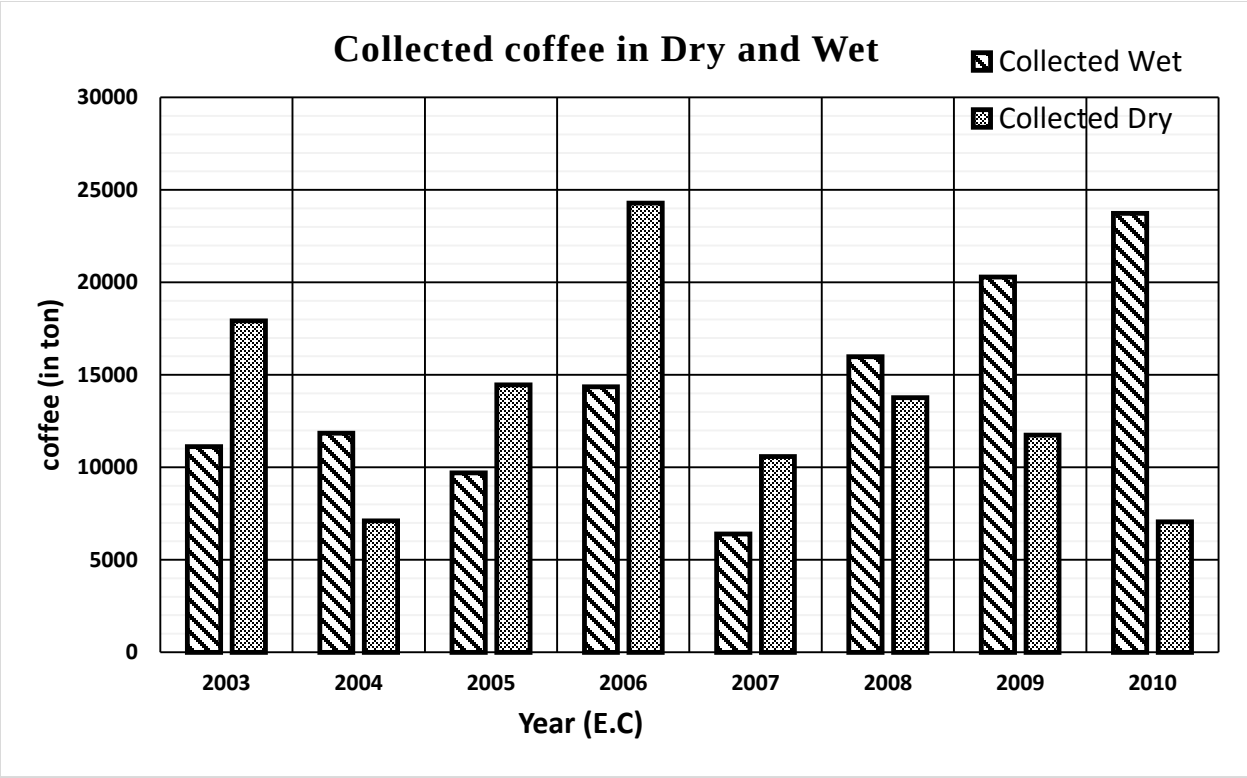

Figure 3.1 Coffee collected in dry and wet

In order to know the average collected coffee per year in the Zone the last two rows of table 3.1 should be taken.

Table 3.2 Total collected coffee in the Zone [in Ton]

Year / Kind	2003	2004	2005	2006	2007	2008	2009	2010
Collected Wet coffee	11127.5	11846.45	9705.45	14351.65	6401.32	15978	20298.09	23740.63
Collected dry coffee	17912.22	7102.84	14454.34	24290	10579.76	13764.31	11739.2	7055.23
Total	29039.72	18949.29	24159.79	38641.65	16981.08	29742.31	32037.29	30795.86

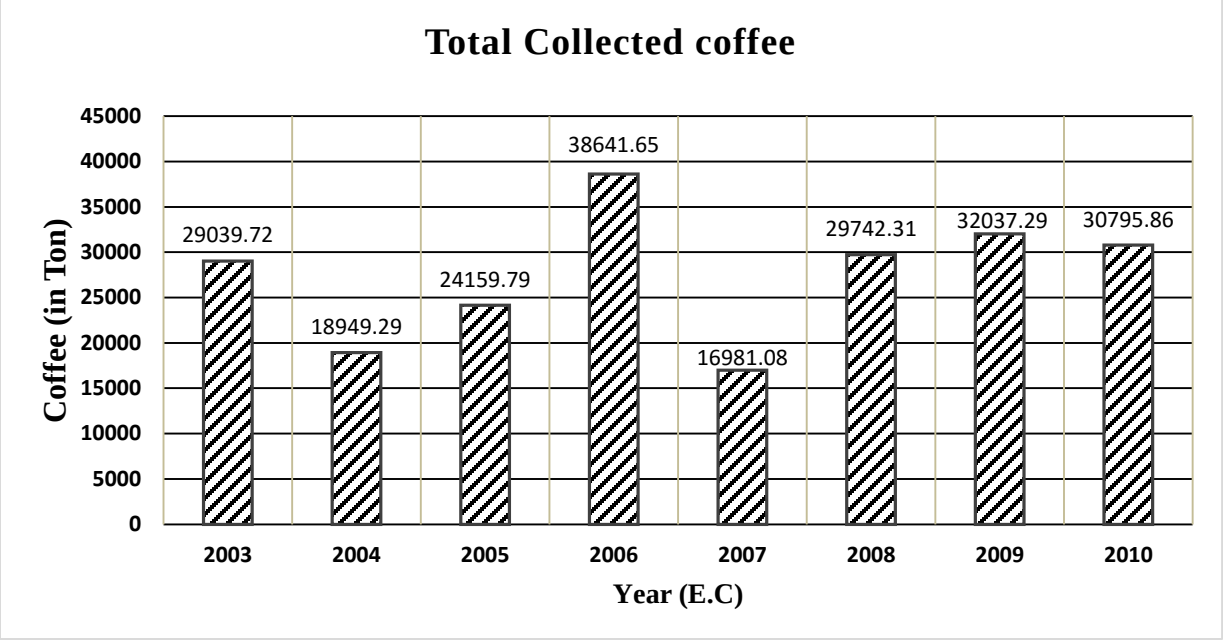

Figure 3.2 Total collected coffee in the Zone

From the data shown above the average annual collected coffee and provide to the industries will be as follows:

= (29039.72 + 18949.29 + 24159.79 + 38641.65 + 16981.08 + 29742.31 + 32037.29 + 30795.86)/8

= 220346.99/8

= **27,543.37 Ton**

3.2.2 Number of coffee processing industries

In sheka zone both the wet and dry processing machines are found. As the date shown below, currently 71 coffee processing factories are available in Sheka Zone and out of these around 70.4% are found in Tepi town. That is the reason for selection of Tepi town in Yeki woreda specifically among three woredas of the Zone.

Table 3.3 Dry and Wet Coffee Processing Industries in three Woredas of Sheka Zone

Wet processing				
Place / Type	Yeki Woreda	Andracha Woreda	Masha Woreda	Sheka Zone
Privet	20	8	1	29
associations	4	-	-	4
S.co	4	7		11
Sum	28	15	1	**44**
Dry Processing				
Woreda	Yeki	Andracha	Masha	Sheka Zone
Privet	18	3	-	21
associations	-	-	-	-
S.co	4	2	-	6
Sum	22	5	-	**27**
Total				
T0tal sum	50	20	1	**71**
Persent	70.4%	28.2%	1.4%	100.0%

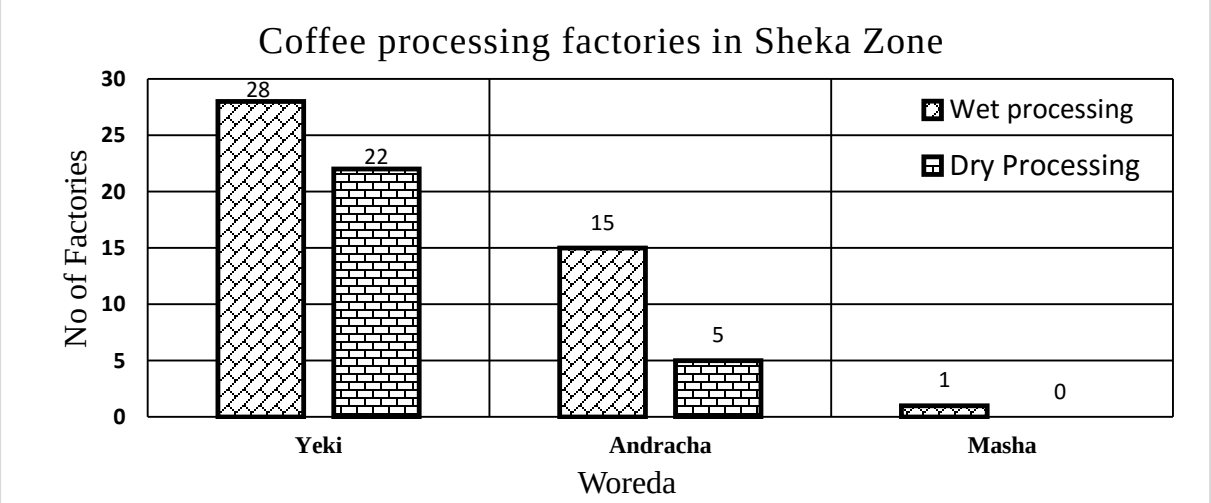

Figure 3.3 Dry and wet processing factories in Sheka Zone

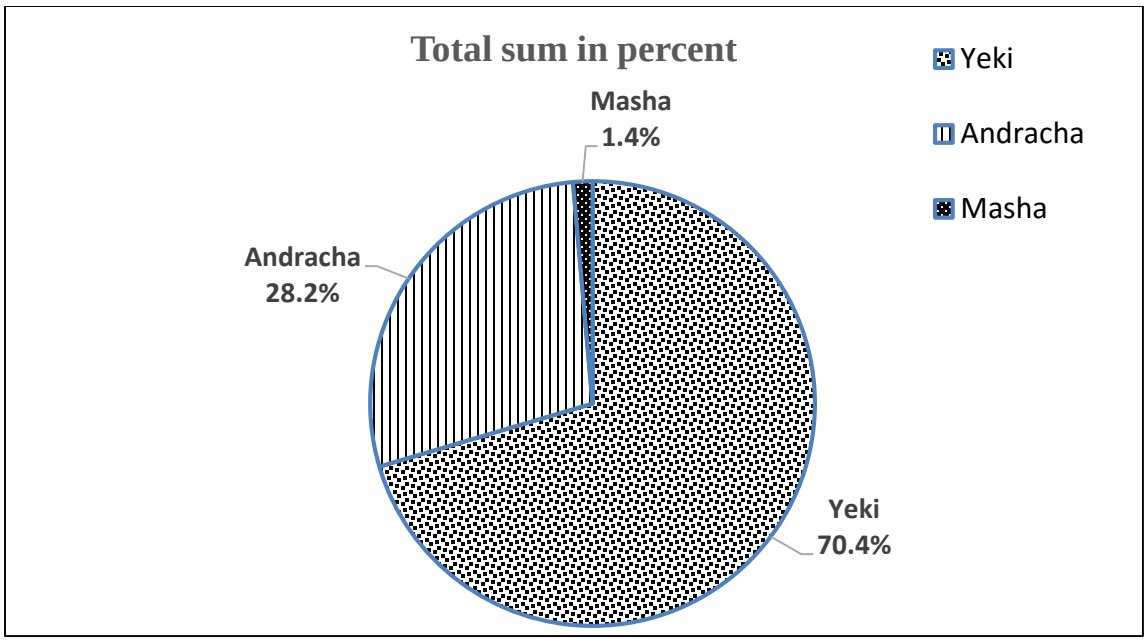

Figure 3.4 Percent of dry and wet processing factories

3.2.3 Average coffee husk generated

In the data that got from Sheka Zone Agricultural and Natural Resource Development Department there is no information about the coffee husk that generated as waste from the industries. therefore during data collection time when I were in my selected area I have tried to know the amount of husk out of one quintal of dry coffee by measuring each product (pure coffee, husk, outer skin of the coffee and others foreign bodies) of the machine. The activity is conducted in "Ato Seyd Aliy dry coffee processing industry" for 10 working days and the result is as follows.

Table 3.4 Estimation of average coffee husk generated from 100 kg of dry coffee

Weight [kg] / Item	day 1	day 2	day 3	day 4	day 5	day 6	day 7	day 8	day 9	day 10
pure coffee	42	44	39	44	40	40	37	41	45	37
Coffee Husk	37	35	42	33	36	34	40	37	31	41
outer skin	14	12	8	10	15	16	18	15	13	14
others	7	9	11	13	9	10	5	7	11	8

Now from the above table it is possible to estimate the average amount of coffee husk per 100 Kg

= (37+35+42+33+36+34+40+37+31+41)/10

= 366/10

= **36.6 kg**

Therefore during coffee processing ~36.8% will be coffee husk the rest 63.2% will be pure coffee and other byproducts.

So the coffee husk generated from the industries per year will be:

= (27,543.37 * 36.8)/100

= **10,135.96 Ton/Year**

3.3 Estimation of Power demand of the factories

As the data indicated above in Sheka zone there are 44 wet and 27 dry coffee processing industries. Almost all the processing industries use electric power for their respective pulping machines. But some of the wet processing machines use fuel as power sources. But nowadays those fuel used industries are on progress to use electric power like others. Therefore in this work it considered as they use electric power.

During data collection period it was difficult to get enough information about their power consumption so to estimate their power demand classified the industries in to three based on the type of machine and average working capacity. The date is found from their annual report paper not from their power cost bile.

1. First representative – This represent the dry processing industries those have relatively high working capacity (They are 8 in number).

Table 3.5 Average cost of power per month for dry processing 1 [Birr]

Month / Year(EC)	September	October	November	December	January	February	March	April	May	June	July	August
2006	3400	3012	1423	4741	4852	5218	3960	1642	3056	3561	1235	2016
2007	1891	1406	812	2151	2762	3016	2108	712	1582	2111	763	1056
2008	1799	2558	1009	3895	4022	4562	3187	2561	1322	2831	802	1397
2009	2245	1602	950	3032	3429	4093	2675	1017	2071	2417	776	1266
Average	2333.75	2144.5	1048.5	3454.75	3766.25	**4222.25**	2982.5	1483	2007.75	2730	894	1433.75

Total average power cost per year = (2333.75 + 2144.5 + 1048.5 + 3454.75 + 3766.25 + 4222.25 + 2982.5 + 1483 + 2007.75 + 2730 + 894 + 1433.75)

= 28,501.00 Birr/Year

Total cost for 8 factories = 28501.00 * 8 = 228,008.00 Birr/Year

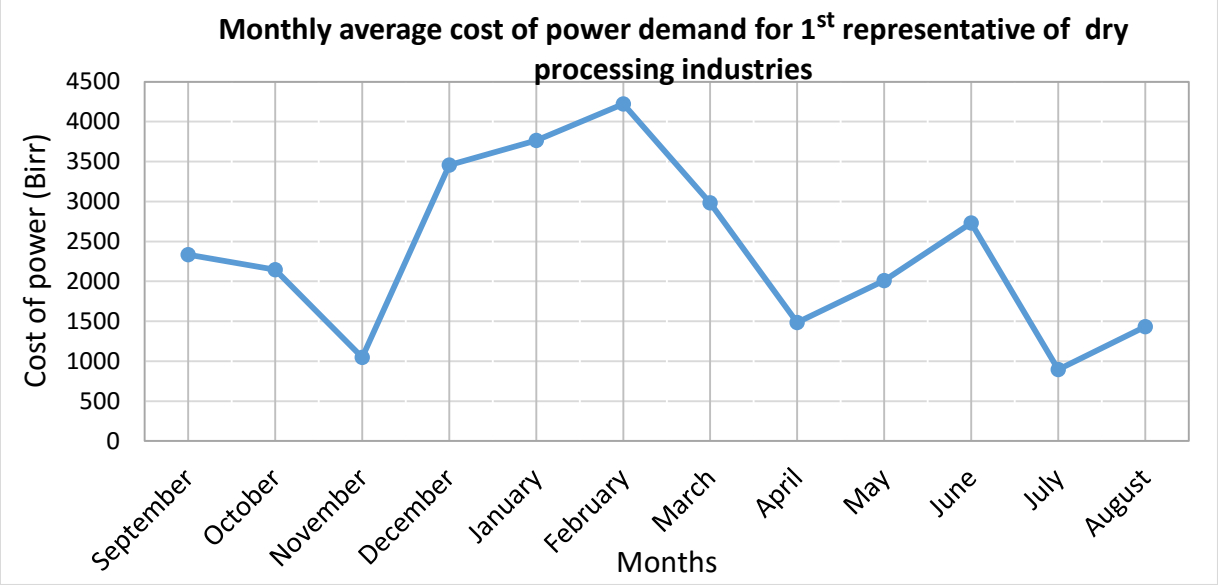

Figure 3.5 Average cost of power for dry processing 1

2. Second representative – represents the dry processing industries those works in low capacity relatively (they are 19 in number).

Table 3.6 Average cost of power per month for dry processing 2 [Birr]

Months / Year(EC)	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
2005	663	991	468	1133	1719	1596	1302	540	1171	1005	406	1118
2007	347	462	267	707	958	1051	693	234	694	520	259	622
2008	459	843	331	1288	1323	1501	1048	844	931	443	262	591
2009	416	527	312	997	1128	803	1345	334	795	681	255	738
Average	585	705.75	344.5	1031.25	**1282**	1237.75	1097	488	897.75	662.25	295.5	653.5

Total average power cost per year = 585 + 705.75 + 344.5 + 1031.25 + 1282 + 1237.75 + 1097 + 488 +897.75 + 662.25 + 295.5 + 653.5

= 9,280.25 Birr/Year

Total cost for 19 factories = 9280.25 * 19 = 176,324.75 Birr/Year

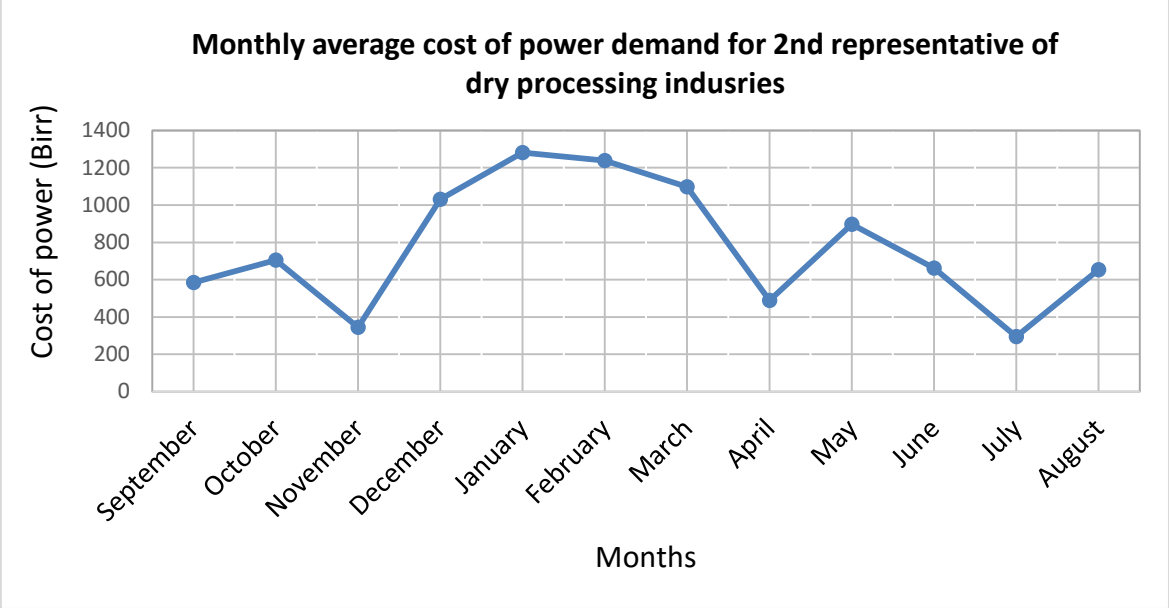

Figure 3.6 Average cost of power for dry processing 2

3. Third representative - All wet processing industries included here (They are 44 in number).

Table 3.7 Average cost of power per month for wet processing [Birr]

Year (E.C)	Months											
	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
2005	184	917	3923	4593	2214	963	1203	453	201	54	91	88
2006	251	1086	4257	5471	2902	1099	708	230	17	76	64	49
2007	96	946	2741	3213	1706	815	1492	210	210	210	37	138
2008	203	1130	5628	7033	3210	1254	361	310	157	140	54	89
2009	62	315	7865	9186	4420	1872	461	110	57	26	97	212
2010	120	1351	11091	10132	7625	1302	391	250	108	101	84	92
Average	152.66	957.5	5917.5	6604.66	3679.5	1217.5	769.33	260.5	125	101.16	71.16	111.33

Total average power cost per year = 152.66 + 957.5 + 5917.5 + 6604.66 +3679.5 +1217.5 + 769.33 + 260.5 + 125 + 101.16 + 71.16 + 111.33

= 19,967.80 Birr/Year

Total cost for 44 factories = 19967.80 * 44 = 878,583.20 Birr/Year

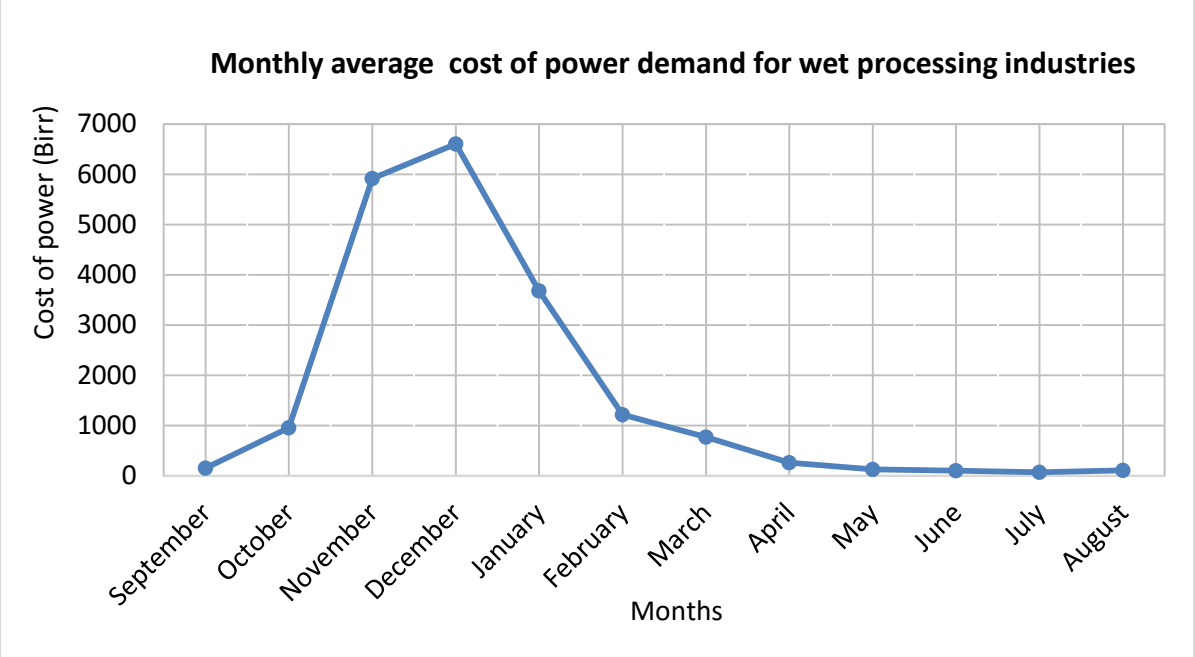

Figure 3.7 Average cost of power for wet processing

Total average cost of power per year of the processing factories becomes:

= 228,008.00 + 176,324.75 + 878,583.20

= 1,282,915.95 Birr/Year for total factories

Average per month of each factory:

= (1,282,915.95/71)/12

= 18,069.24/12

= 1,505.77 Birr/Month/Factory

Total power per year consumed by all processing industries:

According to Ethiopian Electric Power Corporation the current price of electricity or electric tariff is at $0.06 (1.62 Birr) per kWh. Therefore:

$$= \frac{1\text{kWh} * 1{,}282{,}915.95\ \text{Birr}}{1.62\ \text{Birr}} = 791923.4259\ \text{kWh/Year for total factories}$$

$$= 791{,}923.4259\ \text{kWh/Year for total factories}$$

Energy needed by each factory every month

$$= \frac{791{,}923.4259\ \text{kWh}}{71(\text{factories}) * 12(\text{month})} = 929.4876\ \text{kWh/Month/Factories}$$

3.4 Estimation of thermal energy demand of the factories

Estimation of thermal energy demand requires precise knowledge regarding the availability of global solar radiation and its components at the specific location. Since the solar radiation reaching the earth's surface depends upon climatic conditions of the place, a study of solar radiation under local climatic conditions is essential.

3.4.1 Estimation of monthly average daily global radiation on a horizontal surface

The simplest mathematical model used to estimate monthly average daily solar radiation on horizontal surface is the well-known Angstrom equation [49].

$$\frac{\overline{H}}{\overline{H}_o} = a - b\left(\frac{\overline{n}_s}{\overline{N}_s}\right) \ldots\ldots\ldots 3.1$$

Where:

$\overline{H}$ − monthly average daily radiation on horizontal surface.

$\overline{H}_o$ − monthly average radiation out side of the atmosphere (ETR on the horizontal surface) for the same location.

a and b − Empirical constants, (Values are obtained by regression).

$\overline{n}_s$ − Monthly average daily hours of bright sunshine.

$\overline{N}_s$ − Monthly average of the maximum possible daily hours of bright sunshine.

The regression parameters 'a' and 'b' can be determined from:

$$a = -0.110 + 0.235\cos\emptyset + 0.323\left(\frac{\overline{n}_s}{\overline{N}_s}\right)$$

$$b = 1.449 - 0.533\cos\emptyset - 0.694\left(\frac{\overline{n}_s}{\overline{N}_s}\right)$$

$\overline{H}_o$ can be obtained by the Clein relationship.

$$\overline{H}_o = \left[\frac{24 * 3600}{\pi} I_{sc}\right]\left[1 + 0.033\cos\left(\frac{360N}{365}\right)\right]\left[\cos\emptyset\cos\delta\sin\omega_s + \frac{\pi}{180}\,\omega_s\,\sin\delta\sin\emptyset\right]$$

Where:

ω_s − Sunrise hour angle

$\overline{H}_o$ in $\frac{Wh}{m^2 day}$

$I_{sc} = 1367\ W/m^2$, (Solar constant) and

Latitude of Tepi (∅) = 7.6

The length of sunshine hours $\overline{N}_s$ are computed from Cooper's formula:

$$\bar{N}_s = \left(\frac{2}{15}\right)\omega_s$$

$$\omega_s = \cos^{-1}(-\tan\emptyset \tan\delta)$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + N)\right]$$

Where N is recommended average days for the month.

3.4.2 Estimation of monthly average daily diffuse radiation on a horizontal surface

The monthly average daily diffuse radiation on a horizontal surface can be determined from the monthly average daily global radiation on a horizontal surface and the number of bright sunshine hours [49].

$$\frac{\bar{H}_d}{\bar{H}} = 0.931 - 0.814\left(\frac{\bar{n}_s}{\bar{N}_s}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2$$

3.4.3 Estimation of monthly average hourly global radiation on a horizontal surface

The monthly average hourly global radiation on a horizontal surface can be calculated from the knowledge of the monthly average daily global radiation on a horizontal surface [49].

$$\frac{\bar{I}}{\bar{H}} = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s\cos\omega_s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.3$$

Where:

$$a = 0.409 + 0.5016\sin(\omega_s - 60)$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60)$$

3.4.4 Estimation of Monthly Average Hourly Diffuse Radiation on a Horizontal Surface

The monthly average hourly diffuse radiation on a horizontal surface can be calculated from the knowledge of the monthly average daily diffuse radiation on a horizontal surface [49].

$$\frac{\bar{I}_d}{\bar{H}_d} = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s\cos\omega_s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.4$$

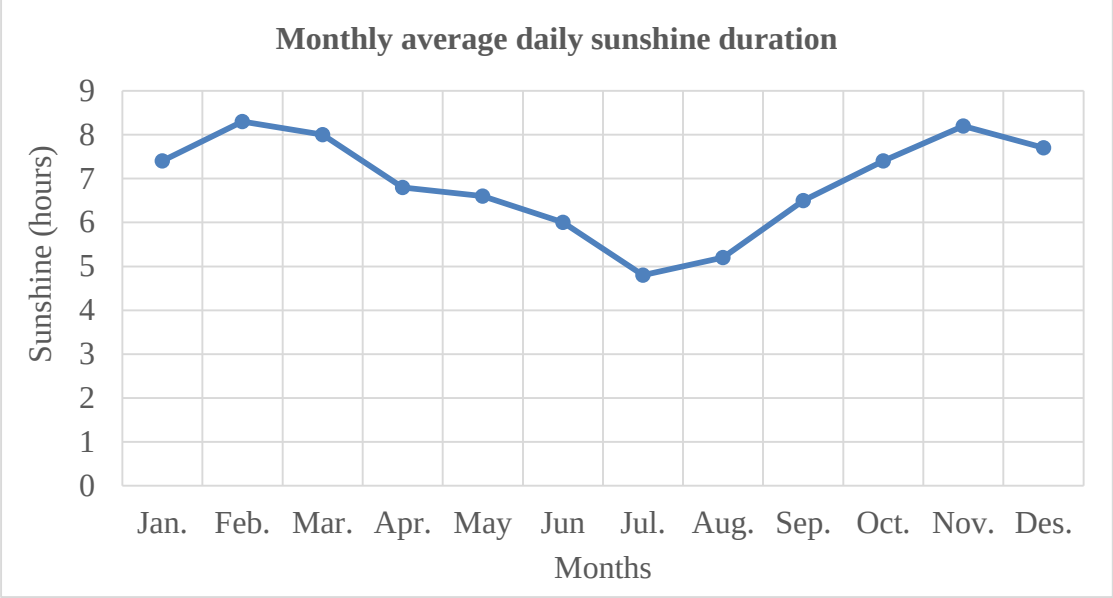

Figure 3.8 Monthly average daily sunshine duration for Tepi

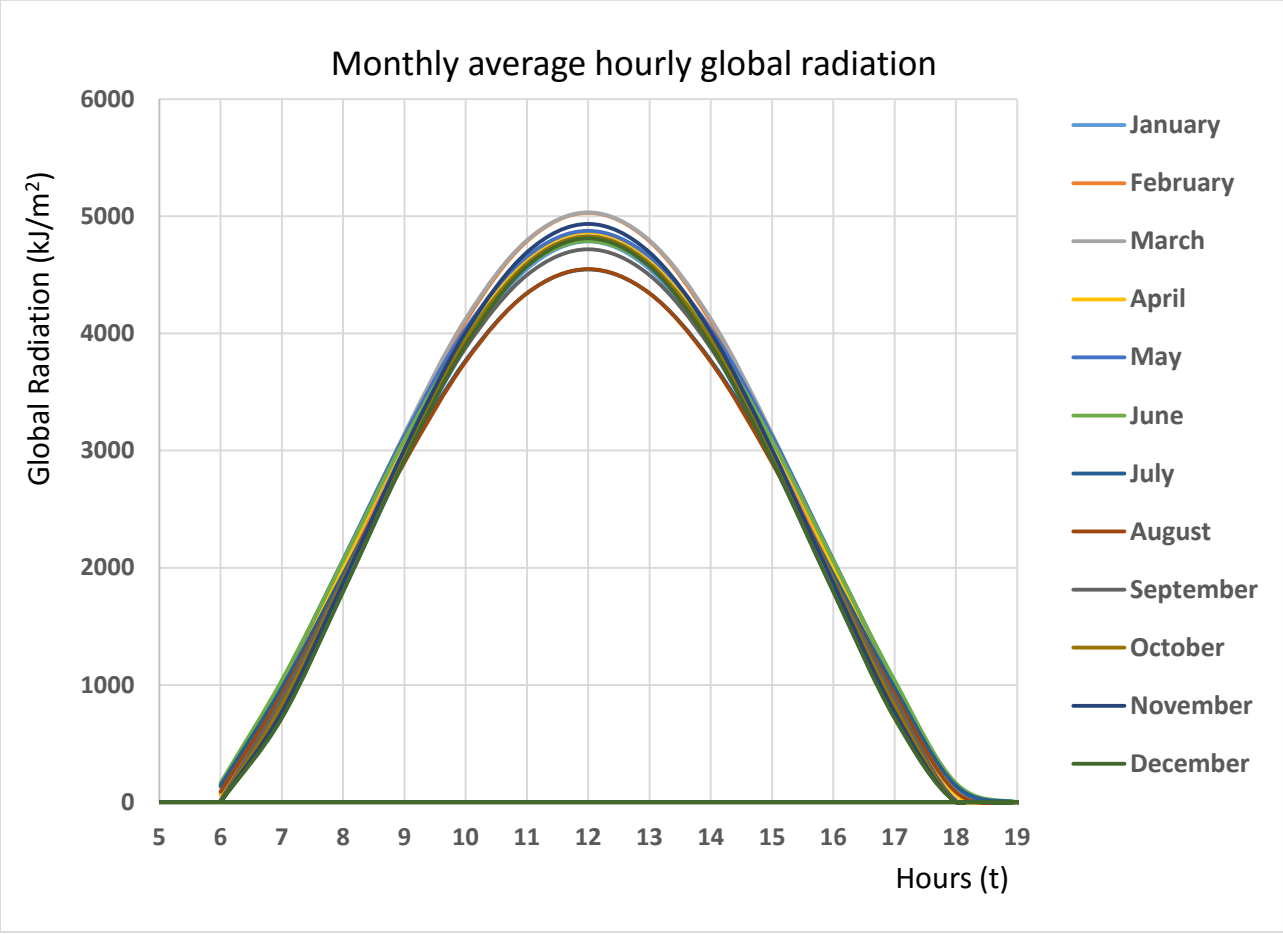

Figure 3.9 Monthly average hourly global radiation on the Horizontal surface for Tepi town

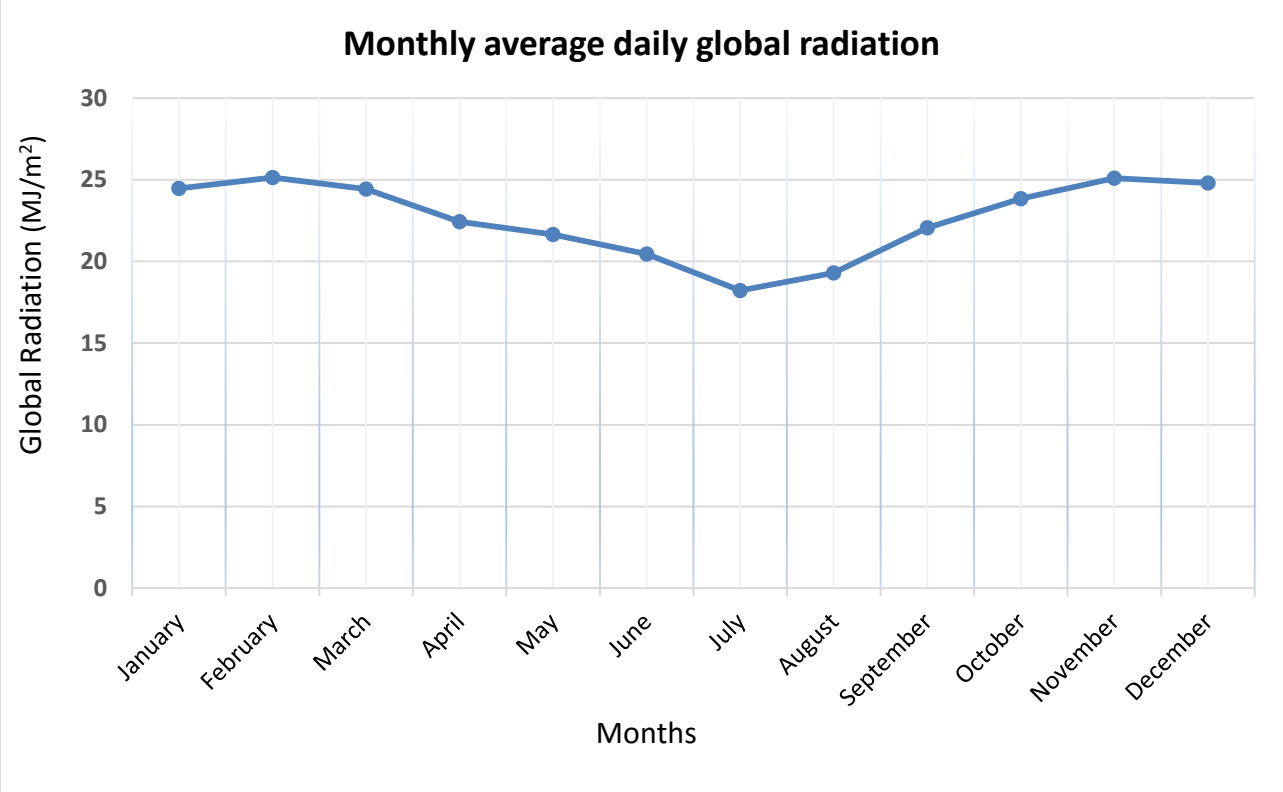

Figure 3.10 Monthly Averages of Daily Global Radiation on the Horizontal surface for Tepi town

The minimum global radiation occurred in July with a value of 18,216.1916 kJ/m^2 and the maximum is in February which is 25,137.5475 kJ/m^2. So for this specific case the minimum global radiation is taken to make the design safe.

The capacity of the drying beds depends on the design and measurements of the beds with wet parchment, washed and cherries. A drying table of 200cm x 80cm can dry up to 45kg of cherries with coffee spread to a depth of 4cm or less. The depth of the coffee mass must be limited to ensure uniform drying. Facilities for sun drying consist primarily of the surface used. Bare earth is widely used whereas cement or brick are widely used in the zone. The structure and location of these facilities has a great influence on their performance. Tables with wire mesh, sisal or bamboo mats are used commonly.

Therefore:

2m * 0.8m used for 45kg

This indicates 1kg of cherries needs:

1.6 m^2/45 = 0.0356 m^2

Thermal energy required for 1kg of coffee cherries will be:

= 0.0356 * 18,216.1916 = 648.4964 kJ/m^2

Drying process takes from 5 to 10 days for fresh cherries depending on the local temperature [15]. Therefore in average it will be:

(5 + 10)/2 = 7.5 days

Average total drying time taken by 1kg of cherry coffee is 7.5 days

Solar energy demand per kg of coffee cherries calculated as follows:

= 648.4964 * 7.5 = 4,863.723 kJ/m^2

= 4,863.723 kJ/m^2

CHAPTER FOUR

EXPERIMENTAL ANALYSIS OF COFFEE HUSK

4.1 Introduction

The experiments were conducted using the facilities in Addis Ababa University and Geological Survey of Ethiopian using some sample of coffee husks which came from one coffee processing factory available in Sheka Zone Tepi town. The proximate and ultimate analyses of the husk were done using standard experimental procedures. In order to obtain information about the combustion mechanisms of the coffee husks. Proximate analysis is used to characterize the coffee husk in order to measure its moisture, volatile matter, fixed carbon, and ash contents. Ultimate analysis gives the actual chemical composition (usually C, H, N, S and O by difference).

The experiment result shows the proximate and ultimate analyses of coffee husks and also other parameters such as dry densities, calorific values and moisture contents of the coffee husks are also given. The ultimate analysis gives the chemical elements that comprise the husk substance, together with ash and moisture. The husk substance consists of organic compounds of carbon, hydrogen and oxygen derived from the original vegetable matter.

4.2 Ultimate Analysis of the Coffee Husk

The elemental analysis of the coffee husk is done using a Flash CHNS/O - analyzer, model EA 1112 in **Addis Ababa Natural Science University**.

Figure 4.1 Flash CHNS/O - analyzer

The analysis starts from sample preparation. During sample preparation for the CHNS analysis 5 mg dried and crushed sample is mixed with an oxidizer (vanadium pent oxide [V_2O_5]) catalyst in a tin capsule, which is then combusted in a furnace temperature of 900°C and oven temperature of 75°C with a condition of carried gas flow rate of 120 ml/min, reference flow rate 100ml/min and oxygen flow rate 250 ml/min. Addition of the V_2O_5 ensures complete conversion of inorganic sulfur in the sample to sulfur dioxide.

Then combustion products CO_2, SO_2, H_2O and NO_2 are carried by a constant flow of carrier gas (helium) that passes through a glass column packed with an oxidation catalyst of tungsten trioxide (WO_3) and a copper reducer both kept at 900°C. At this temperature, the nitrogen oxide is reduced to N_2 and oxidation is completed. The gas mixture N_2, CO_2, H_2O and SO_2 are then transported by the helium to chromatographic column, where separation takes place.

After separation eluted gases are sent to the thermal conductivity detector (TCD) (set at 290°C.) where electrical signals processed by the Eager 300 software provide percentages of nitrogen, carbon, hydrogen, and sulfur contained in the sample. Eager 300 software is used for running the equipment, storing the data and analyzing.

Formulas used

For Carbon content

$$C_d = C_{ad} * \frac{100}{100 - M_{ad}}$$

For Nitrogen content

$$N_d = N_{ad} * \frac{100}{100 - M_{ad}}$$

For Hydrogen content

$$H_d = (H_{ad} - \frac{M_{ad}}{8.937}) * \frac{100}{100 - M_{ad}}$$

Where: d = the dry basis

ad = as determined basis

Mad = the moisture content of the general analysis sample when analyzed

During calibration process six points for every component are taken and the sample was run in duplicate finally the average values to be taken are as follows.

Table 4.1 Laboratory elemental analysis report of coffee husk

Sample Type	C (%)	H (%)	N (%)	S (%)	O (%)
Coffee Husk	46.8314	4.8132	0.4454	0.0500	~ 47.8600

4.3 Proximate Analysis of the coffee husk

Proximate analysis helps to assess the percentage of volatile matter, fixed carbon, moisture and ash contents. This analysis is very important to study the combustion phenomenon of the coffee husk.

Therefore to know the proximate analysis and calorific value of the coffee husk different laboratory equipment are used in **Geological Survey of Ethiopian.** The experiment is conducted with international standard test method using three main apparatus, these are CARBOLITE furnace, Carbolite oven and Adiabatic Calorimeter. 200 gm of coffee husk sample which came from the study area is taken for this analysis.

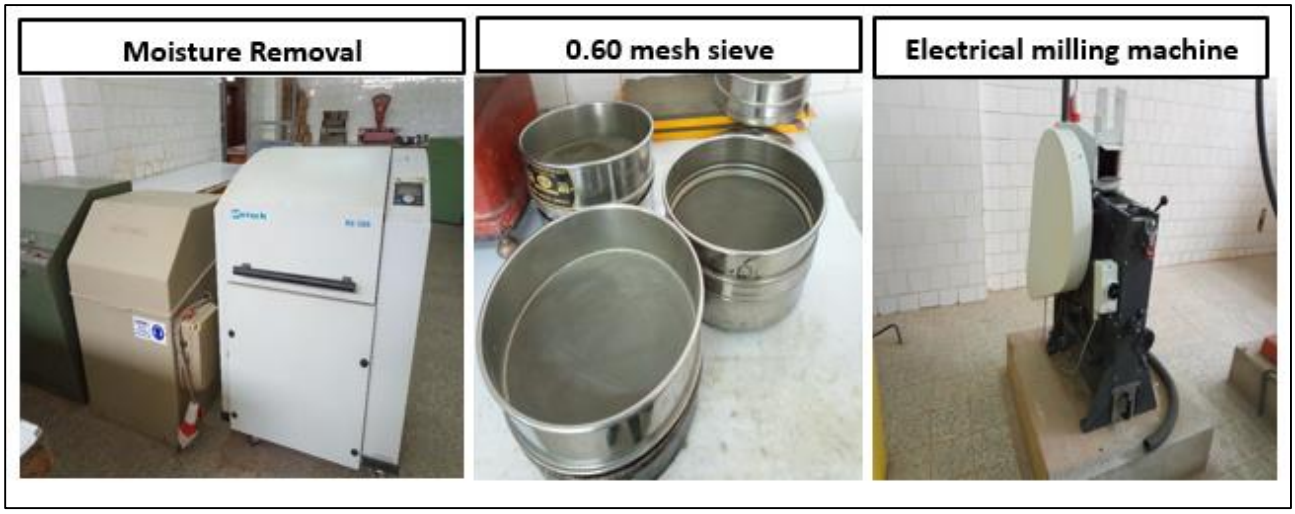

Figure 4.2 Equipment in sample preparation room

The experiment started from sample preparation room. In this room giving a code for the sample was the primary task and Y-M-001 was the sample code number. Next, removal of unwanted moisture from the sample is done in a Retsch model RS 200. Then grinding of sample using electrical milling machine is done. Sieving the crushed sample with the help of 0.60 mesh siever and packing the prepared sample with plastic sheet was the last work in sample preparation room.

After this the sample is sent to the hydrocarbon laboratory where the analysis of the prepared sample conducted.

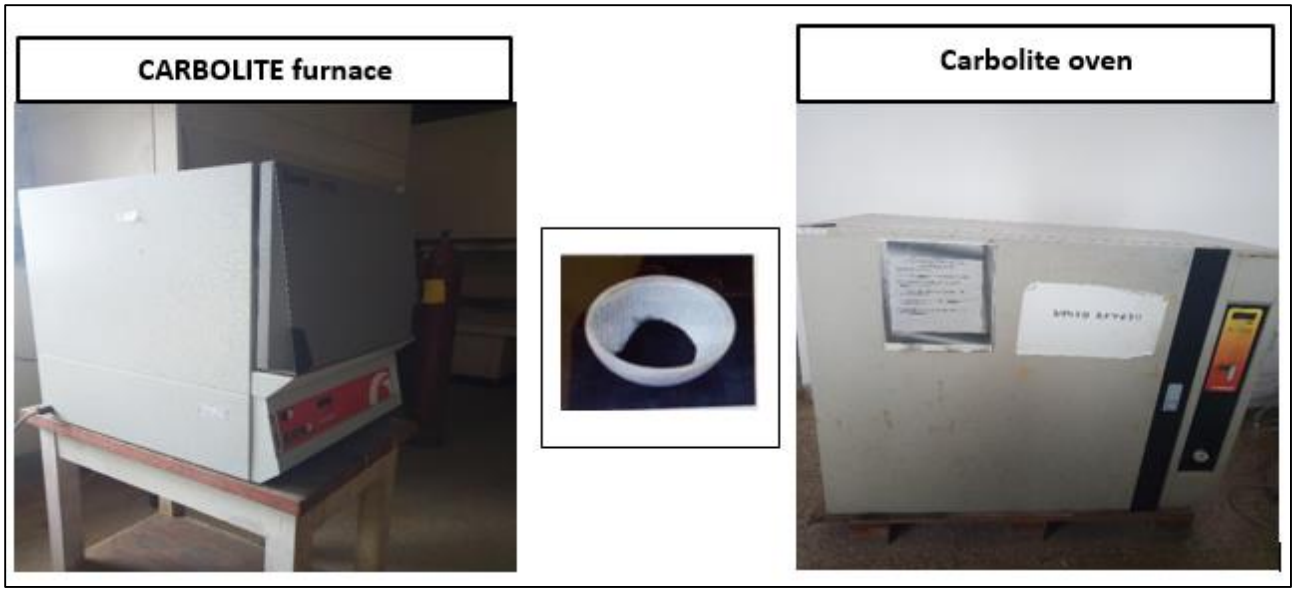

Figure 4.3 Equipment used in hydrocarbon laboratory

Proximate analysis indicates the behavior of husk when it is heated. Therefore the following tasks are conducted in the hydrocarbon laboratory

I. When 1gram sample of husk is subjected to a temperature of about 110^{o}C in the oven for a period of 1 hour, the loss in weight of the sample gives the moisture content of the husk.
II. When 1 gram sample of husk is placed in covered crucible and heated to 950^{o}C inside Carbolite Furnace and maintained at that temperature for about 6 minute. There is a loss in weight due to the eliminating of moisture and volatile matter. So present of volatile matter calculated here.
III. When 1 gram sample of husk is placed in uncovered crucible and heated to 750^{o}C until the husk is completely burned, a constant weight reached, which indicates that there is only ash remaining in the crucible. Complete combustion of husk is determined by repeated weighing of the sample.
IV. The amount of fixed carbon is determine as follows, using subtraction of percentage by mass.

Fixed carbon (FC) + volatile matter (VM) + moisture (M) + ash (A) = 100

FC + VM + M + A = 100

FC = 100-(VM + M + A)

Some of the carbon may have been in the form of hydrocarbons which may have been distilled off while determining the volatile matter. The amount of volatile matter indicates, the husk will burn with a short or long flame, it tends to produce smoke. This means the more volatile the husk, the more it will smoke. In the following table the summery of the entire analysis processes' conditions are shown.

Table 4.2 Summary of analysis conditions

Contents	Lid	Apparatus	Temperature	Time
% Moisture	Without lid	Oven	110 °C	1 hour
% Volatile matter	With lid	CARBOLITE Furnace Covered	950 °C	6 minute
% Ash	Without lid	CARBOLITE Furnace Uncovered	750 °C	3 hour
% Fixed Carbone	Calculated by subtraction of the above three values from 100			

After recording the necessary experimental data from the above conditions of experiment, the required values of the contents of the sample are determined using the equations listed below.

$$\%\ \text{Moisture} = \frac{\text{loss in weight of husk sample}}{\text{weight of husk sample}}\ (100\ \%)$$

$$\%\ \text{Volatile matter} = \frac{\text{loss in weight of husk sample at } 950\ ^{\circ}\text{C}}{\text{weight of husk taken}}\ (100\ \%)$$

$$\%\ \text{Ash} = \frac{\text{weight of the residue in the crucible}}{\text{weight of the husk taken}}\ (100\ \%)$$

% Fixed Carbone = 100 - % of (Moisture + Volatile matter + Ash)

The dry density of the sample is obtained using a 100ml cylinder with the formula given below.

$$\text{Density} = \frac{\text{mass of compressed husk sample in the cylinder}}{\text{volume of the cylinder}}$$

4.4 Calorific Value analysis of the coffee husk

The calorific value (heat of combustion) of a sample may be broadly defined as the number of heat units liberated by a unit mass of a sample when burned with oxygen in an enclosure of constant volume.

In this thesis to determine the calorific value of the coffee husk, oxygen bomb adiabatic calorimeter is used, which is the standard instrument for measuring calorific values of solid and liquid combustible samples in **Geological Survey of Ethiopian**.

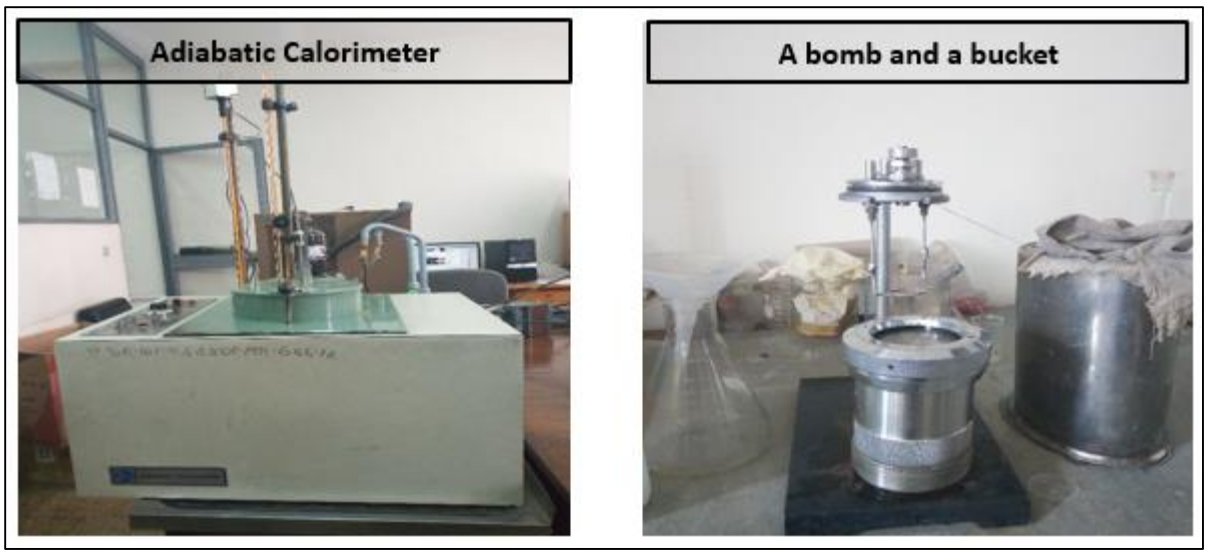

Figure 4.4 Oxygen bomb adiabatic calorimeter

The equipment has four essential parts which are mentioned as follows: (1) a bomb or vessel in which the combustible charges can be burned, (2) a bucket or container for holding the bomb in a measured quantity of water, together with a stirring mechanism, (3) an insulating jacket to protect the bucket from transient thermal stresses during the combustion process, and (4) a thermometer with small sliding microscope for reading a very small fraction of temperature changes on the thermometer.

When the husk sample is tested, sample preparation was the first step and it includes weighing a 0.9936 mg of coffee husk sample in a silica crucible, putting the crucible on the sample holder and attaching a 10 cm ignition wire (fuse) with two electrodes like a 'U' shape above, clothe to the sample and inserting in to the bomb and tying it well. The second step was filling the bomb with oxygen and the bucket with 2 liters of water after putting them inside the calorie meter. Now the sample is ready so after recording the initial temperature, combustion was started and the resultant temperature rise was measured and recorded.

The amount of heat obtained from the sample was then determined by multiplying the observed temperature rise by a previously determined energy equivalent of the calorimeter. Then, by dividing this value by the weight of the sample we obtain the calorific value (heat of combustion) of the sample on a unit weight basis.

Corrections must be applied to adjust these values for any heat transfer occurring in the calorimeter, as well as for any side reactions which are unique to the bomb combustion process.

Formulas used for Post processing

The energy equivalent (W)

$$= \frac{\text{Wight of Standard material} * \text{ Heat of combustion of standard material}}{\text{Temperature rise produced in the test}}$$

$$\text{The gross heat of combustion (Hg)} = \frac{\text{temperature rise} * \text{ energy equivalent}}{\text{weight of the sample}}$$

Therefore the final hydrocarbon laboratory analysis report of the coffee husk is shown below in the following table.

Table 4.3 Laboratory proximate analyses and calorific value report of coffee husk

Sample Code	Volatile Matters (%)	Fixed Carbon (%)	Moisture (%)	Ash (%)	Dry Density	Calorific Value cal/gm
Y-M-001	71.63	16.9	7.92	3.54	0.8	4533.1

4.5 Conclusion of Experimental analysis

From the results of experiments, it can be concluded that Coffee husk is characterized by low moisture contents. The low moisture content is an important factor in the combustion of coffee husks, since problems associated with the combustion of high moisture content of fuels are avoided. One such problem is the effect of moisture on the heating values of fuels. It is seen that husk has higher heating value when I compare it with other agricultural residues.

The ash contents of the husk is also low and is within acceptable range. This gives great advantage during furnace design. Because for the combustion of agricultural residues with high ash contents, such as rice husks, consideration must be given to incorporate an efficient ash removal equipment from the flue gas to eliminate or reduce particulate pollution.

Due to the low contents of sulphur, SO_2 emission problems would not be expected during coffee husks combustion.

High volatile matter content indicates easy ignition of fuel, although it has a significant effect on the combustion mechanisms and consequently on the design and operation of the combustion systems for this fuel.

The coffee husk is lighter and smaller than wood chips and coals burned. Thus there may be a tendency of the particles to be carried out of the furnace with the flue gas. Furthermore, without proper design of the furnace, part of the combustible volatile gases may leave the furnace unburned.

The bulk density of the coffee husks is low, raising the costs of transportation and storage. Furthermore, coffee briquettes are fragile and not suitable for long distance transportation. Coffee husks are therefore more suitable for firing within the production region.

CHAPTER FIVE

COMBUSTION ANALYSIS AND BOILER DESIGN

5.1 Combustion Analysis of Coffee Husk

Combustion chamber of boiler is designed to use the chemical energy in the coffee husk to raise the energy content of fluid in the steam generators (Boiler), so that it can be used for power and heating applications. During the combustion process, oxygen reacts with carbon, hydrogen, and other elements in the husk to produce a flame and hot combustion gases (Flue gas). As these gases are drawn through the boiler it cools as heat is transferred to the working fluid. Eventually the gases flow through a stack and into the atmosphere. As long as husk and air are both available to continue the combustion process, heat will be generated.

Combustion chamber is the most important part of the boiler. It is constructed by bricks that causes to minimize heat dissipation to the surrounding. It also has no involvement to do any kind of work. In addition, the kinetic and potential energies of the fluid streams are usually negligible. Then only total energies of the incoming streams and the outgoing mixture remained same for analysis. The conservation of mass and energy principle requires that these two equal each other that is shown in the figure.

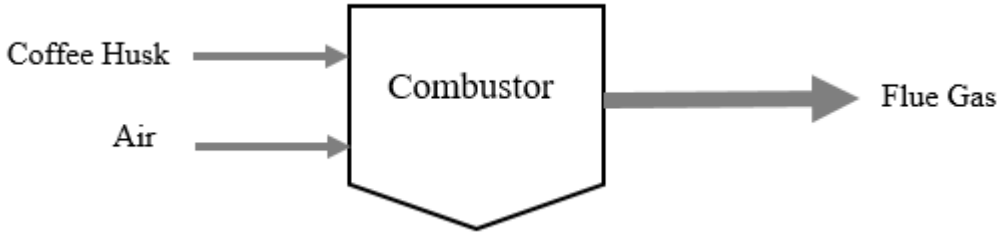

Figure 5.1 Schematic mass and energy balance diagram of combustion chamber

In order to burn a solid fuel completely, four basic conditions must be fulfilled [27]:

- ✓ Supply enough air for complete combustion of fuel.
- ✓ Secure enough turbulence for thorough mixing of fuel and air.
- ✓ Maintain a furnace temperature high enough to ignite the incoming fuel air mixture.
- ✓ Provide a furnace volume large enough to allow time for combustion to be completed.

Calculation of calorific value of the coffee husk to determine the heat contents is carried out using Bomb calorimeter in the Geological Survey of Ethiopia. The result is reported by the unit of cal/gm so for the sake of calculation it has been changed in to J/kg using the following conversion factor [28].

1 cal = 4.187J

Therefore, from Table 3.6 the total heat released by complete combustion of 1 kg of coffee husk is.

CV= 4533.1 cal/gm * 4.187J/0.001

CV= 18.980089 MJ/kg = 18980.089 KJ/kg

5.1.1 Analysis of Mass of Air Required

Considering the theoretical combustion reaction for the organic component of the husk, such as carbon, hydrogen and sulphur, Coskun et al [28] gave the equation for stoichiometric combustion as:

$C + (O_2 + 3.76N_2) \rightarrow CO_2 + 3.76N_2$ ……5.1

$H + 0.25(O_2 + 3.76N_2) \rightarrow 0.5H_2O + 0.94N_2$ ……..5.2

$S + (O_2 + 3.76N_2) \rightarrow SO_2 + 3.76N_2$ ……5.3

And the theoretical minimum air required for complete combustion can be found from this formula, which states:

(2.6667C + 8H + S – O) x 100/ 23 kg per kg of CH……..……..5.4

Combustion process is assumed as in ideal case (stoichiometric). So, nitrogen is not considered to react with oxygen during combustion reaction. It limits the intimacy between the fuel molecules and O_2.

When the fuel composition is known, the carbon balance method is quite accurate for mass balance calculation [9]. In this work combustion takes place with excess air and when free carbon is not present in the products.

5.1.2 Analysis of mass of air supplied by volume

The products of combustion are mainly gaseous. When a sample is taken for analysis it is usually cooled down to a temperature which is below the saturation temperature of the steam present. The steam content is therefore not included in the analysis, which is then quoted as the analysis of the dry product. Since the products are gaseous, it is usual to quote the analysis by volume. An analysis which includes the steam in the exhaust is called a wet analysis [13].

The mass balance equation can be expressed as, $m_{in} = m_{out}$ i.e. the mass of reactants is equal to the mass of products. As indicated in fig. 5.2 mass of reactant is the total mass of coffee husk and

combustion air entering in to the combustion chamber and mass of product is the sum of flue gas (Dry and wet flue gas) and ash.

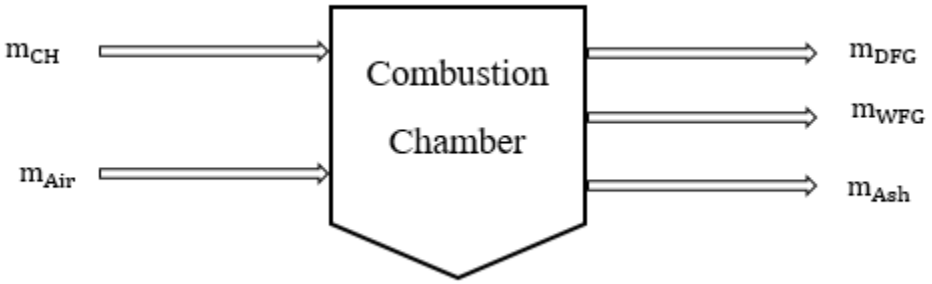

Figure 5.2 Mass balance in combustion chamber

The general formula which helps us for the analysis of the combustion product flue gas will be

$$m_{CH} + m_{Air} = m_{DFG} + m_{WFG} + m_{Ash} \quad \text{..... 5.5}$$

Therefore:

$$m_{DFG} = m_{Air} + m_{CH} - m_{WFG} - m_{Ash}$$

Where:

$$m_{DFG} + m_{WFG} + m_{Ash} = m_{FG}$$

$$m_{CH} + m_{Air} = m_{FG}$$

5.1.3 Flue gas analysis

The following table helps us to get the general formula which is used to know the amount of air by volume supplied to the combustion process.

Table 5.1 Amount of combustion product by volume

Constituents	Volume fraction (V %)	Molecular mass (M)	Mass fraction (X = MV)	% Mass
CO	Y_1	28	$28Y_1$	$28Y_1/\sum Y$
CO_2	Y_2	44	$44Y_2$	$44Y_2/\sum Y$
N_2	Y_3	28	$28Y_3$	$28Y_3/\sum Y$
O_2	Y_4	32	$32Y_4$	$32Y_4/\sum Y$
Total	$\sum Y$		$\sum X$	

Let me take 1kg of flue gas and calculate % C per 1kg of flue gas in CO and CO_2

$$\%C/m_{FG} = \frac{28Y_1}{\sum Y} * \frac{12}{28} + \frac{44Y_2}{\sum Y} * \frac{12}{44}$$

$$\%C/m_{FG} = \frac{12}{\sum Y} * (Y_1 + Y_2)$$

$$\%C = \frac{12}{\sum Y} * (Y_1 + Y_2) * m_{FG}$$

$$m_{FG} = \frac{\%C \sum Y}{12(Y_1 + Y_2)}$$

Mass of air supplied per %N in a kilogram of fuel:

$$m_{AS}/\%N \text{ in 1kg of fuel } = \frac{28Y_3}{\sum Y} * {}^{m_{FG}}/_{\%N \text{ in air (by volume)}}$$

$$m_{AS}/\%N \text{ in 1kg of fuel } = \frac{28Y_3}{\sum Y} * \frac{m_{FG}}{0.77}$$

Then by substitution with the above formula:

$$m_{AS}/\%N \text{ in 1kg of fuel } = \frac{28Y_3}{\sum Y} * \frac{\%C \sum Y}{0.77 * 12(Y_1 + Y_2)}$$

$$m_{AS} = \frac{\%N * \%C}{33(Y_1 + Y_2)}$$

$$m_{AS} = \frac{\%N * \%C}{33(CO_2 + CO)} \quad \ldots\ldots\ldots\ldots 5.6$$

Where: % N and % C are percent of nitrogen and carbon in the fuel and CO_2 and CO must be percent in volume [29].

5.1.4 Heat energy balance in the Furnace

To obtain the maximum temperature attained in the furnace, the analysis of heat balance is necessary. This is calculated by the following equation [30].

$$Q_{CH} = Q_{FG} + Q_{Ste} + Q_{UF} \quad \ldots\ldots\ldots\ldots 5.7$$

Where, Q_{CH} is the heat content of the coffee husk; Q_{FG} is the heat of the flue gas; Q_{Ste} is the heat used in producing steam and Q_{UF} is the heat lost due to unburnt fuel.

$$Q_{CH} = m_{CH} * CV_{CH}$$

Where, m_{CH} and CV_{CH} are the mass and the calorific value of the husks respectively.

$$Q_{FG} = m_{FG} * CP_{FG} * (T_{FG} - T_o)$$

Where, m_{FG} is the mass of the flue gas; CP_{FG} is the specific heat capacity of flue gas; T_{FG} is the maximum temperature attained in the furnace and T_o is the boiler reference temperature.

$$Q_{Ste} = m_{Ste} * (h_1 - h_4)$$

Where, m_{Ste} is the mass of the steam, h_1 and h_4 are respectively specific enthalpy of superheated steam, at a working pressure and specific enthalpy of feed water, at the outlet of the pump.

$$Q_{UF} = m_{UF} * CV_{CH}$$

Where: Q_{UF} is the mass of unburnt fuel.

Substituting will yield:

$$m_{CH} * CV_{CH} = [m_{FG} * CP_{FG} * (T_{FG} - T_o)] + [m_{Ste} * (h_1 - h_4)] + [m_{UF} * CV_{CH}]$$

Where:

$$m_{FG} = m_{DFG} + m_{WFG} + m_{Ash}$$

$$T_{FG} = \frac{m_{CH} * CV_{CH}}{m_{FG} * Cp_{FG}} - \frac{m_{Ste} * (h_1 - h_4)}{m_{FG} * Cp_{FG}} - \frac{m_{UF} * CV_{CH}}{m_{FG} * Cp_{FG}} + T_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.8$$

5.2 Steam generators (Boiler) design

A steam generator generates steam at the desired rate, at the desired pressure and temperature by burning the coffee husk in its furnace. It is a complex integration of combustor, economizer, evaporator and super heater

Steam generator is a closed vessel in which the heat produced by the combustion of fuel is transferred to water for its conversion into steam at the desired temperature and pressure.

Classification of boiler

Boilers can be classified according to different criteria such like, contents of the tubes, position of the furnace, axis of the shell, method of circulation of water and steam and use of boiler [31]

1. Contents of the tubes

Fire tube or smoke tube boiler: "Fire in tube" Boilers long steel tubes through which the hot gasses from a furnace pass and around which the water to be converted in to steam.

Water Tube Boiler: "water in tube" The water passing through the tubes and the hot gasses passing outside the tubes, These boilers can be of single or multiple drum type and can be built to any steam capacity and pressure, have higher efficiency than fire tube boilers. Water tube boiler further classified as follows [3]. Sterling Boiler, Babcox and Wilcox Boiler and Package Boiler

2. Position of the furnace

Internally fired boiler: The furnace is located inside the boiler shell. Most fire-tube boilers are internally fired.

Externally fired boiler: The furnace is arranged underneath in a brickwork setting and is located outside the boiler shell.

3. Axis of the shell

Vertical shell boiler, Horizontal shell boiler and Inclined shell boiler

If the axis of the boiler is horizontal, the boiler is called as horizontal, if the axis is vertical, it is called vertical boiler and if the axis is inclined it is known as incline boilers.

The parts of a horizontal boiler can be inspected and repaired easily but it occupies more space. The vertical boiler occupies less floor area.

4. Method of Circulation of water and steam

Natural circulation steam boilers: The circulation of water is by natural convection currents, which are set up during the heating of water. Most steam boilers operate under natural circulation of water.

Forced circulation steam boilers: The circulation of water is done by a forced pump so here there is a forced circulation of water by centrifugal pumps or ather types of pumps.Forced circulation is used in high-pressure boilers.

5. Use of boiler:

Stationary boilers: Are used for power plant steam, for central station utility power plants, for plant process steam etc. therefore these types of boiler are used in power plant and industrial process work.

Mobile boilers or portable boilers: Include locomotive type, and other small units for temporary use at sites (just as in small coalfield pits). Are those which can be moved from one place to another.

Selection of a boiler

While selecting a boiler the factors should be considered are; the working pressure and quality of steam required which is whether wet or dry or superheated, Steam generation rate, Floor area

available, Accessibility for repair and inspection, Comparative initial cost, Erection facilities, The probable load available, The fuel and water available, Operating and maintenance cost and etc.

Heat exchangers (Steam generators) are devices where two moving fluid streams exchange heat without mixing. A heat exchangers typically involve no work interactions (w=0) and negligible kinetic and potential energy changes for each fluid streams [4].

Depending up on whether the pressure of steam is below or above the critical pressure (221.2 bar), steam generators can be either subcritical or supercritical units. The subcritical steam generators are water tube drum type and they usually operate at between 130 and 180 bar steam pressure. Which produce superheated steam at about 540 – 560 ^{O}C [32].

But here for this specific case a subcritical steam generators which operate at 10 bar is used, for this, satisfies the main goal of this paper that is developing a CHP steam plant with **minimum cost and maximum efficiency.**

The increase in steam pressure is limited by consideration of mechanical stresses and the ensuing higher cost of equipment. And the increase in steam temperature is limited by the properties of the construction materials of boiler and turbine.

Increasing the steam temperature above 540 ^{O}C, increases the metallurgical quality of the nozzle and steam turbine blades by 30% .Very high pressures at the maximum temperature are undesirable because they create material strength problems [25].

Heat transfer to water in the steam generators takes place in the three different regimes. Water is first heated sensibly in the economizer till it becomes saturated liquid. In the evaporator there is phase change from by absorbing the latent heat of vaporization at 10 bar the saturated vapour is farther heated at constant pressure in the superheater.

Boiler accessories

There are the devices which are integral parts of a boiler and which help in the efficient running of a boiler. The working principles and theory behind the most important boiler accessories such as the feed pump, the economizer, the air pre-heater, evaporator and the superheater will be discused below.

A huge quantity of fuel is used in thermal power plant and vary large quantity of heat is carried by the exhaust gases.In the present age for efficent use of fule, it has become necessary to conserve the fuel by utilizing the heat generated during the comustion of the fuel, otherwise it would be wasted to the atmosphere.This is done in all modern power plants, by incorporating economizers and air pre-heaters.

Economizers are placed between the last superheater, reheater and pre-heaters to save the heat by increasing the temperature of feed water passing through the economizer, using waste heat of flue gases, whch results the quantity of heat required per kg of steam generated in the boiler is reduced.

In similar way the temperature of the combustion air is increased by passing it through an air pre-heater where the remaining waste heat of the exhaust gases is utilized.

The rate of heat transfer from flue gases to feed water is given by:

$$Q_{Eco} = \dot{m}_G c_{pFG}(T_{FG1} - T_{FG2}) = \dot{m}_{FW} c_{pFW}(T_{Sat} - T_{FW}) \quad \text{.....5.9}$$

when the fluid inlet temperatures are known and the outlet temperatures are specified or readily determined from the energy balance expressions so it is a simple matter to use the log mean temperature difference (LMTD) method of heat exchanger analysis.

$$Q_{Eco} = U_o A_o F_c \Delta T_{lm} \quad \text{.....5.10}$$

$$\Delta T_{lm} = \frac{\Delta T_{in} - \Delta T_{out}}{\ln\left(\frac{\Delta T_{in}}{\Delta T_{out}}\right)}$$

$\Delta T_{in} = T_{FG1} - T_{Sat}$ and $\Delta T_{out} = T_{FG2} - T_{FW}$

F_C = log mean temperature difference correction factor

The overall heat transfer coefficient U is given by:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{X_W}{K_W} + R_f + \frac{1}{h_o}$$

where h_i and h_o refer to the inside and outside heat transfer coefficient of the flow of fluids, respectively. X_W is tube wall thickness and thermal conductivity of tube material is represented by K_W. During normal heat exchanger operation surfaces are often subject to fouling by fluid impurities, rust formation, or other reactions between the fluid and the wall. This effect is treated in the equation by introducing the fouling factor, R_f.

h_i and h_o are calculated from the following relations:

$$h_i = Nu\frac{K}{d} \text{ and } h_o = \frac{Nu.k}{d_h}$$

d_h is the hydraulic diameter and Nu is the Nusselt number and it may be calculated from different correlatins accordingly the flow type (Turbulent of laminar). Such as:

$$Nu = 0.023(Re)^{4/5}(Pr)^{0.4}$$

$$Nu = 0.023(Re)^{0.8}(Pr)^{1/3}$$

Where the Reynolds number, Re is:

$$Re = \frac{4.\dot{m}}{\pi.d.\mu}$$

However, if only the inlet temperatures are known, it is therefore preferable to employ an alternative approach termed the effectiveness–NTU (NTU) method.

$$NTU = \frac{UA}{C_{min}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.11$$

where C_{min} is equal to C_c or C_h, whichever is smaller. For prescribed cold and hot fluid inlet temperatures respectively.

$$\varepsilon = 1 - \exp(-NTU) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.12$$

It is now logical to define the effectiveness, ε, as the ratio of the actual heat transfer rate for a heat exchanger to the maximum possible heat transfer rate:

$$\varepsilon = \frac{q}{q_{max}} = \frac{C_c(T_{co} - T_{ci})}{C_{min}(T_{hi} - T_{ci})} = \frac{C_h(T_{hi} - T_{ho})}{C_{min}(T_{hi} - T_{ci})} \ldots\ldots\ldots\ldots 5.13$$

By definition the effectiveness, ε which is dimensionless, must be in the range $0 \leq \varepsilon \leq 1$. It is useful because, if ε, T_{hi} *and* T_{ci} are known, the actual heat transfer rate may readily be determined from the expression

$$q = \varepsilon * C_{min} * (T_{hi} - T_{ci}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.14$$

Feed water flowing through tubes.

$$\dot{m} = \left(n_t \frac{\pi d_i^2}{4}\right)\frac{C}{V_f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.15$$

n_t = Number of turns

d_i = Inner diameter of tubes

V_f = Specific volume of the water

C_{FW} = Mean velocity of water throug tubes

If the clearance C is given on two sides of the gas duct of width B, then the number of turns n_t of one coil can be estimated from:

$$n_t = \frac{L}{B - 2C}$$

If the pitch or center to center distance p of consecutive horizontal tubes is known, then the height of the duct occupied by the economizer is:

5.3 Determination of boiler efficiency

Basically boiler efficiency can be tested by the following methods:

1. The Direct Method: Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.
2. The Indirect Method: Where the efficiency is the difference between the losses and the energy input. [33, 18]

For this work I have used indirect method. Indirect method is also called as heat loss method. A detailed procedure for calculating boiler efficiency by indirect method is given below. The principle losses that occur in a boiler are:

1. Percent loss of heat due to dry flue gas (Sensible heat) (L_1)

Dry flue gases leave the furnace in high temperature and thus they carry significant amount of energy away from boiler process. To decrease dry flue gas losses, the gas exit temperature should be decreased. However, the acid dew point of the gases restricts the flue gas temperature. The losses caused by the sensible heat of flue gases can be calculated as:

$$L_1 = \frac{m_{FG} * c_{pFG} * (T_{FG} - T_a)}{\text{GCV of Coffee Husk}} * 100\%$$

Where, m = Total mass of dry flue gas in kg/kg of coffee husk.

But, m = mass of CO_2 + mass of SO_2 + mass of N_2 + mass of O_2

c_{pFG} = Specific heat of flue gas

2. Percent loss of evaporation of water formed due to H_2 in the husk (L_2)

The combustion of hydrogen causes a heat loss because the product of combustion is water. This water is converted to steam and this carries away heat in the form of its latent heat.

$$L_2 = \frac{9 * H_2 * [584 + c_p(T_{FG} - T_a)]}{\text{GCV of Coffee Husk}} * 100$$

Where, H_2 - kg of H_2 in 1 kg of coffee husk

c_p - Specific heat of superheated steam (0.45 kCal/kg °C)

584 is the latent heat corresponding to the partial pressure of water vapour.

3. Percent loss of heat due to moisture in coffee husk (H_2O) (L_3)

This moisture loss is made up of the sensible heat to bring the moisture to boiling point, the latent heat of evaporation of the moisture, and the superheat required to bring this steam to the temperature of the exhaust gas. This loss can be calculated with the following equation:

$$L_3 = \frac{M * [584 + c_p(T_{FG} - T_a)]}{\text{GCV of Coffee Husk}} * 100\%$$

Where, M – percent moisture in 1kg of coffee husk

c_p – Specific heat of superheated steam (0.45 kcal/kg)

4. Percent loss of heat due to moisture in air (H_2O) (L_4)

$$L_4 = \frac{m_{AS} * \text{Humidity Factor} * c_p(T_{FG} - T_a)}{\text{GCV of Coffee Husk}} * 100\%$$

m_{AS} - Actual mass of air supplied /kg of coffee husk.

Cp – Specific heat of superheated steam (0.45 kCal/kg °C)

Humidity factor (humidity of air) = 0.018 kg/kg of dry air

5. Percent loss of heat due to wasted heat in ashes = L_5

Ash can exit the furnace either as bottom ash from bottom of the furnace or as fly ash with flue gases. The losses related to the sensible heat of ash can be calculated as:

$$L_5 = \frac{\dot{m}_{BA} * Cp_{BA} * \Delta T_{BA} + \dot{m}_{FA} * Cp_{FA} * \Delta T_{FA}}{\text{GCV of Coffee Husk}} * 100\%$$

where $\dot{m}_{BA}$ is the mass flow of the bottom ash [kg/s], Cp_{BA} the specific heat of the bottom ash [kJ/(kgK)], ΔT_{BA} the temperature difference between the bottom ash temperature and the reference temperature [°C], $\dot{m}_{FA}$ the mass flow of fly ash, Cp_{FA} the specific heat of fly ash, ΔT_{FA} the temperature difference between the fly ash temperature and the reference temperature [°C]. Usually the reference temperature is 25 °C.

6. Percent loss of heat due to heat transfer (radiation, convection and unaccounted) = L_6

The other heat losses from a boiler consist of the loss of heat by radiation and convection from the boiler casing into the surrounding boiler house.

Normally surface losses and other unaccounted losses is assumed based on the type and size of the boiler as given below. For industrial fire tube / packaged boiler = 1.5 to 2.5%, for industrial water tube boiler = 2 to 3%, for power station boiler = 0.4 to 1% [21].

7. Percent loss of heat due to blow down (water and steam) = L_7

Blowdown water from the steam drum and sootblowing steam (used to remove soot from heat exchanger surfaces within the boiler) use a part of the steam produced by the boiler. This lowers the boiler efficiency. The losses can be calculated as:

$$L_7 = \frac{(\dot{m}_{BDW} * h') + (\dot{m}_{BDS} * h_{BDS})}{\text{GCV of Coffee Husk}} * 100\%$$

$\dot{m}_{BDW}$ is the mass flow of blowdown water [kg/s], *h′* is the specific enthalpy of saturated water (blow down water from steam drum) [kJ/kg], $\dot{m}_{BDS}$ is the mass flow of sootblowing steam, h_{BDS} is the specific enthalpy of steam used for soot blowing (when leaving the boiler) [kJ/kg].

8. Percent losses due to unburned solid fuel (Carbon) = L_8

Unburned fuel can exit the furnace as well as bottom ash or fly ash. The losses [kW] of unburned solid fuels can be calculated as:

$$L_8 = \frac{\dot{m}_{Ash} * CV_{Ash}}{\text{GCV of Coffee Husk}} * 100\%$$

Where, $\dot{m}_{Ash}$ is the total mass flow of unburned solid fuel (bottom ash and fly ash in total) [kg/s], and CV_{Ash}, the heating value of unburned solid fuel (fly ash and bottom ash in total) [kJ/kg]. This loss can be estimated based on known standards.

$$L_8 = \frac{\text{Total ash collected /kg of husk burnt} * \text{GCV of ash}}{\text{GCV of Coffee Husk}} * 100$$

In the above, loss due to moisture in coffee husk and the loss due to combustion of hydrogen are dependent on the husk, and cannot be controlled by design.

Sum of the major losses within the boiler will be:

$$Q_{losse} = L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8 \quad \text{..... 5.16}$$

Indirect method determines the efficiency of a boiler by the sum of the major losses and by the fuel power of the boiler:

$$\eta = 1 - \frac{Q_{Los}}{Q_{in}}$$

Where Q_{Los} is the sum of the major losses within the boiler, and Q_{in} is the fuel power of the boiler.

5.4 Design and performance calculation

5.4.1 Calculation of combustion

Considering theoretical combustion reaction for the elemental analysis of coffee husk shown in the following table.

Table 5.2 Elemental, Moisture and Ash contents of the husk

Element	C	N	H	S	O	Moisture	Ash
Percentage	46.8314	0.4454	4.8132	0.0500	36.4000	7.92	3.54

Required Air for combustion

A) Carbon to carbon dioxide (Complete combustion)

Using equation 5.1 the amount of Oxygen required and Carbon dioxide produced will be:

$C+ (O_2 + 3.76N_2) \rightarrow CO_2 + 3.76N_2$

$C + O_2 \rightarrow CO_2$, or

By mass:

12 kg C + 32 kg $O_2 \rightarrow$ 44 kg CO_2

12 kg C + 32 kg O_2 = 44 kg CO_2, or

1kg C + (32/12) kg O_2 = (44/12) kg CO_2

1 kg C +2.6667 kg O_2=3.6667 CO_2

Which means 1 kg of Carbon needs 2.6667 kg of oxygen to produce 3.6667 kg of carbon dioxide.

Therefore, the amount of oxygen required for 46.8314 % of carbon in the husk becomes:

Oxygen required = 0.468314 * 2.6667 = 1.2488 kg /kg CH

Carbon dioxide produced = 0.468314 * 3.6667 = 1.7172 kg /kg CH

B) Hydrogen to Water

Applying equation 5.2 we able to get the amount of Oxygen required and Steam generated during the reaction below.

$H + 0.25(O_2 + 3.76N_2) \rightarrow 0.5H_2O + 0.94N_2$

$2H_2 + O_2 \rightarrow 2H_2O$, or

By mass:

$2kg\ H_2 + 16kg\ O_2 \rightarrow 18kg\ H_2O$

$2kg\ H_2 + 16kg\ O_2 = 18kg\ H_2O$

$1kg\ H_2 + 8kg\ O_2 = 9kg\ H_2O$

This indicates that 1 kg of Hydrogen and 8 kg of Oxygen needs to produces 9kg of water. Therefore, the amount of oxygen required for 4.8132 % of Hydrogen in the husk becomes:

Oxygen required = $0.048132 \times 8 = 0.3851kg/kg\ CH$

Steam produced = $0.048132 \times 9 = 0.4332\ kg/kg\ CH$

C) Sulphur to Sulphur dioxide

From equation 5.3 it will be possible to find the required mass of oxygen and the produced Sulphur dioxide in the chemical equation below.

$S + (O_2 + 3.76N_2) \rightarrow SO_2 + 3.76N_2$

$S + O_2 \rightarrow SO_2$, or

By mass:

$32kg\ S + 32kg\ O_2 \rightarrow 64kg\ SO_2$

$32kg\ S + 32kg\ O_2 = 64kg\ SO_2$

$1kg\ S + 1kg\ O_2 = 2kg\ SO_2$

Which indicates 1 kg of Sulpfur needs for 1 kg of Oxygen and produces 2 kg of sulphur dioxide. Therefore, the amount of oxygen required for 0.0500 % of Sulphur in the husk becomes:

Oxygen required = $0.0005 * 1 = 0.0005\ kg/kg\ CH$

Sulphur dioxide produced = $0.0005 * 2 = 0.001kg/kg\ CH$

Now if we consider 1 kg of husk with C kg of Carbon, H kg of Hydrogen, S kg of Sulphur and O kg of Oxygen, amount of Oxygen required for complete combustion of the husk would be

Oxygen required per Kilogram of CH = (2.67C + 8H + S – O) kg per kg of husk.

Here the quantity of Oxygen (36.4 %) which is already present in the coffee husk will not be required to be taken from atmospheric air.

Oxygen required per Kilogram of CH = (1.2488 + 0.3851 + 0.0005) Kg – 0.364 kg

= 1.2704 kg

Complete combustion of coffee husk occurs when all molecules of C, H_2 and S in the husk get fully oxidized and become CO_2, H_2O and SO_2 respectively.

The theoretical amount of air required to achieve complete combustion is known as stoichiometric air.

It is usual in combustion calculations to take air as 23.3% O_2, 76.7% N_2, by mass and 21% O_2, 79% N_2, by volume. The small traces of other gases in dry air are included in the nitrogen, which is sometimes called atmospheric nitrogen [34].

Air required per Kilogram of CH = 1.2704/0.233 = 5.4524 kg

Where air is assumed to contain 23.3% O_2 by mass.

This shows that Stoichiometric air fuel ratio will be:

Stoichiometric A/F ratio = 5.4524/1 = 5.4524:1

$m_{\text{Air Sto}} = 5.4524$ kg.

Estimation of Excess air

In a combustion process complete combustion will occur when the proper amounts of fuel and air (Air to fuel ratio) are mixed for the correct amount of time under appropriate conditions of turbulence and temperature. Which means complete burning cannot be accomplished with the exact theoretical amount of air.

In practice, in order to achieve complete combustion, it is necessary to increase the amount of air to the combustion process to ensure the burning of all of the fuel. The amount of air that must be added to make certain all energy will be retrieved is known as excess air.

The valid reason for incomplete combustion of fuel in presence of theoretical amount of air may be due to the fact that each particle of oxygen in the air does not have the intimate contact with the fuel particles in the combustion process. Therefore an excess air is to be supplied.

The amount of excess air supplied varies with the fuel characteristics and the system configuration. It may approach a value of 100% but modern practice is to use 25% to 50% excess air [10].

For this calculation I have taken the average of the two limits. Therefore:

$$= \left(\frac{25 + 50}{2}\right)\%$$

= 37.5 % Excess air

$$\text{Actual A/F ratio} = m_{\text{Air Sto.}} + \left(\frac{m_{\text{Air Exc}}}{100} * m_{\text{Air Sto.}}\right)$$

$$\text{Actual A/F ratio} = 5.4524 + [(37.5/100) * 5.4524] = 7.497$$

Actual A/F ratio = 7.497:1

Therefore the actual amount of air for complete combustion becomes:

$$m_{\text{Air Actual}} = 7.497 \text{ kg per kg of fuel}$$

Therefore:

N_2 supplied = 0.767 * 7.497 = 5.7502 kg

Also O_2 supplied = 0.233 * 7.497 = 1.7468 kg

In the products, then, we have:

Total N_2 = N_2 supplied + N_2 in the coffee husk

Total N_2 = 5.7502 + 0.004454 = 5.7547 kg

Excess O_2 = Oxygen supplied – Oxygen required

Excess O_2 = 1.7468 – 1.2704 = 0.4764 kg

Table 5.3 Summery of air supplied calculation

Constituents	Mass fraction	Oxygen required (kg/kg CH)	Product by mass (kg/kg CH)
Carbon (C)	0.468314	1.2488	1.7172 (CO_2)

Hydrogen (H)	0.048132	0.3851	0.4332 (H_2O)
Sulphur (S)	0.0005	0.0005	0.001 (SO_2)
Oxygen (O)	0.364	-0.364	-
Nitrogen (N)	0.004454	-	0.004454 (N)
Ash	0.0354	-	-
Net Oxygen required	**1.2704**		

Calculation of mass of air supplied by volume

1kmol of any gas = 22.4 m^2

1 mole occupied = 22.4L

Volume occupied by 1 mole is same for all gas

∴ % of mole fraction = % of volume

Compositions of exhaust gas

Table 5.4 Dry and wet volume analysis of coffee husk combustion product constituents

Constituents	Mass (m)	% Mass (G) = (m/∑ m)	Molar mass (M)	Mole (n) = m/M	%V (Dry) (m/M)/ Dry $\sum \frac{m}{M}$	%V (Wet) (m/M)/ Dry $\sum \frac{m}{M}$
CO_2	1.7172	20.4855	44	0.0390	15.0347	13.6842
H_2O	0.4332	5.1679	18	0.0241	–	8.5009
SO_2	0.001	0.0174	64	0.00002	0.0077	0.0071
N_2	5.7547	68.6514	28	0.2055	79.2213	72.4868
O_2	0.4764	5.6833	32	0.0149	5.7440	5.2557
Sum	$\sum m = 8.3825$	100%		Dry $\sum \frac{m}{M} = 0.2594$ Wet $\sum \frac{m}{M} = 0.2835$	~ 100%	~ 100%

The analysis by volume is obtained in the above table. The total of 0.2835 gives the total amount of substances of wet products per kilogram of coffee husk, and by subtracting the amount of substance of H_2O from this total the total amount of substance of the dry products is obtained as 0.2594 and the

last two columns expressed the percentage by volume of the substances of dry and wet products respectively.

Then, from equation 5.6 mass of air supplied can be calculated as follows:

$$m_{AS} = \frac{\%N * \%C}{33(CO_2 + CO)}$$

$$m_{AS} = \frac{72.4868 * 46.8314}{33 * 13.6842}$$

$$m_{AS} = 7.5173 \text{ kg/kg of husk}$$

Mass of combustion air required will be:

$$m_{AR} = \frac{1}{0.233}\left[C * \frac{8}{3} + \left(H - \frac{O}{8}\right)8 + S\right]$$

$$m_{AR} = \frac{1}{0.233}\left[0.4683 * \frac{8}{3} + \left(0.048132 - \frac{0.364}{8}\right)8 + 0.0005\right]$$

$$m_{AR} = \frac{1}{0.233}[1.2488 + 0.0211 + 0.0005]$$

$$m_{AR} = 5.4522 \text{ kg}$$

Excess Air = 7.5173 – 5.4522 = 2.0651 kg

$m_{WFG} = m_{Moi} + m_{H_2O}$ (In the coffee husk)

Using table 5. 1 and 5. 3

$$m_{WFG} = 0.0792 + 0.085009 = 0.1642 \text{ kg}$$

Mass of dry air = Mass of air supplied – Mass of steam

$$m_{DA} = 5.4522 - 0.1642 = 5.2880 \text{ kg}$$

Mass of dry flue gas = Mass of dry air + (Mass of coffee husk – Mass of vapour in the husk) – Mass of ash

$$m_{DFG} = m_{Air} + m_{CH} - m_{WFG} - m_{Ash}$$

Where: Mass of coffee husk – Mass of vapour in the husk will be:

1 – Mass of vapour in the husk = 1 – 0.1642 = 0.8796 kg

$$m_{DFG} = 5.2880 + 0.8796 - 0.0354 = 6.1322 \text{ kg}$$

Then mass of combustion product is = mass of dry flue gas - Excess Air

= 6.1322 - 2.0651 = 4.0671 kg

Mass of unburned fuel included the amount of carbon in the combustion product and the amount of the ash in coffee husk. But here the only unburned substance is the ash content of the husk, the other are included in the dry flue gas.

$m_{Ash} = m_{UF} = 0.0354$ kg

Therefore:

Mass of flue gas $(m_{FG}) = m_{DFG} + m_{WFG} + m_{Excess\ air}$

$m_{FG} = 6.1322 + 0.1642 + 2.0651 = 8.3615$ kg

Flue gas Maximum temperature

Using equation 5.8

$$T_{FG} = \frac{m_{CH} * CV_{CH}}{m_{FG} * Cp_{FG}} - \frac{m_{Ste} * (h_1 - h_4)}{m_{FG} * Cp_{FG}} - \frac{m_{UF} * CV_{CH}}{m_{FG} * Cp_{FG}} + T_0$$

Cp of dry flue gas is 1.045 kJ/kg.k

CV of coffee husk is $18.98 * 10^3$ kJ/kg

h_1 and h_4 are known in energy analysis part of this paper

$m_{Ste} = 0.989$ kg (calculated value on chapter seven)

$$T_{FG} = \frac{0.8796 * 18.98 * 10^3}{8.3615 * 1.045} - \frac{0.989 * (3479.1 - 192.809)}{8.3615 * 1.05} - \frac{0.0354 * 18.98 * 10^3}{8.3615 * 1.05} + 298$$

$T_{FG} = 1910.6491 - 370.1935 - 76.529 + 298$

$T_{FG} = 1761.9266$ k

$T_{FG} = 1488.9266$ ℃

Determination of exhaust flue gas temperature

The flue gases are cooled in heat exchangers (economiser and air preheater) so as to minimize the exhaust losses through chimney the gases, however, shuld never be cooled below the dew point temperature. To determine the temperature of the gas the partial pressure of water vapour in the mixture of gases constituting the flue gas must be known.

Therefore:

$p_{H_2O} = X_{H_2O} * P = X_{H_2O} * 1atm$

Where P is the total pressure of the exhaust gas mixture at the end of chimney which is one atmospere in all utilitiy boilers [39]. And X_{H_2O} is the mole fraction water vapour.

$$X_{H_2O} = \frac{n_{H_2O}}{n_{Total}} = \frac{n_{H_2O}}{n_{CO_2} + n_{O_2} + n_{SO_2} + n_{N_2} + n_{HO_2}}$$

$$= \frac{0.0241}{0.0390 + 0.0149 + 0.00002 + 0.2055 + 0.0241} = \frac{0.0241}{0.2835}$$

$$X_{H_2O} = 0.085$$

Therefore: $p_{H_2O} = 0.085 * 101.325 = 8.6126$ kpa

Then the dew point temperature at 8.6126 kpa from the steam table by interpolation will be:

P(kpa)	Dew T(^{0}C)
7.5	40.29
8.612	DPT
10	45.81

$$DPT = \frac{(10 - 8.612)(45.81 - 40.29)}{10 - 7.5} + 40.29$$

DPT = 43.35 ^{o}C

Therefore 43.35 ^{o}C is a minimum possible temperature at the end of chimney after air preheater.

The temperature of the combustion air before the air preheater is considered as 30 °C (based the local average temperature). The flue gases exiting the boiler are usually kept above 130-160 °C in order to prevent corrosion [39].

The draught (ID) fan draws the flue gases from the furnace and sends them through the stack to the atmosphere. The exiting gas temperature 160 ^{o}C represents an availability loss to the plant but it is accepted because of the following reasons.

- ✓ The gas temperature should be kept well above the dew point temperture of the water vapour in the gases or equal to saturation temperature at the partial presure of water to prevent condesation which would form acids (with SO_2 or SO_3) that would corrode metal components in its path.
- ✓ The flue gas must have enough buoyancy to rise in a high plume above the stack for proper atmospheric dispersion [32].

When analyzing reacting systems it becomes necessary to have a common reference state for all substances. The chosen reference state is 25°C (77°F) and 1 atm, which is known as the standard reference state [30].

Air preheater

The heat carried with the flue gases coming out of economizer is further utilized for pre heating the air before it is supplied to the combustion chamber. An increase of 20℃ in the air temperature increases the boiler efficiency by an about 1% [26].

In modern power plants the air preheaters are not only considered with respect to the boiler efficiency but also as a necessary equipment for supply of hot air for drying the fuel in pulverized fuel system. The principal benefits of preheating the air are improve combustion, successful use of low grade fuel increase thermal efficiency, saving in fuel consumption, and increased steam generation capacity of the boiler.

In order to calculate the heat load for the air preheater, we need to know the combustion air mass flow, the temperature of the flue gases and the incoming air.

$$Q_{APH} = \dot{m}_{Air} * Cp_{Air} * (T_{APH.out} - T_{APH.in}) \quad \text{.....5.17}$$

Where, $\dot{m}_{Air}$ the mass flow rate of combustion air, $T_{APH.in}$ the temperature of combustion air before the air preheater, and $T_{APH.out}$ the temperature of combustion air after the air preheater.

$$Q_{APH} = \dot{m}_{Air} * c_{pAir} * (T_{Air.out} - T_{Air.in}) = -\dot{m}_{FG} * c_{pFG} * (T_{FG.out} - T_{FG.in})$$

Where:

Mass of air ($\dot{m}_{Air}$) = 7.497 kg (calculated value)

Mass of flue gas ($\dot{m}_{FG}$) = 2.089 kg

Cp_{Air} at 30 ^{O}C = 1.005 kJ/kg. k and average c_{pFG} = 1.045 kJ/kg

Outlet temperature of the flue gas ($T_{FG.out}$) = 160 ^{O}C

Assume the air should be heated to 170 ℃

$$7.497 * 1.005 * 10^3 * (170 - 30) = 6.3672 * 1.045 * 10^3 * (T_{FG.in} - 160)$$

$$T_{FG.in} = 318\ ℃$$

$$Q_{APH} = \dot{m}_{Air} * c_{pAir} * (T_{Air.out} - T_{Air.in}) = 7.5173 * 1.005\ (318 - 160)$$

$$Q_{APH} = 1193.672$$

5.4.2 Steam generator design calculation

Economizer:

An economizer is a feed water heater which raises the temperature of feed water to about the saturated liquid temperature at the boiler pressure using the flue gases discharged from the boiler.

The justifiable cost for an economizer depends on the total gain in efficiency. In turn, this depends on the gas temperature out of the boiler and feed water temperature to the boiler.

Economizer tubes are commonly 45-70 mm in diameter. And also the coils are installed at 45-50 mm spacing between them [25].

Determination of inlet flue gas temperature

The actual heat transfer rate Q can be determined by writing an energy balance over either side of the economizer.

$$Q = \dot{m}_G c_{pFG}(T_{FG1} - T_{FG2}) = \dot{m}_{FW} c_{pFW}(T_{FW1} - T_{FW2})$$

where: T_{FW1} is Saturated temperature at the selected pressure (10 bar) which is 179.88 ℃ (from Saturated water Pressure table)

Arithmetic mean temperature of feed water in the economizer

$$T_m = \frac{T_{FW1} + T_{FW2}}{2}$$

where; T_{FW2} is the feed water in let temperature that is 27 ℃

$$T_m = \frac{179.88 + 27}{2} = 103℃$$

Then properties of water at this mean temperature from properties of saturated water table is given as

Density (ρ) = 907.4 kg/m^3, Specific heat (c_p) = 4340 J/kg.K, Thermal conductivity (k) = 0.680 W/m.K, Kinamatics viscosity (μ) = 0.170 * 10^{-3} kg/m.s, Prandtl No (Pr) = 1.09

According to the heat transfer hand book [22] we shall specify the internal diameter and the velocity of the fluid, 50 mm and 0.4 m/s respectively.

$$\dot{m}_{FW} = \rho * A_c * V = 907.4 * \pi * 0.05^2/4 * 0.4 = 0.7127$$

$$\dot{m}_{FW} = 0.7127 \text{ m/s}$$

$$\dot{m}_{FW} c_{pFW} = 0.7127 * 4.340 * 10^3 = 3092.989 \text{ J/℃}$$

$\dot{m}_{FG} c_{pFG} = 6.3672 * 1.045 * 10^3 = 6653.724\ J/℃$

$6653.724\ (T_{FG1} - 318) = 3092.989\ (103 - 27)$

$$T_{FG1} = 318 + \frac{3092.989\ (295 - 27)}{6653.724} = 353.5331$$

$T_{FG1} = 354\ ℃$

Overall heat transfer coefficient

$\Delta T_1 = T_{FG1} - T_{FW1}$

$\Delta T_1 = 354 - 180 = 174\ ℃$

$\Delta T_2 = T_{FG2} - T_{FW2}$

$\Delta T_2 = 318 - 27 = 291\ ℃$

From equation 6.10

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} = \frac{291 - 174}{\ln\left(\frac{291}{174}\right)} = \frac{117}{0.5143} = 227.5078$$

$\Delta T_{lm} = 227.51\ ℃$

The overall heat trasfer coefficient U is given by:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{X_W}{K_W} + R_f + \frac{1}{h_o}$$

Inside heat transfer coefficient

Reynolds number for flow of water through the tube at mean water temperture:

$$Re = \frac{4 * m}{\mu * d_i * \pi} = \frac{4 * 0.7127}{0.170\ *\ 10^{-3} * 0.05 * \pi} = \frac{2.8508}{2.67 * 10^{-5}} = 1.06757 * 10^5$$

Since the flow is turbulent, hence

$$N_u = \frac{h * d}{k} = 0.023(Re)^{0.8}(Pr)^{0.4}$$

$$= 0.023(1.06757 * 10^5)^{0.8}(1.09)^{0.4} = 250.8508$$

$$\text{where: } h = h_i = N_u \frac{K_w}{d_i} = 250.8508 \frac{0.680}{0.05} = 3411.57$$

$\therefore h_i = 3411.57\ W/m^2.℃$

Outside heat transfer coefficient

The outside heat trasfer coefficient based on the flue gas properties is given by:

Flue gas properties at mean teperature [(442+318)/2 = 380 ^{O}C] will be:

$\mu = 1.2 * 10^{-2}$ kg/m. s , $\rho = 1.479$ kg/m^3 , $k = 0.312$ W/m. K and Pr $= 1.35$

then Reynolds number of the out side flow

$$\mathrm{Re} = \frac{\rho * u_m * d_h}{\mu} = \frac{4 * \dot{m}}{\mu * (d_o + d_i) * \pi} = \frac{4 * 6.3672}{0.012 * 2 * 0.05 * \pi} = 6755.81$$

Since Re < 2300 the flow is laminar, assuming uniform temperature the heat transfer coefficient will be:

$$N_u = \frac{h_o * d}{k} = 0.023(6755.81)^{0.8}(1.35)^{0.4} = 30.0333$$

$$h_o = 3.66 * \frac{k}{d} = 30.0333 * \frac{0.312}{0.05} = 187.4078$$

$\therefore h_o = 187.4078$ W/m^2. ℃

In this work inorder to get maximum heat transfer, I have considered as the tube is thin walled and the termal resistance due to tube wall thickness and scale formed are neglected.

Then substituting the values in the above equation overall heat trasfer will be:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o} = \frac{1}{3411.57} + \frac{1}{187.4078} = 177.649$$

$U = 177.649$ W/m^2. K

Heat load calculation of the economizer

$$Q_{Eco} = \dot{m}_{FG} c_{pFG} (T_{FG1} - T_{FG2}) = 6.3672 * 1.045 * 10^3 (442 - 318) = 825061.776\ W$$

$Q_{Eco} = 825.0618$ kW

Heat transfer surface of the economizer

To find log mean temperature difference correction factor (F_c) we have to find P (temperature ratio) and R (capacity ratio).

$$P = \frac{T_{FG1} - T_{FG2}}{T_{FW1} - T_{FW2}} = \frac{442 - 318}{295 - 27} = \frac{124}{268} = 0.4$$

$$R = \frac{T_{FW1} - T_{FW2}}{T_{FG1} - T_{FG2}} = \frac{295 - 27}{442 - 318} = \frac{268}{124} = 2.2$$

With the values of P = 0.4 and R = 2.2 we get Fc =0.87 from correction factor chart [20].

$$Q_{Eco} = U * A_s * F_c * \Delta T_{lm}$$

$$A_s = \frac{Q_{Eco}}{U * F_c * \Delta T_{lm}} = \frac{825.0618 * 10^3}{177.649 * 0.87 * 227.51} = 23.46\ m^2$$

$$A_s = 23.46\ m^2$$

Total length of tubes

Let L is the total length of the tubes, which is the product of an individual loop length and the number of tubes

$$A_s = \pi\ d\ l * N = \pi\ d\ L$$

$$\text{Therefore: } L = \frac{A_s}{\pi\ d}$$

$$L = \frac{23.46}{\pi * 0.05} = 149.3771$$

$$L = 149.377\ m$$

Evaporator

The physical process of evaporation requires the input of energy in the form of heat to convert a liquid into vapor. Since all evaporators use the process of evaporation to remove water, every evaporator requires a source of heat to operate. A second requirement for all evaporators is a means to transfer heat energy from the heat source into the evaporator liquid.

In this case the water inters into the evaporator at saturated condition and comes out as saturated steam, so the temperature during the generation of steam remains constant at 179.88 ℃.

Then from energy balance equation:

heat gined by steam = Heat lost by flue gas

$$Q_{Eva} = \dot{m}_{St} * h_{fg} = \dot{m}_{FG} c_{pFG} (T_{FG1} - T_{FG2})$$

Where:

$\dot{m}_{St}$ = Steam generation rate in the evaporator

h_{fg} = Latent heat of vaporazation at 180 ℃ and 10 bar = 2014.6 kJ/kg

T_{FG1} = Flue gas temperatu which is intering to the evaporator

T_{FG2} = Flue gas outlet temperature = 442 ℃

The product of mass flow rate and the specific heat as a mater of convenience, is defined as the fluid capacity rate (FCR = *C*).

$C_{max} = C_h = \infty$

$C_{min} = C_W = \dot{m}_w * c_{pw} = 1 * 4.18 * 10^3 = 4180\ W/K$

Capacity ratio (R)

$$R = \frac{C_{min}}{C_{max}} \cong 0$$

Therefore by taking the possible maximum effectiveness value of evaporator we can calculate the number of transfer unit or it is possible to use a chat at R = 0.

$\varepsilon = 1 - \exp(-NTU)$

$-NTU = \ln(1-\varepsilon) = \ln(1-0.89) = -2.207$

$NTU = 2.207$

Taking the following properties of water at the constant temperature (180 ℃) temperature:

$c_p = 5.67\ kJ/kg.K$, $h_{fg} = 2014.6\ kJ/kg$, $\rho = 3.46\ kg/m3$, $k = 0.0767\ W/m.K$,

$Pr = 1.59$ and $\mu = 0.7 * 10^{-3}\ Ns/m^2$

Total length of the tube (L)

Consider the flow of steam through tubes:

Mass flow $\dot{m} = A.V.\rho$

Where: V is the velocity of steam in the tube

$$G = \frac{m}{A}\ \text{(mass flow per unit area per unit time)}$$

$$= \frac{A\rho V}{A} = \rho V$$

$$\text{Reynolds number, } Re = \frac{\rho.V.d}{\mu} = \frac{G.d}{\mu}$$

Where G is in kg/m^2.s and μ in Ns/m^2

Let us assume the sturated liqued from the economizer inters in to the evaporater. Therefore from the above calculated value.

$$\therefore \text{Re} = \frac{2565.72/60 * 0.05}{0.7 * 10^{-3}} = 61088.57$$

$$\text{Nusselt number, Nu} = \frac{\text{h d}}{\text{k}} = 0.023(\text{Re})^{0.8}(\text{Pr})^{0.33}$$

$$\text{h} = \frac{\text{k}}{\text{d}} * 0.023(\text{Re})^{0.8}(\text{Pr})^{0.33} = \frac{0.0767}{0.05} * 0.023(61088.57)^{0.8}(1.59\ )^{0.33}$$

$$\text{h} = 277.1929\ \text{W/m}^2.℃$$

Neglecting the other two resistance terms:

$$\text{NTU} = \frac{\text{UA}_\text{s}}{\text{C}_\text{min}} = \frac{\text{h} * \text{A}_\text{s}}{\text{C}_\text{min}}$$

$$\text{A}_\text{s} = \frac{\text{NTU} * \text{C}_\text{min}}{\text{h}} = \frac{2.207 * 4180}{277.1929} = 33.281$$

$$\text{A}_\text{s} = 33.281\ m^2$$

Therefore:

$$\text{A}_\text{s} = \pi * \text{d} * \text{L}$$

$$\text{L} = \frac{\text{A}_\text{s}}{\pi * \text{d}} = \frac{33.281}{\pi * 0.05} = 211.8735$$

$$\text{L} = 211.87\ \text{m}^2$$

Rate of Heat energy trasfered

$$\dot{\text{m}}_\text{St} * \text{h}_\text{fg} = \dot{\text{m}}_\text{FG}\text{c}_\text{pFG}(\text{T}_\text{FG1} - \text{T}_\text{FG2})$$

$$\varepsilon = \frac{\text{T}_\text{FG1} - \text{T}_\text{FG2}}{\text{T}_\text{FG2} - \text{T}_\text{FW2}} = \frac{\text{T}_\text{FG1} - 442}{442 - 180} = 0.89$$

$$\text{T}_\text{FG1} = 0.89(442 - 180) + 442 = 675.18$$

$$\text{T}_\text{FG1} = 675\ ℃$$

$$\dot{\text{m}}_\text{St} = \frac{\dot{\text{m}}_\text{FG}\text{c}_\text{pFG}(\text{T}_\text{FG1} - \text{T}_\text{FG2})}{\text{h}_\text{fg}}$$

$$\dot{\text{m}}_\text{St} = \frac{6.3672 * 1.045 * 10^3(675 - 442)}{2014.6\ * 10^3} = 0.7701$$

$\dot{m}_{St} = 0.7701\ \text{kg/s}$

$Q_{Eva} = \dot{m}_{St} * h_{fg} = 0.7701 * 2014.6\ * 10^3 = 8716.2764 * 10^3$

$Q_{Eva} = 8716.2764\ \text{kW}$

Superheater

The function of superheater in the thermal power plant is to remove the last traces moisture (1 to 2%) from the saturated steam coming out of the boiler and to increase its temperature sufficiently above saturation temperature [6].

Superheaters are commonly classified as either convective superheaters, radiant superheaters or combined superheaters, depending how heat is transferred from the gases to steam.

The superheating raises overall cycle efficiency as well as avoids too much condensation in the last stage of the turbine (below 12%) to prevent the blade erosion [25].

Energy balance of the convective superheater:

$Q_{SH} = \dot{m}_{FG} c_{pFG} (T_{FG1} - T_{FG2}) = \dot{m}_{St} c_{pSt} (T_{St1} - T_{St2})$

$Q_{SH} = U A_s F_c \Delta T_{lm}$

Where:

$\dot{m}_{Ste} = \left(n_t \frac{\pi d_i^2}{4} \right) \frac{C_{Ste}}{V_g}$

The maximum posible outlet temperature of steam

The product of mass flow rate and the specific heat as a mater of convenience, is defined as the fluid capacity rate (FCR = *C*).

$\dot{m}_{FG} c_{pFG} = C_{FG} = \text{hot fluid capacity rate}$

$C_{FG} = 6.3672 * 1.045 = 6.65\ \text{kW}$

$\dot{m}_{St} c_{pSt} = C_{St} = \text{cold fluid capacity rate}$

$C_{St} = 0.7701 * 8.75 = 5.29\ \text{kW}$

$C_{min} = \text{the minimum fluid capacity rate } (C_{FG} \text{ or } C_{St})$

$C_{min} = C_{St} = 5.29\ kW$

$C_{max} = \text{the maxmum fluid capacity rate } (C_{FG} \text{ or } C_{St})$

$C_{\max} = C_{\mathrm{FG}} = 6.65\ \mathrm{kW}$

$$\varepsilon = \frac{C_{\mathrm{FG}}(\mathrm{T_{FG1}} - \mathrm{T_{FG2}})}{C_{\min}(\mathrm{T_{FG1}} - \mathrm{T_{St2}})} = \frac{6.65(750 - 573)}{5.29(750 - 180)} = \frac{1177.05}{2406.95} = 0.489$$

$\varepsilon = 0.49$

Once the heat effetiveness is known, the total heat trasfer rate is calculated as follows.

$\mathrm{Q} = \varepsilon * C_{\min} * (\mathrm{T_{FG1}} - \mathrm{T_{St2}}) = 0.49 * 5.29 * (750 - 180) = 1179.4\ \mathrm{kW}$

$\mathrm{Q} = 1179.4\ \mathrm{kW}$

Therefore:

$\mathrm{Q} = \mathrm{Q_{SH}} = \dot{\mathrm{m}}_{\mathrm{St}} \mathrm{c_{pSt}} (\mathrm{T_{St1}} - \mathrm{T_{St2}})$

$1179.4 = 0.6046 * 8.75(\mathrm{T_{St1}} - 180)$

$$\mathrm{T_{St1}} = \frac{1179.4}{0.6046 * 8.75} + 295 = 517.9384$$

$\mathrm{T_{St1}} = 518℃$

Logarithmic mean temperature difference (LMTD)

The logarithmic mean temperature difference, $\Delta \mathrm{T_{lm}}$ is given as follows:

$$\Delta \mathrm{T_{lm}} = \frac{\Delta \mathrm{T_2} - \Delta \mathrm{T_1}}{\ln(\Delta \mathrm{T_2}/\Delta \mathrm{T_1})}$$

Where:

$\Delta \mathrm{T_1} = \mathrm{T_{FG1}} - \mathrm{T_{St1}} = 750 - 518 = 232℃$

$\Delta \mathrm{T_2} = \mathrm{T_{FG2}} - \mathrm{T_{St2}} = 573 - 180 = 393℃$

$$\therefore \Delta \mathrm{T_{lm}} = \frac{393 - 232}{\ln(393/232)} = \frac{161}{\ln(1.6982)} = 305.4609$$

$\Delta \mathrm{T_{lm}} = 305.46℃$

Overall heat trasfer coefficient (U)

Properties of steam at mean temperature (T = 406.5℃)

$\mathrm{c_p} = 8.75\ \mathrm{kJ/kg}, \mu = 22.7 * 10^{-6} \mathrm{N.s/m^2}, \mathrm{k} = 0.0929 \mathrm{W/m.K}, \mathrm{Pr} = 2.15$

Properties of flue gas at mean temperature (T = 561.5℃)

$c_p = 1.045\ \text{kJ/kg}, \mu = 9.69 * 10^{-3}\text{N.s/m}^2, k = 20.7 * 10^{-2}\ \text{W/m.K}, Pr = 0.883$

The overall heat trasfer coefficient, U is given by:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o}$$

Where: h_i may be estimated from an internal flow correlation and h_o from external flow.

Therefore:

Reynolds number for the flow of steam through tube

$$Re = \frac{4 * \dot{m}}{\pi * d_i * \mu} = \frac{4 * 0.6046}{\pi * 0.05 * 22.7 * 10^{-6}} = \frac{2.4184}{3.5657 * 10^{-6}} = 678.238 * 10^3$$

Accordingly, the flow is turbulent and the convection coefficient may be computed as:

$$Nu = 0.023(Re)^{0.8}(Pr)^{0.4} = 0.023(678.238 * 10^3)^{0.8}(2.15)^{0.4} = 1444.8039$$

$$Nu = \frac{h_i * d}{k} = 0.023(Re)^{0.8}(Pr)^{0.4} = 1444.8039$$

$$h_i = \frac{0.0929 * 1444.8039}{0.05} = 2684.4456$$

$$h_i = 2684.4456\ \text{W/m}^2\text{.K}$$

flow of flue gas outside the tube

$$Nu = \frac{h_o * L}{k} = 0.023(Re)^{0.8}(Pr)^{0.4}$$

$$Re = \frac{\dot{m}}{L * \mu} = \frac{6.3672}{1.8 * 9.69 * 10^{-3}} = 365$$

$$h_o = \frac{365 * 20.7 * 10^{-2}}{1.8} = 41.975$$

$$h_o = 41.975\ \text{W/m}^2\text{.K}$$

Then, by substitution in to the above equaton

$$\frac{1}{U} = \frac{1}{2684.4456} + \frac{1}{41.975} = 0.02419$$

$$U = 41.3288\ \text{W/m}^2\text{.K}$$

The surface area of the superheater (As)

To find the correction factor (F_c) we have to find P (temperature ratio) and R (capacity ratio).

$$P = \frac{T_{FG1} - T_{FG2}}{T_{St1} - T_{St2}} = \frac{750\ - 573}{518 - 295} = \frac{177}{223} = 0.79$$

$$R = \frac{T_{St1} - T_{St2}}{T_{FG1} - T_{FG2}} = \frac{518 - 295}{750\ - 573} = \frac{223}{177} = 1.26$$

With the values of P = 0.79 and R = 1.26 we get Fc = 0.79 from correction factor chart [35].

Therefore:

$$Q_{SH} = UA_sF_c\Delta T_{lm}$$

$$A_s = \frac{Q_{SH}}{UF_c\Delta T_{lm}} = \frac{1179.4 * 10^3}{41.3288 * 0.79 * 305.46} = 142.04$$

$$A_s = 142.04\ m^2$$

Length of required tube (L)

$$A_s = \pi * d * L$$

$$L = \frac{A_s}{\pi * d} = \frac{142.04}{\pi * 0.05} = 904.2547$$

$$L = 904.25\ m$$

Condenser

The condenser of a steam power plant is a heat exchanger in which steam is condensed to liquid water. The tubes are of thin wall construction with aspecified diameter, and steam condenses on their outer surface. The following are assumptions taken for this calculation:

Negligible heat transfer between exchanger and surroundings and negligible kinetic and potential energy changes; Tube internal flow and thermal conditions fully developed; Negligible thermal resistance of tube material and fouling effects and taking constant properties [36].

Determination of cooling water exit temperature

Propertie of wate from water property table assuming the constant mean temperature Tc ≈ 64℃ =337 K.

$c_p = 4.18\ kJ/kg.K\ ; \mu = 855 * 10^{-6}\ N.s/m^2; k = 0.635\ W/m.K\ , \rho = 997\ kg/m^2$ and $Pr = 5.83$

The thermal resistance of tube material and fouling effects are neglected.and let us take the maximum posible flow rate that is 1kg/s [37].

We know that:

$$\dot{m}_w = \rho\, V\, A_c \leftrightarrow V = \frac{4 * \dot{m}_w}{\rho * \pi * d_i^2}$$

$$V = \frac{4 * 1}{997 * \pi * (0.05)^2} = 0.51\ m/s$$

Then, Reynolds number.

$$Re = \frac{\rho\, Vd}{\mu} = \frac{997 * 0.51 * 0.05}{855 * 10^{-6}} = \frac{25.4648}{855 * 10^{-6}} = 29783.3812$$

This shows that the flow is turbulent since Re > 2300

Using the relation,

$$\bar{N}u = 0.023(Re)^{0.8}(Pr)^{1/3} = 0.023(29783.3812)^{0.8}(5.83)^{1/3} = 156.9909$$

$$\bar{N}u = 157$$

Substiting the values in the above equation we get:

$$\bar{N}u = \frac{\bar{h} * d}{k} = 157$$

$$\bar{h} = \frac{157 * 0.635}{0.05} = 1993.7852$$

$$\bar{h} = 1993.7852\ W/m^2.K$$

Throughout the condeser the steam remains at constant temperature. Hence C_{max} is infinity and C_{min} is obviously for cooling water.

Thus:

$$C_{max} = C_h = \infty$$

$$C_{min} = C_W = \dot{m}_w * c_{pw} = 1 * 4.18 * 10^3 = 4180\ W/K$$

Capacity ratio (R)

$$R = \frac{C_{min}}{C_{max}} \cong 0$$

During the condition R = 0 it is obvious no matter how large the exchanger is or how large the overall trasfer coefficient is, the effectiveness (ε) for counter flow may be 50%-100% [26]. Therefore for this work I have taken the average effectiveness of the two limits.

$$Q_{Con} = \varepsilon * C_{min} * (T_{St1} - T_{CW1})$$

$$Q_{Con} = 0.75 * 4180 * (100 - 27) = 228.855$$

$$Q_{Con} = 228.855\ W$$

$$\varepsilon = \frac{T_{CW2} - T_{CW1}}{T_{St1} - T_{CW1}} = \frac{T_{CW2} - 27}{100 - 27} = 0.75$$

$$T_{CW2} = (0.75 * 73) + 27$$

$$T_{CW2} = 81.75$$

$$T_{CW2} = 82\ ℃$$

Then:

$$\varepsilon = 1 - \exp(-NTU)$$

$$0.75 = 1 - e^{-NTU}$$

$$-NTU = \ln(1 - 0.75) = -1.386$$

$$NTU = 1.386$$

The length of the tube

$$NTU = \frac{UA_s}{C_{min}} = \frac{\bar{h}A_s}{C_{min}} = \frac{\bar{h}(\pi dL)}{C_{min}}$$

$$L = \frac{NTU * C_{min}}{\bar{h} * \pi * d} = \frac{1.386 * 4180}{2313.94 * \pi * 0.05} = \frac{5793.48}{363.47} = 15.949$$

$$L = 16\ m$$

The rate of steam condensation

$$\dot{m}_{St} * h_{fg} = \dot{m}_{CW} * c_{pCW} * (T_{CW2} - T_{CW1})$$

$$\dot{m}_{St} = \frac{\dot{m}_{CW} * c_{pCW} * (T_{CW2} - T_{CW1})}{h_{fg}}$$

$$\dot{m}_{St} = \frac{1 * 4.18 * (82 - 27)}{2257} = 0.102$$

$\dot{m}_{St} = 0.102\ m/s$

In my thesis area, since there is large amount river water coming from the local river calling Shay river, therefore no need of cooling water circulation.

5.4.3 The principle losses in the boiler

The flue gas consists CO_2, SO_2, N_2, O_2, and H_2O, so during combustion process some of the heat generated in the combustion chamber may be lost with these flue gas compounds at the end of the process based on their corresponding mass value as calculated before and summarized in table 6.2.

Therefore CO_2 = 1.7172 kg, H_2O = 0.4332 kg, SO_2 = 0.001 kg, N_2 = 5.7547 kg, O_2 = 0.4764 with the total excess air of 3.9333 kg

The principal losses in the boiler are calculated based on the analysis of

Percent of heat carried away by dry products (CO_2 and SO_2)

$$Q_{CP} = \frac{(m_{CO_2} + m_{SO_2})c_p(T_{FG} - T_a)}{\text{GCV of Coffee Husk}} * 100\ \%$$

Where: m_{CP} is mass of dry combustion product

c_p is specific heats of cobustion product = 1.045 kJ/kg.k

T_{FG} and T_a are the exiting gas and reference state temperature respectively.

GCV is heat of coffee husk in kJ/kg

$$Q_{(CO_2+SO_2)} = \frac{(1.7172 + 0.001) * 1.15 * (160 - 30)}{18980} * 100\ \% = \frac{256.8709}{18980} * 100\ \%$$

$$Q_{(CO_2+SO_2)} = 1.3534\ \%$$

Percent of Heat carried away by water vapour (H_2O)

This is the loss of heat due to evaporation of water formed by H_2 and moisture in the husk

$$Q_{H_2O} = \frac{(9H_2 + M) * [584 + c_p(T_{FG} - T_a)]}{\text{GCV of Coffee Husk}} * 100\ \%$$

Where: H_2 - kg of H_2 in 1 kg of coffee husk

M – Percent moisture in 1kg of coffee husk

$m_{H_2O} = 9H_2O + M$ = 0.4332 (calculated value)

c_p = Specific heat of steam (1.013 kJ/kg °C)

584 is the latent heat corresponding to the partial pressure of water vapour.

$$Q_{H_2O} = \frac{0.4332 * [584 + 1.013(160 - 30)]}{18980} * 100\ \% = \frac{310.0369}{18980} * 100\%$$

$$Q_{H_2O} = 1.6335\ \%$$

Percent of heat carried away by oxygen and nitrogen (O_2 and N_2)

$$Q_{(O_2+N_2)} = \frac{(m_{O_2} + m_{N_2})c_p(T_{FG} - T_a)}{\text{GCV of Coffee Husk}} * 100\ \%$$

Where: $m_{O_2} = 0.4764 + 1.7468 = 2.2232$ kg

$m_{N_2} = 5.7547 + 2.1868 = 7.9415$ kg

$$Q_{(O_2+N_2)} = \frac{(2.2232\ + 7.9415) * 1.05 * (160 - 30)}{18980} * 100\ \% = \frac{1387.4815}{18980} * 100$$

$$Q_{(O_2+N_2)} = 7.3102\ \%$$

Percent of heat in the steam generated

$$Q_{Ste} = \frac{m_{Ste} * (h_1 - h_4)}{\text{GCV of Coffee Husk}} * 100\ \% = \frac{Q_{Eco} + Q_{Eva} + Q_{SH}}{18980} * 100\ \%$$

$$Q_{Ste} = \frac{825.0618 + 8716.2764 + 1179.4}{18980} * 100\ \% = \frac{10720.7382}{18980} = 56.4844\ \%$$

$$Q_{Ste} = 56.48\ \%$$

Table 5.5 Summery of the balance sheet of the boiler

Heat type	Value (in kJ/kg)	Value (in %)
Q_{Ste}	10720.7382	56.48
$Q_{(CO_2+SO_2)}$	256.8709	1.3534
Q_{H_2O}	310.0369	1.6335
$Q_{(O_2+N_2)}$	1387.4815	7.3102
Q_{APH}	1193.672	6.2891
Sum	13868.7995	73.0662

From the above table:

Total heat carried away by flue gases:

$$Q_{FG} = Q_{(CO_2+SO_2)} + Q_{H_2O} + Q_{(O_2+N_2)} = 256.8709 + 310.0369 + 1387.4815 = 1954.3893$$

$$Q_{FG} = 1954.3893 \text{ kJ}$$

$$\text{Then, Proportion of CV in flue gas} = \frac{Q_{FG}}{CV} * 100\% = \frac{1954.3893}{18980} * 100\% = 10.297\%$$

Combustion efficiency = 100 – 10.297 = 89.7%

Therefore, other losses calculated as follows:

Other losses = 100 – 73.0662 = 26.9338 %

26.93 % of heat goes to the surrounding in different forms.

CHAPTER SIX

DESIGN OF COFFEE DRYER

The term drying refers an operation in which the liquid generally water present in a wet solid is removed by vaporization to get a relatively liquid free solid product. Drying of a solid does not demand or ensure complete removal of the moisture. Sometimes it is desirable to retain a little moisture in the solid after drying.

Drying may be defined as the removal of moisture from a substance. In general drying is accomplished by thermal techniques and thus involves the application of heat, most commonly by convection from current of air. Throughout the convective drying of solid materials two processes occur simultaneously namely transfer of energy from the local environment in the dryer and transfer of moisture from within the solid. Therefore this unit operation may be considered as simultaneous heat and mass transfer operation.

6.1 Introduction to Coffee Drying

Drying of coffee is critical process to both wet and dry processing. Flavor, bean color and other quality factors are materially affected at this stage. Production of high quality beans requires the correct combination of temperatures, duration of heat, ventilation and light. Depending on the processing method employed, the whole fruit, the crushed fruit, parchments (bean enclosed by the inner integument), or naked beans may be dried at this drying process.

Drying can be initiated directly after harvest or the crop can be sorted in one way or another before drying. Only ripe cherries are appropriate for the wet-processing of coffee (represented by several methods that share the step of separating the seeds from fruit tissues before drying).

The coffee fruit or ‘cherry’ provides an additional degree of physical protection to the beans. Cherry coffee, however, requires more time and energy to dry since it has approximately twice the quantity of water per unit of dry product as does parchment [16].

Parchment coffee has a fairly uniform initial moisture content, around 55-60%, whereas dry coffee cherries, because of strip harvesting, can vary in moisture content from 25 to 70%. Drying methods vary depending on the processing system [10].

Drying process takes from 5 to 10 days for fresh cherries depending on the local temperature. Sun drying of cherries take place on heavy duty polythene sheets spread on either slightly graded ground beds, cement floors, or drying tables. It has high labor and space requirements.

The drying energy requirement is reduced from that indicated by sun drying by the Removal of fruit tissues in the pulping step of wet-processing. So the time required to achieve dryness is very much reduced.

Mechanical dryers reduce weather risks, take up less space, require less labor, and are faster than sun drying. However, such equipment is typically expensive, and often expensive to run, and does not accept fully wet coffee. Thus in addition to the mechanical drying facility some form of pre drying equipment, typically a sun drying terrace, must also be provided.

Pre-drying in the sun followed by machine drying is often practiced as a means of reducing capital and energy costs. Over or under drying at incorrect temperatures or for inappropriate lengths of time adversely affect both bean quality and storing qualities. Moisture content should be reduced from to 10-15% as soon after washing as possible [47].

6.2 Classification of Dryers and Drying Process

Drying processes and equipment may be categorized according to several criteria including the nature of material and the method of heat supply and the method of operation.

In general industrial dryers may be classified according to the physical characteristics of the material being dried, the method of transferring the thermal energy to wet product, the source of the thermal energy, the method of physical removal of the solvent vapor, and the method of dispersion (in case of wet solids) in the drying operation.

It can be classified based on mode of operation such as batch or continuous. In case of batch dryer the material is loaded in the drying equipment and drying proceeds for a given period of time, whereas in case of continuous mode the material is continuously added to the dryer and dried material continuously removed. In some cases vacuum may be used to reduce the drying temperature. Some dryers can handle almost any kind of material, whereas others are severely limited in the style of feed they can accept [40, 41].

6.2.1 Types of Continuous Dryer

I. Rotary Dryer

The rotary drier is basically a cylinder, inclined slightly to the horizontal, which may be rotated, or the shell may be stationary and an agitator inside may revolve slowly. In either case the wet material is fed in at the upper end, and the rotation or agitation advances the material progressively to the lower end where it is discharged. In direct heat revolving rotary driers hot air or a mixture of flue gases and air travels through the cylinder. The feed rate, the speed of rotation or agitation, the volume of heated air or gases, and their temperature are so regulated that the solid is dried just before discharge.

II. Drum Dryer

This type of dryer mainly handles the materials that are too thick for a spray dryer and too thin for a rotary dryer. The solid collects on an apron in front of the knife and rolls to a container or to a screw conveyor. The operation of the drum drier is continuous so the drum is rotated continuously. In drum dryers a liquid containing dissolved solids or slurry carrying suspended solids forms a thin layer on the outside surface of a large rotating drum. For a single drum unit thickness of the film can be controlled by an adjustable scraping blade. In case of a double drum unit thickness can be controlled by the gap between the drums. A gas, normally air may be blown over the surface for rapid removal of moisture. The rotation of the drum adjusted so that all of the liquid is fully vaporized and a dried deposit can be scrapped off with the help of flexible or adjustable knife.

III. Flash Dryer

These types of dryer are mainly used for drying of heat sensitive or easily oxidizable materials. The flash driers are similar in their operating principle to spray dryer. The materials that are to be dried (solid or semisolid) are dispersed in finely divided form in an upward flowing stream of heated air. A solid particle takes few seconds to pass from the point of entry into the air stream to the collector. The drying rate is very high for these dryers but the solid temperature does not rise much because of the short residence time. A flash dryer is not suitable for particles which are large in size or heavy particles.

IV. Fluidized Bed Dryer

Fluidized bed dryer consist of a steel shell of cylindrical or rectangular cross section. A grid is provided in the column over which the wet material is rests. In this type of dryer, the drying gas is passed through the bed of solids at a velocity sufficient to keep the bed in a fluidized state. Mixing and heat transfer are very rapid in this type of dryers. Fluidized bed dryers are suitable for granular

and crystalline materials. Rapid and uniform heat transfer, short drying time, good control of the drying conditions are the main advantage of this type of dryer

V. Screen Conveyor Dryers

In these types of dryer the solids to be dried are fed on to endless, perforated conveyor belt through which hot air is forced. The belt is housed in a long rectangular drying chamber or tunnel. The chamber is divided into series of separate sections, each with its own fan and air heater. Then the solid is carried through the tunnel and discharged at the opposite end. Thermal efficiency of this type of dryer is high.

6.2.2 Types of Batch Dryer

I. Tray Dryer

Tray dryers usually operate in batch mode, use racks to hold product and circulate air over the material. It consists of a rectangular chamber of sheet metal containing trucks that support racks. Each rack carries a number of trays that are loaded with the material to be dried. Hot air flows through the tunnel over the racks. Some moist air is continuously vented through exhaust duct; makeup fresh air enters through the inlet. Then, when the process is completed the racks with the dried product are taken to a tray dumping station.

These types of dryers are useful when the production rate is small. They are used to dry wide range of materials, but have high labor requirement for loading and unloading the materials, and are expensive to operate. Drying operation in case of such dryers is slow and requires several hours to complete drying of one batch

II. Pan Dryer

A pan drier has a jacketed round pan in which a stirrer (mill) revolves slowly, driven from below. The slow moving stirrer exposes fresh surfaces and thereby raises the rate of evaporation and hence, of drying. The pan drier is a batch machine and is limited to small batches. It may be used first to evaporate a solution to its crystallizing concentration and then can function as a crystallizer by sending cold water instead of steam into the jacket.

III. Agitated Vacuum Dryer

It is similar in principle to a pan dryer and essentially consists of a jacketed cylindrical vessel arranged for hot water, steam or a suitable thermal fluid flow through the jacket for heating. Doors are provided on the shell, at the top for loading the feed material and at the bottom for discharging. Due to the agitation of the product in the agitated vacuum dryer the drying time is substantially reduced.

Drying processes can also be categorized according to the physical state of the feed such as wet solid, liquid, and slurry. Type of heating system such as conduction, convection and radiation is another way of categorizing the drying process. Heat may be supplied by direct contact with hot air at atmospheric pressure, and the water vaporized is removed by the air flowing. Heat may also be supplied indirectly through the wall of the dryer from a hot gas flowing outside the wall or by radiation.

To reduce heat losses most of the commercial dryers are insulated and hot air is recirculated to save energy. Now many designs have energy saving devices, which recover heat from the exhaust air or automatically control the air humidity. Computer control of dryers in sophisticated driers also results in important savings in energy.

6.2.3 Wet Solid Drying Process

In drying process the goal of many operations is not only to separate a volatile liquid, but also to produce a dry solid of specific size, shape, porosity, texture, color or flavor. So, well understanding of liquid and vapor mass transfer mechanism prior to design work is strongly recommended.

In drying of wet solids, drying characteristics, constant rate period, falling rate period, moisture content and diffusion concept are the main factors which essentially are used in process design. Calculation of dryers should be defined in accordance with mass and heat transfer principles, process conditions and drying behavior [35, 42].

6.2.3.1 Drying characteristics.

The drying characteristics of wet solids is best described by plotting the average moisture content of material against elapsed time measured from the beginning of the drying process. The drying rate curve is derived from the drying time curve by plotting slopes of the latter curve against the corresponding moisture content. The distinctive shape of this plot illustrates the constant rate period, terminating at the critical moisture content, followed by the falling-rate period.

The variables that influence the constant rate period are the so called external factors consisting of gas mass velocity, thermodynamic state of the gas, transport properties of the gas and the state of aggregation of the solid phase changes in gas temperature, humidity and flow rate will have a profound effect on the drying rate during this period. The controlling factors in the falling rate period are the transport properties of the solids and the primary design variable is temperature.

The characteristic drying behavior in these two period are markedly different and must be considered in the design. In the context of economics, it shall be costlier to remove water in the falling rate period

than it is removed in the constant rate period accordingly it is recommended to extend the length of the constant rate period with respect to falling rate as much practicable.

6.2.3.2 Constant rate period.

It is the drying period during which the rate of liquid removal per unit of drying surface is constant. In which the first major drying period is called the constant rate period. During this period, the solid is so wet that a continuous film of water exists over the entire drying surface and this water acts as if the solid were not there. If the solid is nonporous, the water removed in this period is mainly superficial water on the solid's surface. The evaporation from a porous material is subject to the same mechanism as that from a wet bulb thermometer. The drying rate in constant rate period can precisely be calculated which is a steady state relationship between heat and mass transfer.

6.2.3.3 Moisture Content

It is the ratio of water and water vapor by mass to the total volume (gram per cubic meter). It has also two parts.

Critical Moisture Content

The critical moisture content is the average material moisture content at which the drying rate begins to decline. The critical point occurs when the superficial moisture is evaporated. In porous solids this point is reached when the rate of evaporation become the same as obtained by the wet bulb evaporative process.

Equilibrium Moisture Content

The equilibrium condition is independent of drying rate or drying method but is a material property. Only hydroscopic materials have equilibrium moisture content under specific conditions of temperature and humidity.

6.2.3.4 Falling rate period.

The part of drying time which the drying rate varies in time. Estimation of the drying for the falling rate period primarily depends on experimental data. However, the drying rate during this period is considered to be a complex function of transport, physical, and thermodynamic properties of the solid phase, as well as of the same properties of the gas phase. Since the mechanisms of internal liquid and vapor flow during falling rate drying are complex, the falling rate can rarely be described with mathematical precision.

6.2.4 Determining of Drying Time

The following methods are generally used in order of preference for determining of drying time:

1. Conduct tests in a laboratory dryer simulating conditions in the commercial machine or obtain performance data directly from the commercial machine.
2. If the specific materials is not available obtain drying data on similar material by either of the above methods. This is subject to the investigator's experience and judgment.
3. Estimate drying time from theoretical Equation or any such appropriate theoretical formulas.

Working principle

As shown in Figure 6.1, first the air impelled by a blower and passed through a duct and it is heated by a set of heat exchanger and then it entered the dryer in countercurrent flow with the coffee. The air outlet is opposite to the coffee inlet. The solid coffee is feeding by a container and is removed on the side opposite to the coffee inlet. The dryer cylinder is 9.46 m long with a diameter of 1.54 m.

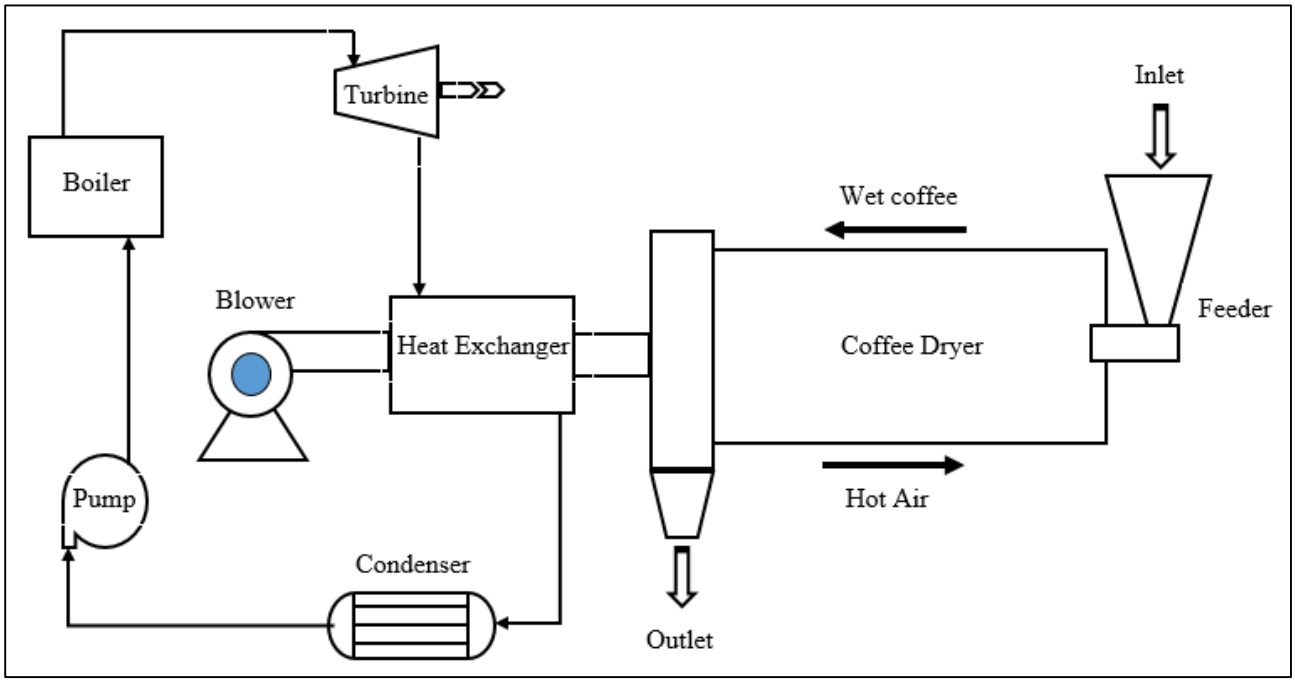

Figure 6.1 Schematic of an integrated counter rotary coffee dryer with main plant components

Rotary dryer is a class of dryer commonly used in industry to dry particulate solids. It is made of a long cylindrical shell that is rotated. The shell is usually slightly inclined to the horizontal to induce solids flow from one end of the dryer to the other. In direct heat rotary dryers, a hot gas flowing through the dryer provides the heat required for vaporization of the water. To promote gas-solid contact, most direct heat dryers have flights placed parallel along the length of the shell, which lift solids and make them rain across the dryer section. The transport of solids through the drum takes

place by the action of the solids cascading from the flights, each cascade comprising the cycle of lifting on a flight and falling through the air stream.

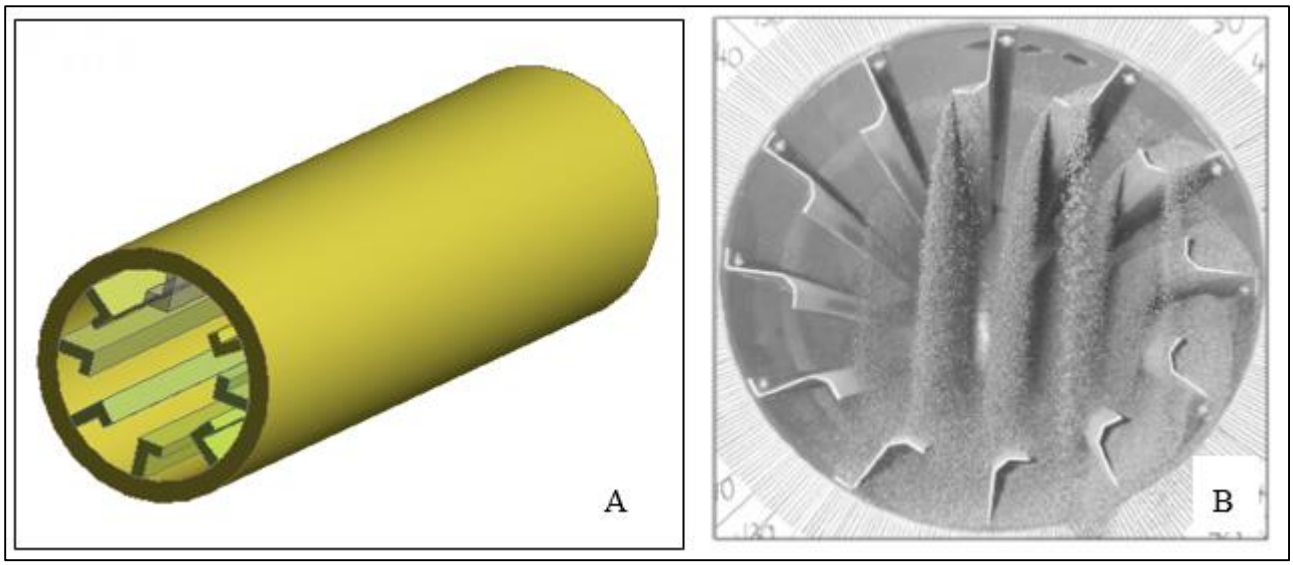

Figure 6.2 A. A rotary dryer B. Solids cascading inside the dryer [50]

6.3 Selection of Drying Process and Equipment

Dryer and drying process selection for a specific operation is a complex problem and many factors have to be taken into account. Though, the overall selection and design of a drying system for a particular material is dictated by the desire to achieve a favorable combination of a product quality and process economics. In general with respect to the rate and total drying time dryer performance is dependent on the factors such as air characteristics, product characteristics, equipment characteristics etc.

As a consequence of dryer specialization the selection of the type of dryer appropriate to the specific product to be dried becomes a critical step in the specification and design of the processing plant. The choice of the wrong type of dryer can lead to inefficient operation, reduced product quality, and loss of profit.

6.4 Design Calculation of dryer

The design calculation is implemented on a continuous mode rotary dryer of wet solid drying process system and heat is supplied by direct contact with hot air and the water vaporized is removed by the air flowing. Physical characteristics of the drying material (cherry coffee, parchment coffee and green coffee), the end quality of the product coffee, cost and simplicity of equipment, need of labor power, knowledge required for operating and the likes are my basic considerations during selection of the dryer type.

In the dry process the red cherries which initially contain approximately 70% moisture content are sun dried until they reach approximately 10-12% moisture content. After the cherries are dried they are put through a dry mechanical pulping process in which the green coffee bean is separated from the outer residue material (skin and husk) of the cherry. According to the data from the owners of the industries of the studying area the minimum capacity of the dry mechanical pulping machines is 700 kg/h. therefore for this thesis have used the same drying capacity for the selected dryer in the following design calculation [43].

Once the capacity of the dryer is known, the drying gas flow rate, its temperature and humidity are decided considering a number of factors. And the following moisture & enthalpy balances need to be satisfied. The gas and solid temperatures at the stage boundaries are obtained by moisture and energy (enthalpy) balances. The number of heat transfer unit for each zone is also calculated.

In design of dryer a fairly large number of variables are involved such as solid to be dried per hour, the inlet and exit moisture contents of the solid, the critical and equilibrium moisture contents, temperature and humidity of the drying gas. The design procedure based on the basic principles and available correlations is discussed below.

Mass Balance:

$$\dot{m}_{G2}Y_2 + \dot{m}_{S1}X_1 = \dot{m}_{G1}Y_1 + \dot{m}_{S2}X_2 \quad \text{……6.1}$$

Where, $\dot{m}_G$ is air flow rate in kg dry air /h, $\dot{m}_S$ is solid flow rate in kg dry solid /h, 'Y' and 'X' are absolute humidity in kg water/kg dry air and solid moisture content dry basis (by water/kg dry solids) respectively.

Energy Balance:

$$\dot{m}_{G2}H_{G2} + \dot{m}_{S1}H_{S1} = \dot{m}_{G1}H_{G1} + \dot{m}_{S2}H_{S2} + q \quad \text{……..……6.2}$$

Where H_G is thermal energy of air kJ/kg of dry air, H_S refers thermal energy of product kJ/kg dry solid and q is energy loss from the drying system

Therefore:

$$H_G = C_s(T_G - T_o) + YH_L$$

$$C_s = 1.005 + 1.88Y \text{ and}$$

$$H_L = \text{latent heat of vaporization} = 2500 \text{ KJ/kg}$$

$$H_S = C_{pS}(T_S - T_o) + XC_{pw}(T_S - T_o)$$

The gas and solid temperatures at the section boundaries are obtained by moisture and energy (enthalpy) balances. The number of heat transfer unit for each zone is calculated. For the stages.

The number of heat transfer units is given by:

$$N_{TU} = \frac{T_{G2} - T_{G1}}{\Delta T_m} \quad \ldots\ldots 6.3$$

Where: N_{TU} is heat transfer unit for a section ΔT_m is mean temperature difference and T_G is gas temperature.

The total length of dryer is given by:

$$L = (L_{TU})_I (N_{TU})_I + (L_{TU})_{II} (N_{TU})_{II} + (L_{TU})_{III} (N_{TU})_{III} \ldots\ldots 6.4$$

Length of transfer unit (L_{TU})

$$L_{TU} = G' CH / U_a$$

$$L_{TU} = 0.0063 CH. D. G_S^{0.84}$$

Here, CH = Average humid heat, and D = dryer diameter

The shell diameter is calculated from the dry gas flow rate and suitable gas flow velocity or gas mass flow rate.

Therefore volumetric gas solid heat transfer coefficient.

$$U_a = \frac{273 (G')^{0.67}}{D} \quad \ldots\ldots 6.5$$

Here, G' = gas mass flow rate (kg/m^2.h) and D = dryer diameter

Solid retention time:

$$RT = \frac{0.23 L}{S N^{0.9} D} \pm 1.97 \frac{B L G'}{F} \quad \ldots\ldots 6.6$$

(+ve sign is for counter flow: − ve sign is for parallel flow of the gas and solid)

Where:

RT is the retention time (min), S is slope of the dryer (m/m), G' is gas mass flow rate (kg/m^2.h), F represents feed rate (kg/m^2.h) dry basis, L is dryer length (m), N and d_p are speed (rpm) and Weight average particle diameter (micron) respectively.

$B = 5 (d_p)^{-0.5}$

d_p = D = Dryer diameter

Design calculation of rotary dryer

In the wet solid drying process three sub processes are take place. Therefore the dryer is divided into three zones and the section wise calculation of temperature and humidity of the stream can be obtained by material and energy balance [44].

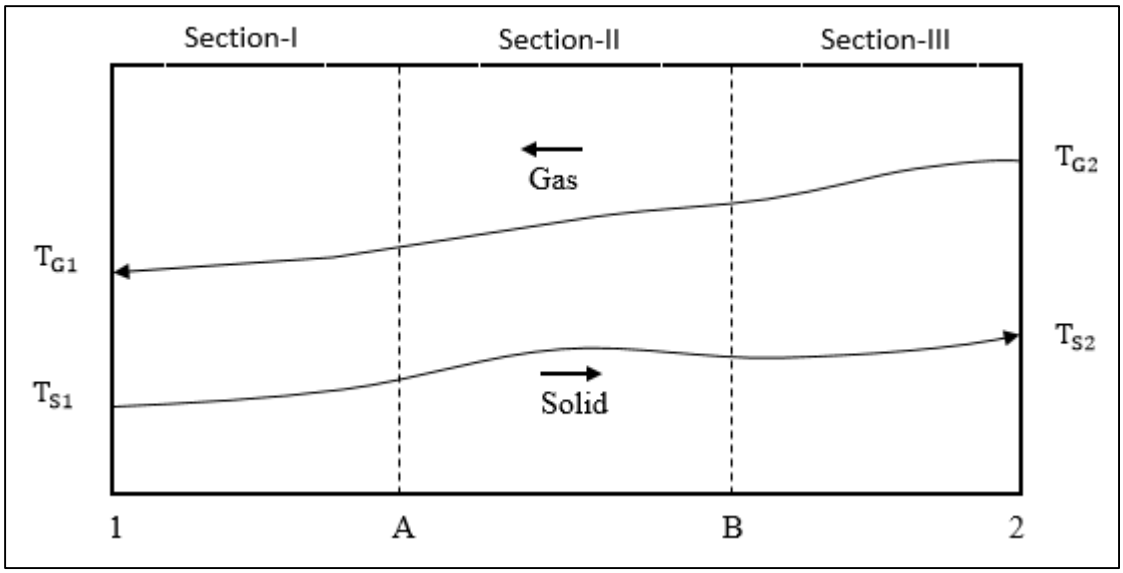

Figure 6.3 Temperature profile for solid and gas in a counter rotary dryer

Basis of calculation is 1 hour operation and the initial and final moisture values of the solid (Cherry, Parchment, and Washed coffee) are taken from literature data (Dry coffee processing hand book) which are tabulated data conducted in the laboratory of Panama research [43].

In Sheka Zone there are two types of dry coffee processing machineries (local and foreign) with a working capacity of 700-1000 and 1200-1500 kg/h respectively [15]. Since the dryer is the supplier for the processing machineries so, as much as possible it must be work with the same working capacity of the pulping machine. Therefore to make the design safe the minimum working capacity 700 kg/h is taken for this work.

For Cherry Coffee

Initial moisture = 70%

Final moisture = 10%

Drying rate = 700 kg/h

If the dry solid (Dry coffee cherry) contains

Mass of dry cherry = $\dot{m}_S$ = 700(1 - 0.1) = 630 kg/h

Moisture in the wet cherry = X_1 = 70/30 = 2.3333

Moisture in the dry cherry = X_2 = 10/90 = 0.1111

Water evaporated $= \dot{m}_S(X_1 - X_2)$ = 630(2.3333 – 0.1111) = 1399.986 ≅ 1400 kg

Inlet gas thermal energy calculation

Let us assume that the exit temperature of the air is T_{G1}= 60^{o}C and for solid T_{S2} = 100^{o}C and the hot air enters the dryer (T_{G2}) at 135^{o}C with a humidity (Y_2) of 0.015 (from table)

Now enthalpy of different streams (suppose reference temperature (T_o) = 0^{o}C)

$H_{S1} = C_{pS1}(T_{S1} - T_o) + X_1 C_{pw}\,(T_{S1} - T_o)$

Where: $C_{pS1} = 0.85$ and $C_{pw} = 4.187$

$H_{S1} = (0.85 + 4.187X_1)(T_{S1} - 0) = (\,0.85 + (4.187)2.3333)(26 - 0)$

$H_{S1} = 276.1077$ KJ/kg

$H_{S2} = (0.85 + 4.187X_2)(T_{S2} - 0) = (\,0.85 + (4.187)0.1111)(100 - 0)$

$H_{S2} = 131.5176$ KJ/kg

$H_{G1} = C_s(T_{G1} - T_o) + Y_1 H_L = [1.005 + 1.88Y_1][T_{G1} - T_o] + Y_1 H_L$

$H_{G1} = [1.005 + 1.88Y_1][60 - 0] + Y_1(2500) = 60.3 + 2612.8Y_1$

$H_{G2} = C_s(T_{G2} - T_o) + Y_2 H_L = [1.005 + 1.88Y_2][T_{G2} - T_o] + Y_2 H_L$

$H_{G2} = [1.005 + 1.88(0.015)][135 - 0] + 0.015(2500) = 176.982$ KJ/kg

Rate of mass of gas Calculation:

Using overall mass balance equation (equation 6.1)

$\dot{m}_{G2}Y_2 + \dot{m}_{p,1}X_1 = \dot{m}_{G1}Y_1 + \dot{m}_{p,2}X_2$

Where: $\dot{m}_{G2} = \dot{m}_{G1} = \dot{m}_G$ and $\dot{m}_{S1} = \dot{m}_{S2} = \dot{m}_p$

$\dot{m}_G(Y_1 - Y_2) = \dot{m}_S(X_1 - X_2)$

$\dot{m}_G(Y_1 - 0.015) = 1400 = $ Water evaporated

$\dot{m}_G = 1400/(Y_1 - 0.015)$

From energy balance (equation 6.2)

$\dot{m}_{G2}H_{G2} + \dot{m}_{S1}H_{S1} = \dot{m}_{G1}H_{G1} + \dot{m}_{S1}H_{S2} + q$

Where: $\dot{m}_{G2} = \dot{m}_{G1} = \dot{m}_G$

$\dot{m}_{S1} = \dot{m}_{S2} = \dot{m}_S$ and $q = 0$

$\dot{m}_G(H_{G2} - H_{G1}) = \dot{m}_S(H_{S2} - H_{S1})$

$1400/(Y_1 - 0.015) * [176.982 - (60.3 + 2612.8Y_1)] = 630\ (131.5176 - 276.1077)$

$1400/(Y_1 - 0.015) * (116.682 - 2612.8Y_1) = -91{,}091.763$

$116.682 - 2612.8Y_1 = -65.0655(Y_1 - 0.015)$

$Y_1 = 0.0454$ and

$\dot{m}_G = 1400/(Y_1 - 0.015) = 1400/(0.0454 - 0.015)$

$\dot{m}_G = 46{,}052.6316$ kg/h

Heat Transfer Unit

The section wise calculation of heat transfer unit of the stream can be obtained by material and energy balance over each section.

Section-III

Very less water left for vaporization in stage III. Consider solid is at T_{SB}, the wet bulb temperature of the air at location between III & II.

Assume: $T_{SB} = T_{SA} = 41℃$

Enthalpy of solid at the inlet to section III

$H_{SB} = [c_{pS} + (\dot{m}_S)\ (C_{pw})]\ (T_{SB} - T_o)$

H_{SB} = [0.85 + (0.00301) (4.187)] (41-0)

$H_{SB} = 35.37$ kJ/kg dry solid

Humid heat of gas entering stage III

$C_{HB} = [1.005 + (1.88)\ (0.015)]$

$C_{HB} = 1.003$ kJ/kg. K

Heat balance over stage III

$\dot{m}_S(H_{S2} - H_{SB}) = \dot{m}_G(\ C_{HB,III})(\ T_{G2} - T_{GB})$

$630(131.5176 - 35.37) = 46{,}052.6316(1.003)(135 - T_{GB})$

$1.3114 = 135 - T_{GB}$

$T_{GB} = 133.6886℃$

Adiabatic saturation temperature of air entering stage II (133.7^{O}C & humidity (Y_B) of 0.015) is 41.8^{O}C.

At the boundary B and end 2 change in temperature:

$\Delta T_B = T_{GB} - T_{SB} = 133.7 - 41 = 92.7℃$ and

$\Delta T_2 = T_{G2} - T_{S2} = 135 - 100 = 35℃$ and

$$LMTD_{III} = \Delta T_{m,III} = \frac{\Delta T_B - \Delta T_2}{\ln(\Delta T_B/\Delta T_2)} = \frac{92.7 - 35}{\ln(92.7/35)} = 59.239\ ℃$$

The number of heat transfer units in section-III is given by:

From equation 6.3

$$N_{TU,III} = \frac{T_{G2} - T_{GB}}{\Delta T_{m,III}} = \frac{135 - 133.7}{59.239} = 0.022$$

Section-II

Use heat balance equation over section II to calculate the value of T_{GA}. The calculated T_{GB} value can be use to estimate the number of transfer units.

Since Y_B = 0.015

$H_{GB} = [1.005 + 1.88\,Y_B](T_{GB} - 0) + 2500\,(Y_B)$

$H_{GB} = [1.005 + 1.88(0.015)](133.7 - 0) + 2500\,(0.015) = 175.6388\ KJ/Kg$

$H_{SA} = \left[0.85 + C_{pS}X_1\right](T_{SA} - 0) = [0.85 + 4.187(0.25)](41) = 77.7668\ KJ/(Kg\ dry\ solid)$

Enthalpy balance:

$\dot{m}_S(H_{SB} - H_{SA}) = \dot{m}_G(H_{GB} - H_{GA})$

$630(35.37 - 77.7668) = 46{,}052.6316\,(175.6388 - H_{GA})$

$H_{GA} = 176.2188\ KJ/Kg$

Then T_{GA} can be calculated, once H_{GA} value is known using the following energy balance equation.

$$H_{GA} = \left[C_{pG} + C_{pS}Y_1 \right](T_{GA} - 0) + Y_1(2500)$$

$$= [1.005 + 1.88(0.0454)](T_{GA} - 0) + 0.0454(2500)$$

$$T_{GA} = 112.4\ ℃$$

Temperature difference of gas and solid at boundary-A (ΔT_A) will be:

$$\Delta T_A = T_{GA} - T_{SA} = 112.4 - 41 = 71.4℃$$

$$LMTD_{II} = \Delta T_{m,II} = \frac{\Delta T_B - \Delta T_A}{\ln(\Delta T_B / \Delta T_A)} = \frac{92.7 - 71.4}{\ln(92.7/71.4)} = 81.6℃$$

Number of heat transfer units in section-II:

$$N_{TU,II} = \frac{T_{GB} - T_{GA}}{\Delta T_{mII}} = \frac{133.7 - 112.4}{81.6} = 0.2636$$

Section-I

The temperature difference at 1 will be:

$$\Delta T_1 = T_{G1} - T_{S2} = 60 - 26 = 34℃$$

$$\Delta T_A = 71.4$$

$$LMTD_I = \Delta T_{m,I} = \frac{\Delta T_A - \Delta T_1}{\ln(\Delta T_A / \Delta T_1)} = \frac{71.4 - 34}{\ln(71.4/34)} = 50.4℃$$

$$N_{TU,I} = \frac{T_{GA} - T_{G1}}{\Delta T_{mI}} = \frac{112.4 - 34}{50.4} = 1.56$$

$$N_{TU} = N_{TU,I} + N_{TU,II} + N_{TU,III} = 0.022 + 0.2636 + 1.56$$

$$N_{TU} = 1.84$$

According to the condition number of heat transfer unit (NTU) should be between 1.5 to 2. Therefore the above mean temperature value can be accepted [41].

To Calculate the Diameter of the Dryer

Air entering the drier is 46,052.6316 Kg/h. But for designing purpose air is taken in excess so that the loss of heat from the drier is compensated [45].

Air entering the drier can be taken as ~ 47,000 Kg/h

Assume that the maximum superficial air mass velocity to be = 5000 kg/ (h m^2)

$$G_G * S = 47{,}000\left[1 + 0.0165\frac{46{,}052.6316}{47{,}000}\right] = 47{,}759.8684 \text{ Kg/h}$$

Where S is cross sectional in m^2

Total heat is calculated as:

$$= 46{,}052.6316[1.005 + 1.88(0.0454\ )][60 - 0] + 0.0454\ (2500)$$

$$= 3.0129 * 10^6$$

$$\text{Humid of inlet air} = \ 1.005\ +\ 1.88(0.015) = 1.0332$$

$$\text{Total heat}\ = G'_G * \text{Humid of inlet air} * (T_{G2} - T_{G1}) = 3.0129 * 10^6$$

$$G_G = \frac{3.0129 * 10^6}{G'_G * \text{Humid of inlet air} * (T_{G2} - T_{G1})} = \frac{3.0129 * 10^6}{(5000/3600) * 1.0332 * (135 - 60)}$$

$$= \frac{3.0129 * 10^6}{117.625} = 25614.4527$$

$$G_G * S = 47{,}759.8684$$

$$S = \frac{47{,}759.8684}{25614.4527} = 1.8646\ m^2$$

Therefore:

$$S = \frac{\pi * D^2}{4} \leftrightarrow D = \left(\frac{4 * S}{\pi}\right)^{0.5} = \left(\frac{4 * 1.8646}{\pi}\right)^{0.5} = 1.54$$

$$D = 1.54\ m$$

Length of Transfer Unit

$$\text{Average mass flow rate } (\dot{m}_{Ava}) = \frac{\dot{m}_G(1 + Y_2) + \dot{m}_G(1 + Y_1)}{2}$$

$$= \frac{46{,}052.6316(1 + 0.015) + 46{,}052.6316(1 + 0.0454\ )}{2}$$

= 47,443.4211 kg/h

$$\text{The gas mass flow rate, } G' = (47{,}443.4211\ /3600)/\pi/4 * (1.54)^2$$

$$G' = 42.9795\ kg/m^2.S$$

$$\text{Volumetric heat transfer coefficient} = U_a = \frac{273(\ G')^{0.67}}{D} = \frac{273(\ 42.9795\ )^{0.67}}{1.54}$$

$U_a = 8{,}874.6191\ W/m^2.K$

Humid heat at the ends ($C_{H1}$and C_{H2}) calculated as follows

$C_{H2} = 1.005 + 1.88(Y_2) = 1.005 + 1.88(0.015) = 1.0332$

$C_{H1} = 1.005 + 1.88(Y_1) = 1.005 + 1.88(0.0454) = 1.09$

Then average humid heat $= C_H = \frac{C_{H1} + C_{H2}}{2} = \frac{1.09 + 1.0332}{2} = 1.0616\ kJ/kg.K$

Length of transfer unit $= L_{TU} = \frac{G' * C_H}{U_a} = \frac{42.9795\ * 1061.6}{8{,}874.6191} = 5.1413\ m$

Length of dryer

Length of dryer $= L = N_{TU} * L_{TU} = 1.84 * 5.1413\ = 9.46\ m$

$L = 9.46\ m$

L/D ratio check:

$L/D = 9.46/1.54 = 6.1428$

Which checks the condition that the L/D ratio is between 3- 10. Therefore the above diameter and length can be accepted [45].

To calculate the speed of the rotation of the drier:

Assume the peripheral speed of rotation to be 20 m/min

Revolution per min (RPM) = peripheral speed / diameter

$RPM = \frac{20}{4.5} = 4.44$

The revolution of the drier varies between 2 and 5 [36]. Therefore the above value can be accepted.

CHAPTER SEVEN

ENERGY ANALYSIS OF THE COGENERATION POWER PLANT

The cogeneration thermal power plant analysis is based on a simple Rankine cycle, steam generated from saturated liquid water (feed water) is used as the working fluid. The super saturated steam flows through the turbine, where its internal energy is converted into mechanical work to run an electricity generating system. And the steam comes out from the turbine supplies heat to the dry process. Not all the energy from steam can be utilized for running the generating system because of losses due to friction, viscosity, bend on blades, heat losses from boilers i.e. hot flue gas losses, radiation losses and blow down losses etc [31].

Rankine cycle is the theoretical cycle constructed from four main processes on which the cogeneration steam power plant works. The main processes in the Rankine cycle are:

Process 1-2: Reversible adiabatic expansion in the turbine.

Process 2-3 (2'-3'): Constant pressure transfer of heat in the condenser (Drying processes).

Process 3-4: Reversible adiabatic pumping processes in the feed pump.

Process 4-1: Constant pressure transfer of heat in the boiler.

Then, I am going to analyze energy of the cogeneration plat considering 1 kg of fluid and applying steady flow energy equation (SFEE) to Steam generators (boiler), Turbine, Condenser and Pump.

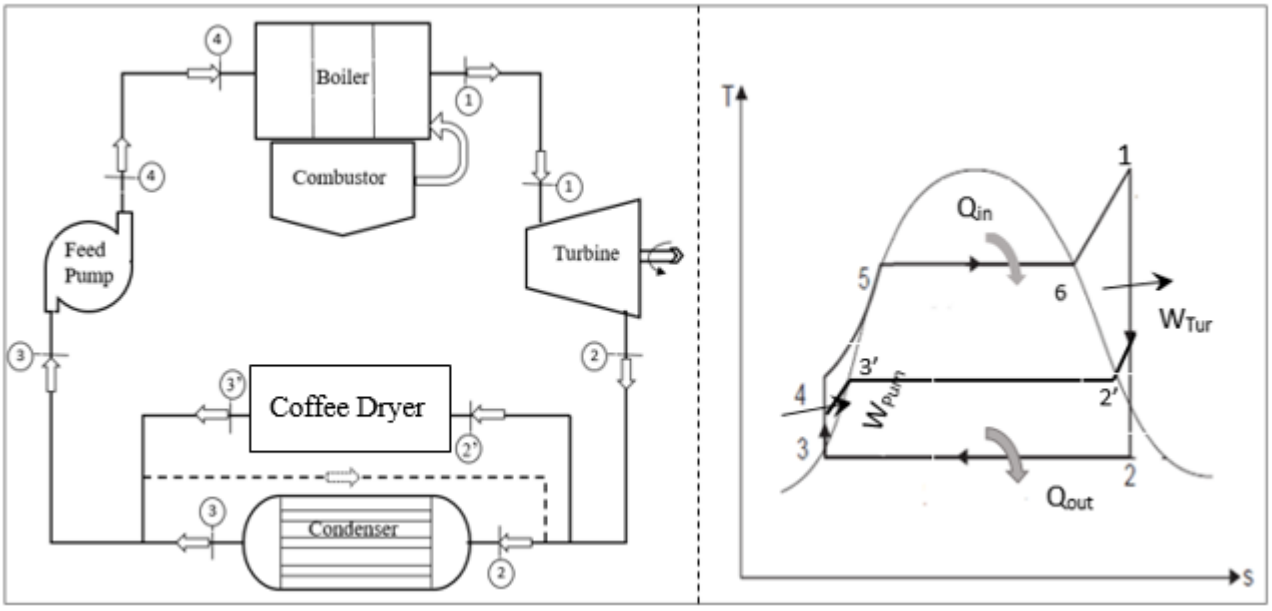

Figure 7.1 Schematic and T-S diagram of the cogeneration plant.

7.1 Design of Steam Generators

The boiler is considered as a single cross flow steam production chamber. The performance of the steam production chamber plays an important role of the boiler efficiency. Heat is transferred from the hot fluid to the cold one through the wall separating them.

7.1.1 Economizer (Process 4-5)

Where sensible heat is added in to the working fluid (feed water).

The rate of heat transfer from the flue gases to the feed water is given by:

$$Q_{Eco} = \dot{m}_{FW}(h_5 - h_4) = \dot{m}_{FW} * Cp_{FW} * (T_5 - T_4) \quad \text{..... 7.1}$$

Where $\dot{m}_{FW}$ is the mass flow rate of feed water in the economizer [kg/s], h_5 is the specific enthalpy of feed water after the economizer [kJ/kg], h_4 the specific enthalpy of feed water before the economizer and T_5 is the saturated temperature of the feed water.

7.1.2 Evaporator (Process 5-6)

Where phase change (boiling) occurs from liquid (water) to vapour (steam) by applying the latent heat essentially at constant pressure and temperature.

The heat load of the evaporator part of the boiler can be calculated as:

$$Q_{Eva} = \dot{m}_{St}(h_6 - h_5) = \dot{m}_{St}\, h_{fg} \quad \text{..... 7.2}$$

Where, $\dot{m}_{St}$ is the mass flow of steam before super heater [kg/s], h_6 & h_{fg} the specific enthalpy of saturated steam at steam drum pressure [kJ/kg], the specific enthalpy after economizer h_5 the specific enthalpy of saturated water at steam drum pressure [kg/s].

7.1.3 Superheaters (Process 6-1)

Where more heat is added at constant pressure to increase the temperature of steam up to the desired point.

In the super heater the heat load added can be calculated as:

$$Q_{SH} = \dot{m}_{St}(h_1 - h_6) = \dot{m}_{St} * c_{pSt} * (T_1 - T_6) \quad \text{..... 7.3}$$

Where $\dot{m}_{St}$ is the mass flow of steam before the superheater [kg/s], h_1 the specific enthalpy of steam at the outlet of super heater [kJ/kg], h_6 the specific enthalpy of steam at the inlet of super heater and T_1 is the maximum temperature of the superheated steam.

Performance evaluation

The percentage of total heat absorbed in the economizer, evaporator and superheater are:

$$\% \text{ Heat in Economizer} = \frac{Q_{Eco}}{Q_{Eco} + Q_{Eva} + Q_{SH}} * 100 = \frac{h_5 - h_4}{h_1 - h_4} * 100$$

$$\% \text{ Heat in Evaporator} = \frac{Q_{Eva}}{Q_{Eco} + Q_{Eva} + Q_{SH}} * 100 = \frac{h_6 - h_5}{h_1 - h_4} * 100$$

$$\% \text{ Heat in Superheater} = \frac{Q_{SH}}{Q_{Eco} + Q_{Eva} + Q_{SH}} * 100 = \frac{h_1 - h_6}{h_1 - h_4} * 100$$

$$Q_{in} = h_1 - h_4 = Q_{Eco} + Q_{Eva} + Q_{SH}$$

From energy balance the mass flow rate of stem will be.

$$Q_{in} = m_{Ste}(h_1 - h_2)$$

$$m_{Ste} = \frac{Q_{in}}{(h_1 - h_2)} \quad \ldots \ldots \ldots 7.4$$

Energy balance equation for the system

$$E_{in} - E_{out} = 0$$

$$E_{in} = E_{out}$$

$$m_{CH} * CV_{CH} = m_{Ste} * (h_1 - h_4) + Q_{loss}$$

Heat loss

$$Q = m_{CH} * CV_{CH} - m_{Ste} * (h_1 - h_4)$$

Equivalent ratio

$$\text{Equ. R} = \frac{m_{Ste} * (h_1 - h_4)}{m_{CH} * CV_{CH}} \quad \ldots \ldots \ldots 7.5$$

Efficiency of steam generators

$$\eta_{Boi} = \frac{m_{Ste} * (h_1 - h_4)}{m_{CH} * CV_{CH}}$$

7.2 Analysis of Steam Turbine

Steam turbine is a type of turbo machine which is an assembly of nozzles and blades. It converts part of the energy of high temperature and high pressure steam into mechanical energy (or shaft work).

The fluid enters the nozzle with a relatively small velocity and high pressure. As it flows through the nozzle, its pressure falls and a part of the enthalpy of steam gets converted into kinetic energy. The amount of energy which converts into kinetic energy depends on the pressure ratio and the type of expansion. Generally, nozzles are used to obtain isentropic expansion which imparts maximum conversion.

Energy balance equation for turbine is:

$\Delta PE = 0$, $\Delta KE = 0$ (as their values are very small compared with enthalpies)

$Q = 0$ (there is no addition or rejection of heat)

Applying energy equation to the system.

$$h_1 + 0 = W_{Tur} + h_2$$

$$W_{TU} = h_1 - h_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.6$$

The sign of W is positive because work is done by the system (or work comes out of the boundary).

In nozzles the flow is considered adiabatic ($q = 0$) and no work is done on or by the fluid ($w = 0$).

Thermal efficiency of the turbine is:

$$\eta = \frac{W_{net}}{Q_{in}}$$

Where: $W_{net} = W_{TU} - W_{PU}$ and Q_{in} amount of heat added.

Therefore, $Q_{in} = h_1 - h_4$

7.3 Energy Analysis of the Condenser

The condenser is used to condense the steam using water as cooling medium.

Energy balance equation for condenser is:

$\Delta PE = 0$, $\Delta KE = 0$ (as their values are very small compared with enthalpies)

$W = 0$ (since neither any work is developed nor absorbed)

Using energy equation to steam flow

$$Q + h_2 = 0 + h_3$$

$Q = h_3 - h_2$

Q = -Ve

$Q = h_2 - h_3$ ……..…..…7.7

$Q_{Con} = h_{fg}$ at the condenser pressure $= h_{Con.in} - h_{Con.out}$

Where: Q_{Con} = Heat lost by 1 kg of steam passing through the condenser.

Assuming there are no other heat interactions except the heat transfer between steam and water, then

Q_{Con} = Heat gained by cooling water passing through the condenser

$= m_{wat}(h_{Wat,out} - h_{wat,in}) = m_{wat} * Cp_{wat} * (T_{wat,out} - T_{wat,in})$

Substituting this value of Q_{Con} we get:

$h_2 - h_3 = m_{wat} * (h_{wat,out} - h_{wat,in}) = m_{wat} * Cp_{wat} * (T_{wat,out} - T_{wat,in})$

$h_2 - h_3 = m_{wat} * Cp_{wat} * (T_{wat.out} - T_{wat.in})$

where, m_{Wat} = Mass of cooling water passing through the condenser, and

Cp_{wat} = Specific heat of water at the condencer preassure.

7.4 Energy Analysis of Feed water Pump.

Energy balance equation for pump is:

ΔPE = 0, ΔKE = 0 (as their values are very small compared with enthalpies)

Q = 0 (since neither any significant heat is developed nor absorbed)

Using energy equation the energy balance equation for feed pump:

$0 + h_4 = W_{FP} + h_3$

$W_{FP} = h_4 - h_3$

It is also possible to use:

$W_{FP} = V_3(P_5 - P_3)$……7.8

Where:

V_3 is V_f at the condenser pressure and P_5 and P_3 are the boiler and condenser pressure respectively.

7.5 Equivalent Evaporation of Boiler

This is the amount of water evaporated at 100 ^{0}C, forming dry and saturated steam at 100 ^{0}C, at normal atmospheric pressure. As the water is already at the boiling temperature, it requires only latent heat at a certain pressure to convert it into steam at the temperature (100 ^{o} C). The value of this latent heat is taken as 2257 kJ/kg. Thus, the equivalent evaporation, E of a boiler, from and at 100 ^{o} C is [26]:

$$E = \frac{m(h_1 - h_4)}{2257} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.9$$

Where: $m = \frac{m_{Ste}}{m_{CH}}$

And the factor $\frac{(h_1 \ - h_4)}{2257}$ is known as factor of evaporation, and is usually denoted by F_e**.** Its value is always greater than unity for all boilers.

7.6 Internal power consumption

The power plant itself consumes a part of the electricity produced. This is due to the various auxiliary equipment required like feed water pumps, circulation pumps and air/flue gas blowers.

In forced circulation boilers the share of electricity consumed by the circulation pump is about 0,5 % of the electricity produced by the plant. Normally the internal power consumption is about 5 % of the electricity produced by the power plant. For this context since the power used is electrical (and taken from the grid), the internal power consumption share is reduced from the final boiler efficiency in boiler calculations [25].

7.7 calculation of the cycle

Feed water pump energy balance

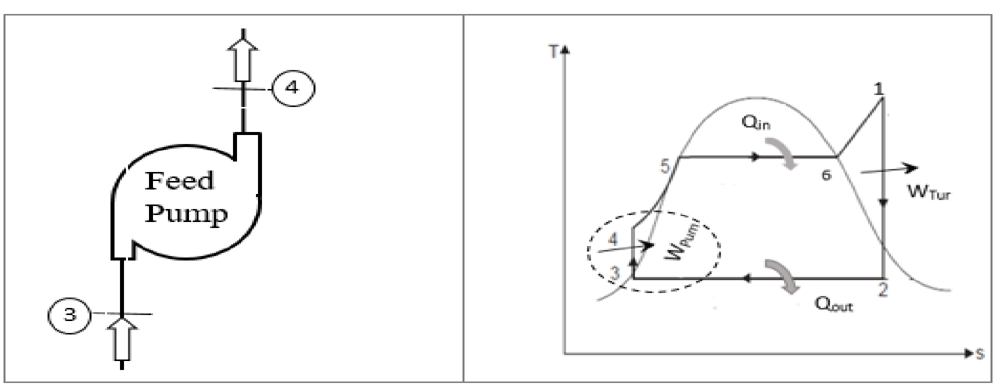

Figure 7.2 Schematic and T-S diagram of feed pump

Processes 3-4 (water pump)

Here, the minimum possible condenser pressure is 0.01MPa therefore the saturation temperature at this condenser pressure from saturated water pressure table is 45.81℃

The condenser pressure = $P_3 = P_2$

$W_{FP} = V_3(P_5 - P_3)$

Where, from table:

$V_3 = V_f \text{ at } 10 \text{ kPa} = 0.00101 m^3/kg$

P_5 is the boiler pressure $= 10 \text{ bar} = 1000 \text{ kPa}$

P_3 is the codenser pessure whic is 10 kPa

$W_{FP} = 0.00101 * (1000 - 10) = 0.9999 \text{ kJ/kg}$

$W_{FP} = 0.9999 \text{ kJ/kg}$

Calculation of heat loads of Steam Generators

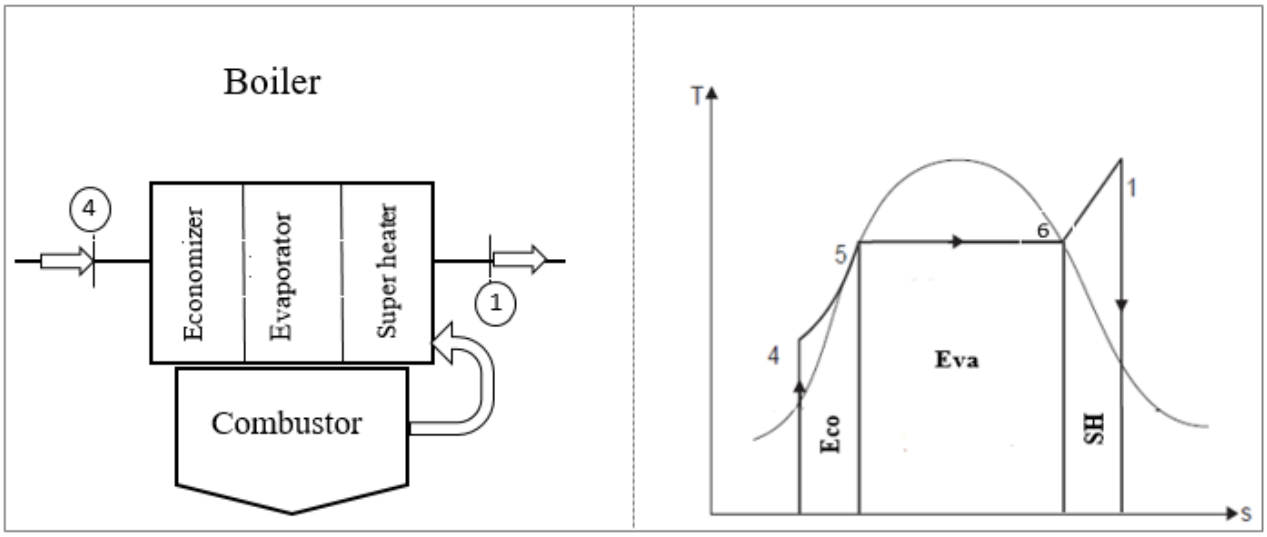

Figure 7.3 Schematic and T-S diagram of steam generators (boiler) and combustor.

Process 4-5 (Economizer)

Based on the above work of pump calculation and the selected boiler pressure 10 bar

$Q_{Eco} = h_5 - h_4$

Where:

$h_4 = h_3 + W_{FD}$ but $h_3 = h_f \text{ at } 10 \text{kPa} = 191.81 \text{ kJ/kg}$

$h_4 = 191.81 + 0.999 = 192.809\ kJ/kg$

At $P_5 = P_6 = 1000$ kPa, $T_5 = T_6 = 179.88\ ^{O}C$ (From Saturated water Pressure table)

$h_5 = h_f$ at $1000\ kPa = 762.51\ kJ/kg$

$Q_{Eco} = 762.51 - 192.809 = 569.701\ kJ/kg$

$Q_{Eco} = 569.701\ kJ/kg$

Process 5-6 (Evaporator)

$Q_{Eva} = h_6 - h_5 = h_{fg}$ at 1000 kPa

At $P_5 = 1000$ kPa, $T_{sat} = 179.88\ ^{O}C$

$h_5 = h_f$ at $1000\ kPa, Sat.\ liquid = 762.51\ kJ/kg$

$h_6 = h_g$ at $1000\ kPa, Sat.\ vapor = 2777.1\ kJ/kg$

h_{fg} at $1000\ kPa = 2014.6\ kJ/kg$

$Q_{Eva} = 2777.1 - 762.51 = 2014.59 kJ/kg = 2014.6\ kJ/kg$

$Q_{Eva} = 2014.6\ kJ/kg$

Process 6-1 (Superheater)

$Q_{SH} = h_1 - h_6$

Where, from superheated water table:

h_1 = h at 1MPa (179.88°C) and 500 ^{O}C, Sat. steam

$h_1 = 3479.1\ kJ/kg$

$h_6 = h_g$ at $1000\ kpa, Sat.\ vapor = 2777.1\ kJ/kg$

$Q_{SH} = 3479.1 - 2777.1 = 702\ kJ/kg$

$Q_{SH} = 702\ kJ/kg$

The percentage of total heat absorbed in the economizer, evaporator and superheater is:

$Q_{in} = h_1 - h_4 = Q_{Eco} + Q_{Eva} + Q_{SH}$

$Q_{in} = 3479.1 - 192.809 = 569.701 + 2014.6 + 702 = 3286.301\ kJ/kg$

$$\%\ Heat\ in\ Economizer = \frac{Q_{Eco}}{Q_{Eco} + Q_{Eva} + Q_{SH}} * 100\% = \frac{569.701}{3286.301} * 100\% = 17.3356\%$$

$$\%\ Heat\ in\ Evaporator = \frac{Q_{Eva}}{Q_{Eco} + Q_{Eva} + Q_{SH}} * 100\% = \frac{2014.6}{3286.301} * 100 = 61.3029\%$$

$$\%\ \text{Heat in Superheater} = \frac{Q_{SH}}{Q_{Eco} + Q_{Eva} + Q_{SH}} * 100\% = \frac{702}{3286.301} * 100\% = 21.3614\%$$

Calculation of the steam turbine energy

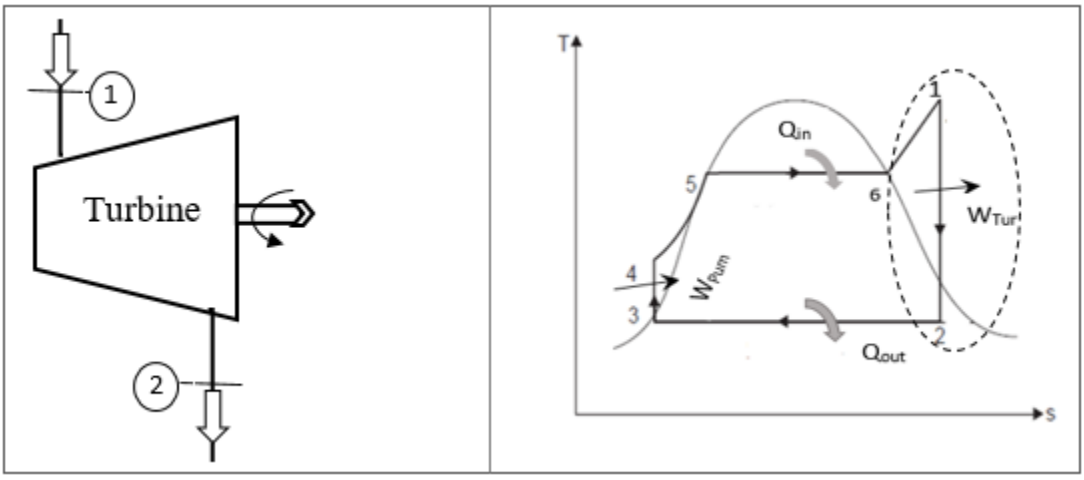

Figure 7.4 Schematic and T-S diagram of steam turbine

Process 1-2 (steam turbine)

$P_1 = 1\text{MPa}$ and $T_1 = 500\ ℃$. Then from the table

h_1 = h at 1 MPa (179.88℃) and 500 ^oC, Sat. steam = 3479.1 kJ/kg

$S_1 = S$ at 1 Mpa (179.88 ℃) and 500 ℃, Sat. steam $= 7.7642\ \text{kJ/kg.K}$

$h_2 = h_{f,2} + X_2 h_{fg,2}$ where:

Let us assume the condenser working pressure is 0.01 MPa

Then the saturation temperature at this pressure will be:

$T_{Sat} = 45.81℃$ Therefore the quality of steam calculated as follows:

$h_{f,2} = h_f$ at 10 kpa and 46℃ , Sat. liquid $= 191.81\ \text{kJ/kg}$

$h_{fg,2} =\ h_{fg}$ at 10 kpa and 46℃ , Sat. mixture $= 2392.1\text{kJ/kg}$

$X_2 = \frac{S_2 - S_f}{S_{fg}}$ where: $S_2 = S_1 = 7.4542\ \text{kJ/kg.K}$ (from steam table)

S_f at 10 kpa and 46℃ , Sat. liquid $= 0.6492\ \text{kJ/kg.K}$

S_{fg} at 10 kpa and 46℃, Sat. mixture $= 7.4996\ \text{kJ/kg}$

$$X_2 = \frac{7.4542\ - 0.6492}{7.4996} =\ 0.91$$

$h_2 = 191.81 \ + (0.91 * 2392.1\ ) = 2362.3578\ \text{kJ/kg}$

$W_{TU} = h_1 - h_2 = 3479.1\ - 2362.3578 = 1116.7421\text{kJ/kg}$

$W_{TU} = 1116.7421\text{kJ/kg}$

$W_{net} = W_{TU} - W_{PU} = 1116.7421 - 0.9999\ = 1115.7422\ \text{kJ/kg}$

$W_{net} = 1115.7422\ \text{kJ/kg}$

$$\text{Work ratio} = \frac{W_{TU} - W_{PU}}{W_{TU}} = \frac{1116.7421 - 0.9999}{1116.7421} = 0.9937$$

Thermal efficiency

$$\eta_{The} = \frac{W_{net}}{Q_{in}} = \frac{1115.7422\ \text{kJ/kg}}{3286.301\ \text{kJ/kg}} * 100 = 33.9513\ \%$$

Condenser energy balance

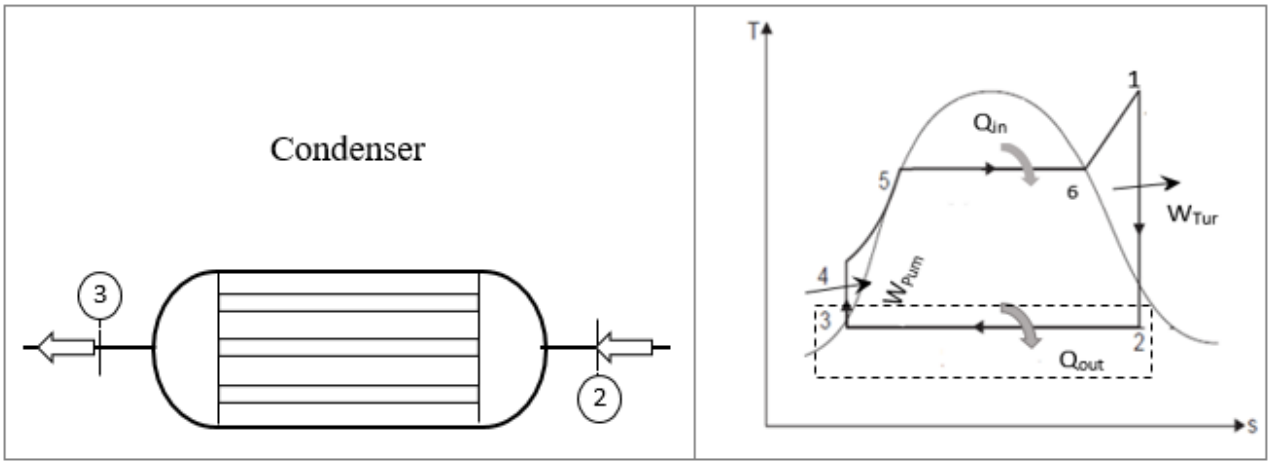

Figure 7.5 Schematic and T-S diagram of condenser

Processes 2-3 (Condenser)

$Q_{Con} = h_2 - h_3$ where:

$h_2 = h_{f,2} + X_2 h_{fg,2} = 2362.3578\ \text{kJ/kg}$ (calculated value before)

$h_3 = h_f$ 10 kpa and 46℃ $= 191.81\ \text{kJ/kg}$

$Q_{Con} = 2362.3578 - \ 191.81 = 2170.5478\ \text{kJ/kg}$

The maximum loss of energy takes place in the condenser where heat is rejected to cooling water and this lost heat from the working fluid (steam) is equal to the heat gained by the cooling water, so this gives us.

Heat lost by steam = heat gained by cooling water

$Q_{Con} = Q_{Wat} = 2170.5478\ \text{kJ/kg}$

The rise in water temperature is calculated in chapter 5, which is 82℃.

The inlet temperature of the cooling is taken as 27 ^{O}C.

$Q_{Wat} = m_{Wat} * Cp_{Wat} * (T_{in} - T_{out})$ where: Cp_{Wat} at mean temperature $(82 + 27/2 = 54.5℃)$
$= 4.18\ \text{kJ/kg.k}$ and $T_{out} = 82℃$

So, from energy balance on condenser it is possible to estimate the quantity of circulating cooling water as follows.

$m_{Wat} * Cp_{Wat} * (T_{out} - T_{in}) = m_{Ste} * (h_2 - h_3)$ where,

$$m_{Wat}/m_{Ste} = \frac{h_2 - h_3}{Cp_{Wat} * (T_{out} - T_{in})} = \frac{2362.3578 - 191.81}{4.18 * (82 - 27)} = \frac{2170.5478}{229.9} = 9.4413\ \text{kg}$$

$m_{Wat} = 9.4413\ \text{kg/kg of steam}$

This indicates that 9.4413 kg of calling water is required to condense 1 kg of steam in the condenser at the specified condenser pressure.

7.8 power produced by the plant

$$\text{Specific Steam Consumption (SSC)} = \frac{1}{W_{net}}.\frac{kg}{\text{KWs}} = \frac{1}{1115.7422} = 8.9626 * 10^{-4}\ \frac{kg}{\text{KWs}}$$

$$= \frac{3600}{W_{net}}.\frac{kg}{\text{KWh}} = \frac{3600}{1115.7422} = 3.2266\ \frac{kg}{\text{KWh}}$$

From energy balance the mass flow rate of stem will be.

$Q_{in} = m_{Ste}(h_1 - h_{4)}$

$$m_{Ste} = \frac{Q_{in}}{h_1 - h_4} = \frac{3286.301}{3479.1 - 192.809} = 0.989\ \text{kg/s}$$

Equivalent evaporation of the boiler.

$$E = \frac{m\ (h_1\ -\ h_4)}{2257}$$

Where: $m = \frac{m_{Ste}}{m_{CH}} = \frac{0.989}{3.055 * 10^{-4}} = 3237.3159\ \text{kg}$

$$E = \frac{3237.3159\ *\ (3479.1 -\ 192.809)}{2257} = 3.6544\ \text{kg/s}$$

And the steam raised per hour will be:

$\text{Steam Raised } = 3.6544 * 3600 \text{ kg/h} = 11615.76 \text{ kg/h}$

From data analysis in chapter three the amount of coffee husk generated from the industries per year is 10135.96 Ton. So based on the available amount of coffee husk rate of consumption per hour by the plant will be:

$$\text{Rate of consumption} = \frac{10135.96 \text{ ton}}{365 * 24} = 1.1570731 \text{ Ton} = 1157.0731 \text{kg/h}$$

$$\text{Rate of consumption} = 1157.0731 \text{ kg/h}$$

Then, amount of steam:

$$\text{Mass of steam per kg of coffee husk}(m_{Ste}) = \frac{\text{Steam Raised}}{\text{Rate of consumption}} = \frac{11615.76}{1157.0731} = 10.0389$$

$m_{Ste} = 10.0389$ kg per kg of coffee husk

Net power output becomes:

$P_{out} = m_{Ste} * W_{net} = 10.0389 * 1115.7422 = 11200.8425$ kW

$P_{out} = 11.2$ MW

7.9 Overall CHP plant efficiency

$$\eta_{Overall} = \frac{\text{Net work output + process heat delivered}}{\text{Toral heat input}} = \frac{W_{net} + Q_{Pro}}{Q_{in}}$$

$$= \frac{1115.7422 + 1643.0270}{3278.2824} = 0.8415$$

$\eta_{Overall} = 84.15\ \%$

CHAPTER EIGHT

RESULTS AND DISCUSSION

8.1 Parameters for solution of the analysis design equations

The results of the calculated parameters for analysis of a coffee husk fired cogeneration plant analysis equations from the previous sections are shown below.

Table 8.1 Summary of results

Description	Symbols	Formulas Used	Result
Mass of air	m_{Air} [kg]	$m_{Air\ Sto.} + (\frac{m_{Air\ Exc}}{100} * m_{Air\ Sto.})$	7.497
Mass of flue gas	m_{FG} [kg]	$m_{DFG} + m_{WFG} + m_{Ash}$	6.3672
Mass of coffee husk	m_{CH} [kg]		
Flue gas temperature	T_{FG} [°C]	$\frac{m_{CH} * CV_{CH}}{m_{FG} * Cp_{FG}} - \frac{m_{Ste} * (h_1 - h_4)}{m_{FG} * Cp_{FG}} - \frac{m_{UF} * CV_{CH}}{m_{FG} * Cp_{FG}} + T_0$	1489
Heat of economizer	Q_{Eco} [kW]	$\dot{m}_{FG} c_{pFG} (T_{FG1} - T_{FG2})$	825.061
Heat transfer surface of the economizer	$A_s[\ m^2]$	$\frac{Q_{Eco}}{U * F_c * \Delta T_{lm}}$	23.46
Total length of tubes of the economizer	L [m]	$\frac{A_s}{\pi\ d}$	149.377
Heat of evaporator	Q_{Eva}[kW]	$\dot{m}_{St} * h_{fg}$	8716.2764
Heat transfer surface of evaporator	$A_s[\ m^2]$	$\frac{NTU * C_{min}}{h}$	33.281
Total length of evaporator	L [m]	$\frac{A_s}{\pi * d}$	211.87
Rate of steam	$\dot{m}_{St}$[kg/s]	$\frac{\dot{m}_{FG} c_{pFG} (T_{FG1} - T_{FG2})}{h_{fg}}$	0.7701
Heat rate of super.	Q_{SH}[kW]	$\varepsilon * C_{min} * (T_{FG1} - T_{St2})$	1179.4

Transfer surface of superheater	$A_s[m^2]$	$\frac{Q_{SH}}{UF_c\Delta T_{lm}}$	142.04
Mass of dry cherry	$\dot{m}_S$ [kg/h]	$\dot{m}_{Che}(100\% - X\%)$	1350
Moisture in the wet cherry	X_1 [%]	IM/100% - IM	2.3333
Moisture in the dry cherry	X_2 [%]	FM/100% FM	0.1111
Water evaporated	m [kg]	$\dot{m}_S(X_1 - X_2)$	3000
Inlet gas thermal energy	$H_{G2}[KJ/kg\ ]$	$C_s(T_{G2} - T_o) + Y_2H_L$	176.982
Rate of mass of gas	$\dot{m}_G$ [kg/h]	$\dot{m}_G(Y_1 - Y_2) = \dot{m}_p(X_1 - X_2)$	98684.21
Heat transfer units in section-III	$N_{TU,III}$	$\frac{T_{G2} - T_{GB}}{\Delta T_{m,III}}$	0.022
heat transfer units in section-II	$N_{TU,II}$	$\frac{T_{GB} - T_{GA}}{\Delta T_{mII}}$	0.2636
Total transfer units	N_{TU}	$N_{TU,I} + N_{TU,II} + N_{TU,III}$	1.84
Diameter of the dryer	D [m]	$\left(\frac{4 * S}{\pi}\right)^{0.5}$	1.54
Length of dryer	L [m]	$N_{TU} * L_{TU}$	9.46
Revolution per min	RPM	peripheral speed / diameter	4.44
Flue gas loss	$L_{FG}[\%]$	$L_{(CO_2+SO_2)} + L_{H_2O} + L_{(O_2+N_2)}$	10.297
Other losses	$L_{Oth}[\%]$	By subtraction	26.9338
Total heat absorbed in boiler	Q_{in} [kJ/kg]	$h_1 - h_4$	3286.301
Work of feed pump	W_{FP} [kJ/kg]	$V_3(P_5 - P_3)$	0.9999
Work of turbine	W_{TU} [kJ/kg]	$h_1 - h_2$	1116.7421
Net work	W_{net} [kJ/kg]	$W_{TU} - W_{PU}$	1115.742
Net power output	P_{out} [MW]	$m_{Ste} * W_{net}$	11.2
Overall CHP plant efficiency	$\eta_{Overall}$ [%]	$\frac{W_{net} + Q_{Pro}}{Q_{in}}$	84.15

8.2 Parameters for solution of the performance equations

The results of the calculated parameters for the performance of a coffee husk fired cogeneration plant analysis equations from the previous sections are shown below in table 9.2.

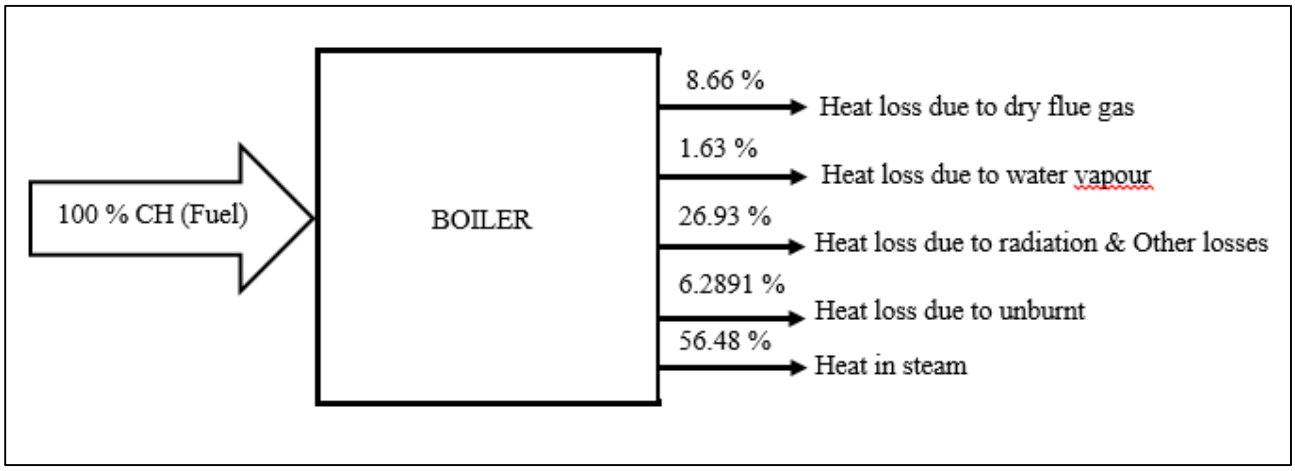

Figure 8.1 Principal losses of the boiler

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

In this work, the coffee husk fired cogeneration plant have been investigated using the designed water tube boiler and rotary type cherry coffee dryer with the selected pump and condensate steam turbine components after the detail analysis of the combustion of coffee husk using its chemical properties resulted from the laboratory. The following conclusions have been drawn from the work:

Coffee husk is characterized by high content of volatile matter and low contents of fixed carbon and ash. Due to the low contents of sulphur, SO_2 emission problems would not be expected during coffee husks combustion. The calorific value of the coffee husk has been carried out in the laboratory. The result of 18,980 KJ/kg. With this heating value, maximum temperature of the flue gas was calculated from the heat balance equation in the furnace.

Thermal analysis of the coffee husk fired CHP done with the operational conditions taken into account, hence, for an efficient use of coffee husk as a fuel for generation of steam in boiler, the design calculation dimension results of different components of the plant should be used.

The designed CHP plant configuration and its evaluation based on the identified potential in a coffee processing industries results 11.2 MW of electrical output from the waste coffee husk. Among this 1.05 MW is used to meet the total demand of the factories but the rest 10.15 MW is supply to national grid for community service.

The work also suggested by doing a detailed thermodynamic analysis of the plant as it could be cover the thermal demand of the factories from the combustion of coffee husk which shifts their drying method to the advanced one.

Shifting the industries mode from natural drying to thermal drying mode using the steam generated during cogeneration power plant process increases the quality of coffee with a low usage of man power and less drying space besides transfer of technology of waste to energy conversion.

The work also able us to see the power consumed by the coffee processing industries is very small. Therefore planting a coffee husk fired cogeneration plant in Sheka zone has a great role to support the community and the government beyond covering their power and heat demand.

9.2 Recommendations

The following points can be recommended for the future work.

- During the combustion of coffee husk problems of agglomeration, fouling, slagging and corrosion will be expected. These problems can lead to an increase in the cost of operation and maintenance of the combustion system. Therefore there is a need for more research to be done in this area to find a suitable solution for the low sintering properties of coffee husks ash. Techniques such as the use of additives and co-firing with other agricultural residues will need to be tested in real combustion situations.
- The same work can also be done using other types of dryers to increase the performance of drying process.
- To optimize the operation of a boiler, it is necessary to identify where energy wastage is likely to occur. A significant amount of energy is lost through flue gases as all the heat produced by the burning husk cannot be transferred to water or steam in the boiler. Since most of the heat losses from the boiler appear as heat in the flue gas, the recovery of this heat can result in substantial energy savings. This indicates that there are huge savings potentials of a boiler energy savings by minimizing its losses.

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