DURBAN UNIVERSITY OF TECHNOLOGY

AN ENERGY EFFICIENCY EVALUATION OF A BAGASSE GASIFICATION SYSTEM FOR THE SOUTH AFRICAN SUGAR INDUSTRY

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Abstract

The sugar industry in South Africa has been in existence for over a century. During this period, it has experienced different challenges both in production and market value, but recently; it is experiencing some difficulties in terms of relying solely on the sugar market.

Recently, with South Africa undergoing energy-mix processes, the sugar industry has identified an opportunity for the utilization of this excess bagasse. The generation of excess electricity can then be exported into the national grid after all factory electrical requirements have been fulfilled. Several studies have been conducted to develop a system that would be more efficient than the current system which is the direct combustion of bagasse and coal in some factories.

This research followed a case study approach. Two systems, direct bagasse combustion and bagasse gasification, were evaluated for their thermal efficiency and their impact on the operation of the sugar industry. According to the available data, bagasse gasification system is said to be at least 50% more efficient than the current direct combustion system. The gasification system utilizes a bagasse gasifier instead of a conventional direct combustion boiler. The gasifier is used to gasify bagasse into synthetic gas, also known as syngas. This gas can be used in gas turbines to generate electricity, and it can be integrated into an existing steam system as a source of steam for process operations.

The system analysis showed bagasse gasification system thermal efficiency as 55% as compared to the direct bagasse combustion system thermal efficiency of 19.68%. The knowledge contribution of this study was that of a practical evaluation of the current direct bagasse combustion system and the theoretical evaluation of the bagasse gasification system with similar inputs to identify the benefit of the utilizing the bagasse gasification system.

Declaration

This dissertation is the candidate's own work except where indicated in the text. It has not been submitted in part or in whole, at any other University.

This research was conducted at the Durban University of Technology under the supervision on Mr. G.F. D'almaine and Professor Ian Lazarus.

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APPROVED FOR FINAL SUBMISSION

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Professor Ian Joseph Lazarus: Co-Supervisor

Dedication

This study is dedicated to Our Creator who has given me life and the mind to be able to achieve this as one of my many goals in my life.

Acknowledgements

First and foremost, my appreciation goes to the Almighty for allowing me the opportunity to pursue my dreams.

I would like to thank my supervisor, Mr. G F D'Almaine and Prof. Ian Lazarus, for their thoughtfulness, patience, guidance and support.

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A special thank you goes to all those who supported me on this research, and who provided me with encouragement to continue when the going got tough.

Last but not least, a special appreciation goes to my family for their support.

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Acronyms

Bar	Pressure measurement unit _ 1bar = 100kilo-pascals/kPA
BFW	Boiler Feed Water
BIG-CC	Biomass Integrated Gasification Combined Cycle
BIG-GT	Biomass Integrated Gasification Gas Turbine
BIG-ISTIG	Biomass Integrated Gasification Steam Injection with Intercoolers
BIG-OC	Biomass Integrated Gasification Open Cycle
BIG-STIG	Biomass Integrated Gasification Steam Injection
BIG-ICR-Cycle	Biomass Integrated Gasification Intercoolers and Regeneration
c_p	Specific Heat of Steam
CO	Carbon Monoxide
c_v	Specific Heat of Steam
D	Bore
FD Fan	Forced Draft Fan
GCV	Gross Calorific Value
HCV	Higher Calorific Value
HP	High Pressure

HRSG	Heat Recovery Steam Generator
ID Fan	Induced Draft Fan
IGCC:	Integrated Gas Combined Cycle
k	Isentropic Coefficient
kcal	Kilocalorie
LCV	Lower Calorific Value
mm	Millimetre
MCR	Maximum Continuous Rating
Mv	Heat units transferred to steam
MW	Mega-Watts
NB	Nota bene
psia	Pounds per square inch absolute
p.s.i.g.	Pounds per square inch gauge
PI	Real-time data infrastructure solutions by OSIsoft LLC
q	Sensible heat lost in flue gases
rpm	Revolutions per minute
S	Stroke
SA Fan	Secondary Air Fan

TA	Turbo-Alternator
TPH	Tons per hour
α	Coefficient of losses due to unburned solids
β	Coefficient of losses due to radiation
η	Coefficient of losses due to incomplete combustion
$\boldsymbol{\mu}$	Micro (also used for efficiency representation)
$\boldsymbol{\mu m}$	Symbol used for Bagasse gasification efficiency

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CHAPTER ONE: Introduction

1.1. Background

In most cane sugar factories, the main source of electrical power is the power generation plant. This plant uses turbo-alternators to generate electrical power. The turbo-alternators rely on the steam supply from the steam boilers. The boilers used are steam boilers and they, traditionally, use coal and/or bagasse as the source of fuel. The coal and/or bagasse is burnt in the boilers, usually a water tube boiler, to boil the water in order to produce steam which is then used by the turbo-alternators to convert mechanical energy into electrical energy. This is effected by directly coupling the alternator onto the steam turbine, thus giving the unit the name turbo-alternator.

The price of coal increases on a regular bases and it has become a major cost concern to the industry. The coal prices have increased from about R110/ton in 1996 to as high as R1150/ton in 2008 and currently it was approximately R791.89/ton as at April 2014 [1]. The coal prices fluctuate so much that it is impossible to accurately estimate the future coal cost for a plant as the prices change monthly at some instances. For a factory that uses coal exclusively as its main source of boiler fuel, this can amount to very high expenses for the factory.

Due to technological advancements, other fuel sources have been widely used to replace or reduce coal consumption by the cane sugar industry, thereby reducing the steam and power generation plants operational costs.

In the past few decades, the cane sugar industry has opted to using a rather freely available fuel source, the bagasse. Bagasse is a by-product in the cane sugar production process. Bagasse is the remaining fibre after the juice has been extracted for processing from the sugar cane stalk. This makes the bagasse an almost free energy source. Another advantage of using bagasse besides the fuel cost factor is that the emitted flue gasses are less harmful to the environment as compared to coal [2]. Theoretically, the amount of carbon dioxide produced in burning bagasse is the same as the amount used in the process of growing the sugar cane resulting in that bagasse. [3]

The direct burning of bagasse generates enough thermal energy as required by the boilers. Through investigation, it was found that the efficiency of this system is very low. This statement can be justified by taking into consideration the contents of the bagasse normally used in the boilers. The average bagasse would have moisture content ranging between 48% and 51% [4]. This implies that at least 51% of the bagasse content is moisture.

Some of the bagasse is normally stored in an open area such as the outside of the bagasse shed and used after a number of days. This means that under normal circumstances, the bagasse would be at an atmospheric temperature of approximately 27°C.

The above statement implies that for the bagasse to be burnt, some of the energy generated is utilized in evaporating the 51% moisture from the bagasse and to heat up the bagasse before it can burn. This results in elevated thermal losses in the system.

In order for the steam and power generation plants of the cane sugar industry to survive in this tough environment, there needs to be another way of doing things. This can be referred to as continuous improvement. The industry has been in existence for many years, operating the same in terms of the steam and power generation processes. A new system such as bagasse gasification needs to be evaluated in order to determine if it can prove or disprove the scholarly theories and the limited experiments that state that the steam and power generation plants' efficiencies will be improved when using a bagasse gasification system.

The objectives of this study were as follows:

- To offer a clear understanding of what is entailed in a bagasse gasification system,
- To offer understanding of the different types of bagasse gasification systems designs,
- To highlight the cost implications and benefits of adopting a bagasse gasification system,
- To give a conclusion into the feasibility of converting current bagasse fired boilers system into IGCC for the basis of the study presented in this dissertation,
- To make recommendations regarding the possibility of improving the energy efficiency in the cane sugar industry utilizing a bagasse gasification system,
- To evaluate the efficiency improvement of the steam/power generation plant of a typical sugar factory using the process of bagasse gasification, and,
- To recommend the feasible type of bagasse gasifier that would be simpler to integrate into the current direct combustion system.

After the literature survey, a fixed bed down draft bagasse gasifier was chosen for the basis of this paper study. This is because of the simplicity in its design and operation.

Due to inaccessibility of prototypes, the study was based on theoretical studies and previous research that were done on the practical evaluation of the system. The process undertaken in this research study was therefore as follows:

- A specific system that uses the direct bagasse combustion system was chosen as the basis of the study,
- The operational efficiencies were calculated using raw data from the system,
- Calculations were done based on other research and experiments to determine the equivalent efficiency of a bagasse gasification system, and,

- The efficiencies between the actual current direct bagasse combustion system and the theoretical bagasse gasification efficiencies were analysed.

It was thus concluded that the cane sugar industry would largely benefit if a bagasse gasification system was to be used. This would be due to the larger amount of electricity generated at higher efficiencies which is vital for the industry if it decides to adopt the co-generation route to assist in the country's electricity demand and providing enough electricity for the onsite plant equipment. The benefit will not only be on the revenue generated through excess electricity exported into the National Grid, but also that the cane sugar industry can be sustainable even under challenging circumstances in the sugar market. The resilience of the South African Sugar Industry, in general, would be feasible due to the diversification of revenue. The thermal efficiency of a bagasse gasification system was calculated to be 55% as compared to the thermal efficiency of the direct combustion system which was 19.6 %. This clearly showed that the benefits of a bagasse gasification system over the direct bagasse combustion system. As the research study was theoretical, due to inaccessibility of bagasse gasification plants in South Africa to undertake practical experiments, it was recommended that the South African Sugar Industry as a whole should invest in at least a medium sized prototype system that would allow comprehensive tests to be undertaken resulting in tangible proof that would be convincing enough to investors in the event of acquiring a bagasse gasification system.

1.2. Research Objectives

The research project was aimed at evaluating the efficiency improvement of the steam and power generation plant of a typical cane sugar factory using a process of bagasse gasification. The research also gives further advice on what benefits would the cane sugar industry have from retrofitting the current direct bagasse combustion boilers with a bagasse gasification system.

1.3. Approach

The approach of the study involved the following:

1. General literature survey was conducted on the bagasse gasification processes and systems that covers the following:

    1.1.1. Defining the bagasse gasification system,

    1.1.2. Explaining different types of bagasse gasifiers, and,

    1.1.3. Choosing the appropriate type of a bagasse gasifier to base the study on.

2. Evaluating the thermal efficiency of the current direct bagasse combustion system.

3. Analyzing an equivalent system when using a bagasse gasification system.

4. In reporting the results, a comparison between a typical cane sugar factory using a direct combustion of bagasse and that of the same plant if it were to use the bagasse gasification system was undertaken. This comparison assisted in justifying whether the bagasse gasification system could be adopted throughout the cane sugar industry or not.

A single system was selected and all comparisons and typical system layouts were based on that particular system. The system chosen was at Illovo Sugar Limited Eston Mill.

The final report includes, but is not limited, to the following:

- A clear understanding of what is entailed in a bagasse gasification system,

- The understanding of the different types of bagasse gasification system designs,

- The cost implications and benefits of adopting a bagasse gasification system, and,

- A conclusion into the feasibility of converting current bagasse fired boilers system into IGCC.

1.4. Structure of the dissertation

Chapter one gives a general introduction of the study, the research objectives and the research approach. Chapter two focuses on the literation reviewed. Chapter three gives the research approach in details the two systems that were considered and the approach used for the final results discussions. Chapter four discusses the results from both systems under evaluation and Chapter five presents the conclusion of the study which also includes the recommendations.

CHAPTER TWO: Literature Review

2.1 Introduction

The gasification system has been studied in the energy environment for many years. This system has been implemented in countries that utilize carbonaceous compounds as their source of energy. The main objective of this study is to research new ways or systems and find cheaper and more efficient methods to generate electrical energy. Most of the work on the gasification systems has been done successfully with coal [5].

Since the principle of gasification relies on the carbon content of the mother compound, this has resulted in the idea of developing a system that uses bagasse. As in any sugar cane sugar producing factory, bagasse is an abundant commodity and an almost free fuel source, countries such as Brazil, Australia, India and China have undertaken experimental projects in the bagasse gasification field. It is believed that the success of the bagasse gasification system in the cane sugar industry could result in an improved energy efficiency of at least 45% compared to the current system, which is the direct bagasse combustion system [6]. There are, however, some obstacles that need to be overcome before the system can be adopted. One of the problems in countries such as South Africa is the inaccessibility of the experimental equipment to verify the benefits of the system from theoretical studies.

Much research, nonetheless, has been undertaken and the results show that the system would result in higher steam/power plant efficiencies. Although the main focus would be an improved energy efficiency system, some studies undertaken have shown that the chemical content and the resulting by-products of the system need to be taken into consideration. This includes the disposal facilities or alternative usage of the by-products of the bagasse gasification process.

There have been a number of papers presented on this topic [5] [6] [7] [8] [9]. Most of these papers in South Africa have concentrated on the evaluation of tests or experiments undertaken in other countries and relied on the accuracy of the data collected to conclude that this system can improve the efficiency of a steam and power generation plant. According to a paper presented by KTKF Kong Win Chang, *et al,* on Bagasse Gasification Technologies for Electricity Production in the Sugar Industry [7];

"The conventional steam cycle using condensing turbo-alternator sets has a potential of producing annual exportable electricity of only 115kWh/t cane compared with 275kWh/t cane with the biomass integrated gasification gas turbine technology (BIG-GT)." [7]

This statement was based on the assumption that the bagasse used would be the same quantity used in the conventional direct bagasse combustion system. It is further stated that if the trash and tops of the cane were to be used, the estimated electrical energy that could be exported would rise to approximately 2050 GWh per annum. The exported amount is estimated based on the assumption that the electricity requirements of the Mauritian sugar industry have been fulfilled. The paper further compares the annual electricity production potential between using conventional steam cycle and using BIG-GT technology. Table 1 below tabulates the annual electricity production potential in Mauritius [7].

Table 1: Example of Electricity Production Potential

	Conventional Steam Cycle		BIG-GT Technology	
	kWh/t cane	**GWh**	**kWh/t cane**	**GWh**
All bagasse for electricity production	143	825	303	1751
Less electricity for factory	28	162	28	162
Annual exportable electricity	115	663	275	1589
Cane tops and leaves @72% moisture	45	258	88	509
Less electricity for CTL processing	8	47	8	47
Annual exportable electricity	37	211	80	462
Total Exportable Energy	151	874	355	2051

The table above shows that using the conventional steam cycle, the electrical power generated would be 874 GWh compared to 2051 GWh if the BIG-T technology was to be used. This data is related to the cane/bagasse quantities of the Mauritian sugar industry taken in 1996.

Other publications such as Gasification Technology by P.A Hodson *et al*, also support the theory of improved energy efficiency of the bagasse gasification system [8].

Some models that have been studied or developed have been based on new installations. However, the first step in the South African sugar industry - since possibilities of constructing new plants are diminished by the economic situation of the country (and the sugar industry at large) - would be to focus on systems that can be easily integrated into the current systems. This is shown in a paper by KTKF Kong Win Chang *et al*, from the Mauritius Sugar Industry Research Institute in Reduit, Mauritius, on Bagasse Gasification Technologies for Electricity Production in the Sugar Industry, which contains a possible system arrangement for a BIG-GT system that can easily be integrated into the current system [9].

One of the methods that can be used to compare the conventional system to a bagasse gasification system requires the understanding of the technical content of these systems. According to the theory of heat engines developed by William John Macquorn Rankine, (1820 – 1872): “an ideal condition of heat energy converted to work system will only have an efficiency of between 22 – 26%”. This would be depending on the thermal conditions and assuming 100% boiler efficiency [10]. Comparing the standard back-pressure or condensing turbines used in the sugar industry these days to the gas turbines that would be used on the bagasse gasification system, it can be shown that the efficiencies are 45 – 50% for the steam turbines system and 60 – 85% for the gas turbine system respectively. The other main limiting factor of the direct combustion system is the entry temperature to the turbines which is typically 565°C (the creep limiting of stainless steel, with which most commercially available turbines are designed) [10], whereas the gasification plant can be operated at higher temperatures e.g. 900° to 1400°C [11].

A typical diagram of a Rankine Cycle is shown below;

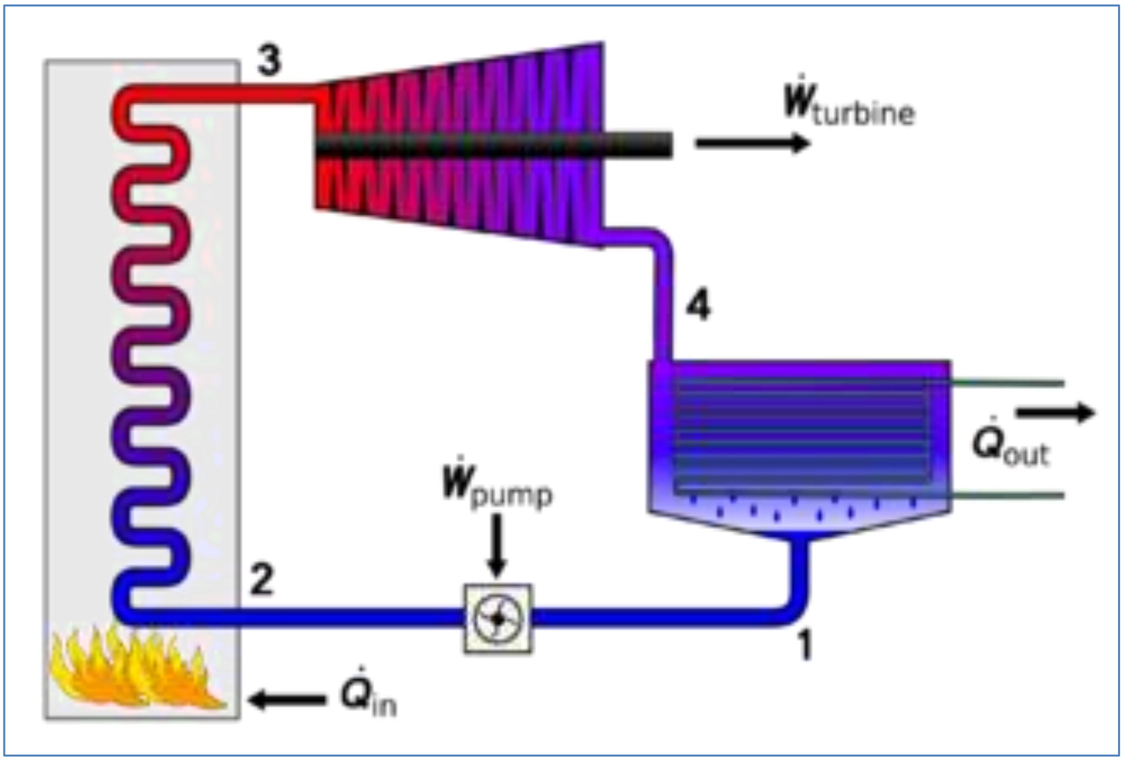

Figure 1: Rankine Cycle

From the data collected in papers surveyed, it can be clearly concluded that the bagasse gasification system would have higher efficiencies as compared to the current direct combustion of bagasse in the boilers.

2.2 Defining the Gasification Process

Gasification is a process whereby carbonaceous materials are converted into carbon monoxide and hydrogen by the reaction process of raw materials at high temperatures with a controlled amount of oxygen and/or steam. It can be referred to as a method for extracting energy from different types of organic materials. The resulting gas mixture is called synthesis gas or syngas. The efficiency of using the syngas is significantly higher than the efficiency of the direct combustion of bagasse due to its combustion at higher temperatures, so the thermodynamic upper limit to the efficiency (determined by Carnot's Rule, which is a principle that specifies limits on the maximum efficiency any heat engine can obtain) is higher.

A gasifier is a cylindrical enclosed reactor that is used to convert carbonaceous compounds into synthesis gas.

There are four main types of gasification processes currently available, these are:

- Counter-Current Fixed Bed (up-draft),
- Co-Current Fixed Bed (down draft),
- Fluidized Bed Reactor and
- Entrained flow gasifier

a) Counter-Current Fixed Bed (up-draft)

This system has a fixed bed of carbonaceous fuel (e.g. coal or biomass) through which the gasification agent (steam / oxygen) flows in a counter-current flow configuration. The thermal efficiency of this system is high as the gas exit temperatures are relatively low. The tar and methane production (in coal as a gasification agent) is high at typical operating temperatures. The product gas must be cleaned before use and the tar can be recycled to the reactor.

b) Co-Current Fixed Bed (down-draft)

In this type of gasification system, the gasification agent flows in a co-current configuration with the fuel entering downwards. The heat is added to the upper part of the bed, by the combustion of small amounts of the fuel or external heat sources. The energy efficiency of this system is the same as the up-draft gasifiers and the tar levels are lower than that of the up-draft gasifier.

c) Fluidized Bed Gasifier

In this type of a gasifier, the fuel is fluidized in oxygen and steam or air. The ash is removed dry or as heavy agglomerates that de-fluidizes. The fuel required for this system must be highly reactive. The fuel throughput is higher than in the fixed bed gasifiers and the system is most useful to fuels with a high corrosive ash.

d) Entrained Flow Gasifier

In this system, dry pulverized solid, an atomized liquid, or fuel slurry is gasified with oxygen in a co-current flow. The tar and methane are not present in the product gas. The oxygen requirement is higher than in the other gasifiers meaning that most of the energy consumption is used for oxygen production which is required for the process rather than the gasification process itself.

2.3 Gasification of other fuel sources: Tested systems

There have been many of projects done to test the effectiveness of the gasification processes. Most of the processes used coal as the carbonaceous material to be gasified. A brief process and plant layout of an IGCC plant as presented by *Wikipedia Interaction Forum* [12] and is shown below:

Integrated Gasification Combined Cycle

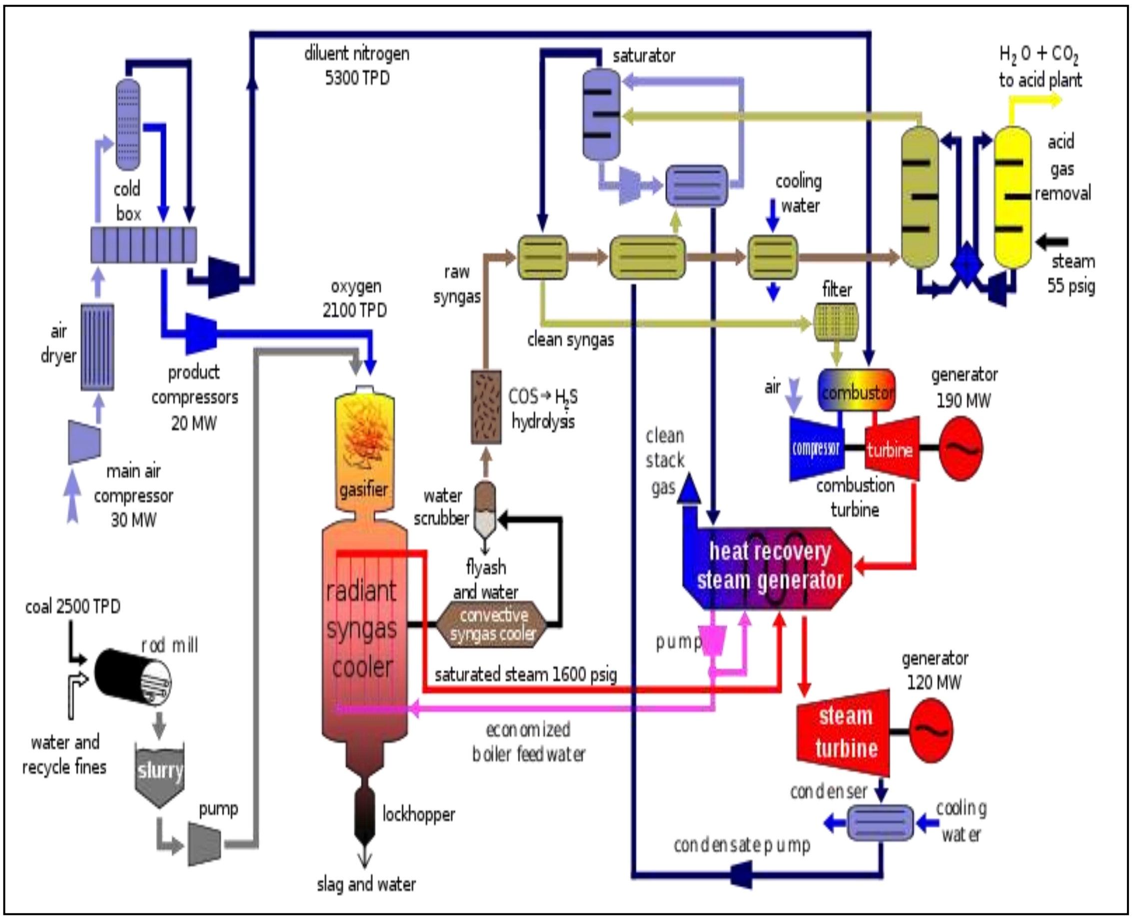

Figure 2: Block Diagram of IGCC Plant which Utilizes HRSG

The above plant is called integrated because its syngas is produced in a gasification unit in the plant which has been optimized for the plant's combined cycle. In this example, the syngas produced is used as fuel in a gas turbine which produces electrical power. To improve the overall process efficiency, heat is recovered from both the gasification process and the gas turbine exhaust in waste heat boilers that produces steam. This steam is then used on the steam turbines to produce additional electrical power. In the case of the sugar industry, this steam would also be used as process steam. Process steam, in the context of a cane sugar factory, is the steam used for the process heating or boiling of the juice extracted from cane.

2.4 Relation to the Cane Sugar Industry

If a new cane sugar mill was to be designed or constructed, a similar set-up could be adopted with the difference in the fuel being bagasse rather than coal. However, due to the current economic crisis in South Africa, the cane sugar industry would prefer to modify the existing plants rather than building new ones.

A paper titled: *Bagasse Gasification Technologies for Electricity Production in the Sugar Industry presented at the Proceedings of the South African Sugar Technologists Association Congress (1999)73 by KTKF Kong Win Chang et al,* [9] has compiled the different technologies that could easily be integrated into the current cane sugar industry steam generation plants. This paper presented the following Biomass Integrated Gasification Gas Turbine systems:

- BIG-OC- Open Cycle,
- BIG-CC-Combined Cycle, and
- BIG-STIG-Steam Injection
- BIG-ISTIG-Steam Injection with Intercoolers and
- BIG-ICR-Cycle with Intercoolers and Regeneration

Where: BIG-OC, BIG-CC and BIG-STIG are the currently available technologies in the market while BIG-ISTIG and BIG-ICR are possible future technologies.

2.5 Chosen gasification system for further study

From the Literature survey, the option of choosing a preferred system was based on the available information. The system chosen was a Co-Current Fixed Bed System. In this system, the energy efficiency is maintained by transferring most of the heat generated during the process to the gasification agent entering into the top of the bed. The tar levels of this type are lower than the up-draft system. The main advantage of the down draft co-current gasifier is the possibility of producing a tar-free gas suitable for engine application.

A BIG-CC system would be an ideal system as it can allow the gasification plant to be operated in conjunction with, but independent of, the conventional direct bagasse combustion boiler system. The BIG-CC system can be selected due to its ease of availability as it is a currently used technology around the world as a combination of gas powered turbines and heat recovery systems in a combined cycle for power and steam generation plant. The advantage of this system is that there is less energy wastage as the exhaust heat from the gas turbine or engine is used in the generation of steam for further use on the turbo-alternators for generation of electricity. In the sugar industry, the exhaust steam from the turbo-alternator is used on the sugar manufacturing process. This increases the overall thermal efficiency of the steam and power generation system.

CHAPTER THREE: Research Design

3.1 Introduction

It is vital to understand the basic efficiency calculations approach for a conventional bagasse fired high pressure steam boiler before any studies of new systems can be undertaken. This chapter entails the format and design followed during the study.

The first step was to determine a typical bagasse fired boiler efficiency using the conventional direct combustion bagasse fired water tube high pressure boilers. The data used for the calculations were actual data values courtesy of ISL: Eston Factory Data [13]. The next step was the determination of a bagasse gasification system using similar quantities or inputs as that of the conventional direct bagasse combustion system. One of the outcomes expected from this chapter was the understanding of the operational efficiency of a bagasse fired steam boiler using the conventional direct combustion method as the fire combustion method.

3.2 Current System Analysis

3.2.1 Introduction

It is vital to understand the basic efficiency calculations approach for a conventional bagasse fired high pressure steam boiler before any studies of new systems can be undertaken. This section entails the calculations undertaken to determine a typical bagasse fired boiler efficiency using the conventional direct combustion bagasse fired water tube high pressure boilers. The data used for the calculations were actual data values courtesy of ISL: Eston Factory Data [13].

3.2.2 Procedure

As the intent of this chapter was to report on the basic calculations involved in determining the boiler and/or energy efficiency of a system, the approach was to discuss the general quantities that are required in order to calculate the operational boiler efficiency. The values used in the calculations are actual values from data collected from a specific boiler. The two main operating factors to be considered for a satisfactory operation of a boiler are its efficiency and capacity.

3.2.3 Understanding Bagasse

The fuel used in the boiler referred to in this context is bagasse. Bagasse is the fibrous material that remains after juice has been extracted from the sugar cane. The main contents of bagasse are [14]:

- Water which amounts to between 45% and 50%,
- Insoluble material, consisting mainly of cellulose and comprising the fibre content of the bagasse, and,
- Substances in solution in the water consisting of sugar and impurities.

Reducing the above contents to actual values in a sugar factory can be explained as follows:

- The water (45 – 50%) is referred to as bagasse moisture
- The insolubles are referred to as the ash content in the bagasse
- The substances in the water are referred to as pol percent in bagasse where:
    - pol (polarization) is defined as the apparent sucrose content expressed as a mass percent measured by the optical rotation of polarized light passing through a sugar solution accurate only for pure sucrose solutions (non-pol negligible) [15].

3.2.4 Quantities Calculated

The following quantities first needed to be calculated in order to find the final overall boiler efficiency.

- Higher Calorific Value (HCV) of the sampled bagasse
- The enthalpy of the sampled high pressure steam
- The enthalpy of the sampled boiler feed water

- The quantity of steam in tons generated per ton of fuel consumed, given by boiler evaporation coefficient (x)
- The quantity of steam in tons generated per ton of cane crushed

The overall boiler efficiency was then calculated based on the higher calorific value (HCV).

3.2.5 Calculations

Table 2: Steam Boiler Data: Actual Data: 23/08/2014

QUANTITY	**VALUE**
Bagasse Moisture (w_w)	51.41 %
Bagasse Brix Content/Pol Content (w_{rds})	1.49 %
Bagasse Ash Content (w_a)	4.52 %
HP Steam Pressure	31000 kPa
HP Steam Temperature	400 °C
Exhaust Steam Pressure	120 kPa
Exhaust Steam Temperature	130 °C
Furnace Temperature	1350 °C
Feed water Temperature	100 °C
Ratio of weight of air used for combustion to weight theoretically necessary	1.5
Coefficient of losses due to unburned solids (α)	0.99
Coefficient of losses due to radiation (β)	0.97
Coefficient of losses due to incomplete combustion (η)	0.90

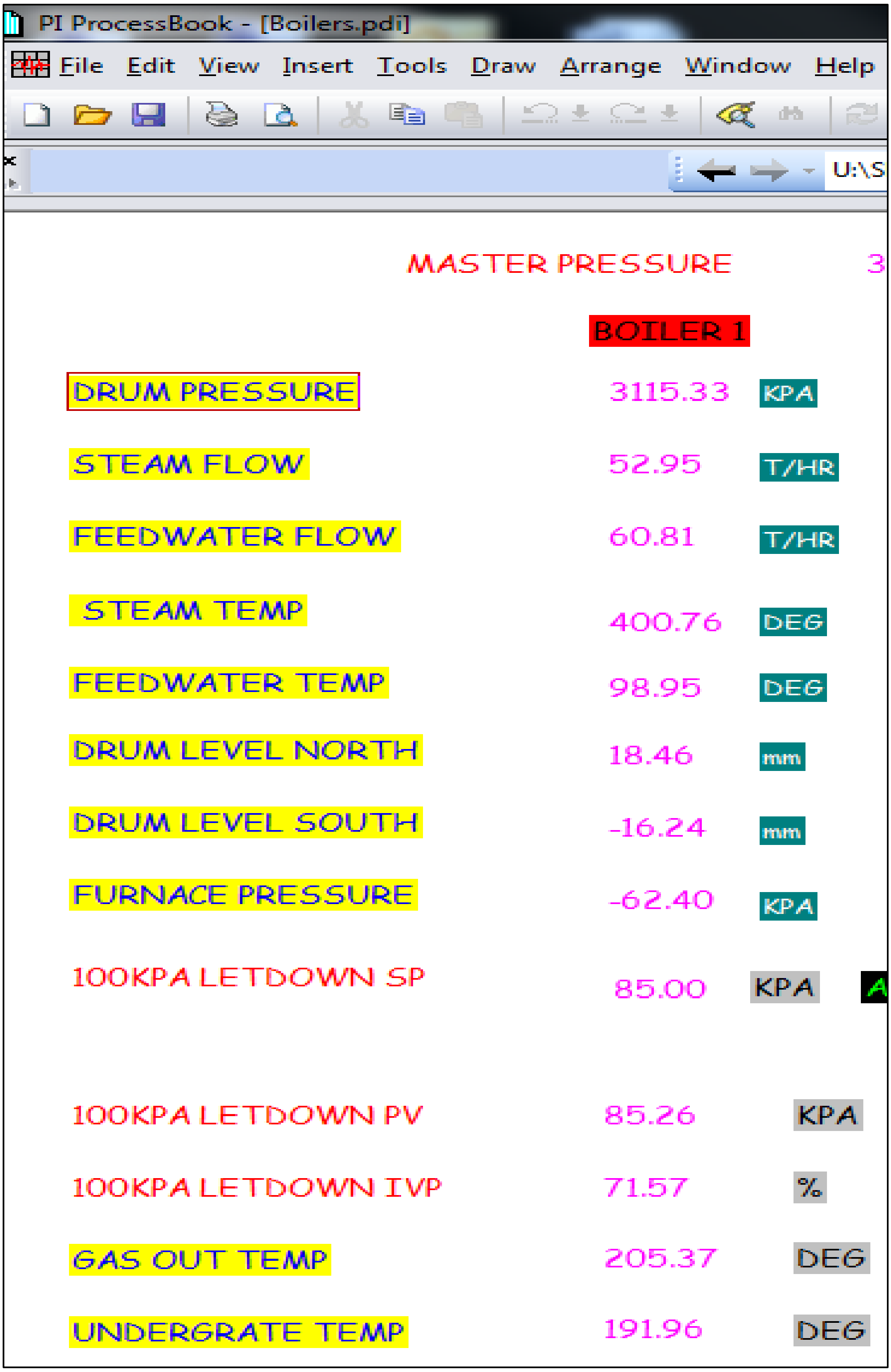

Figure 3: Screen shot of boiler quantities - PI System [16]

Higher Calorific Value (HCV) of the bagasse

The HCV or Gross Calorific Value (GCV) is the theoretical value which is calculated by assuming that the water present in the fuel as well as the water formed by combustion of the hydrogen entering into its composition is consequently condensed [14]. The following are the HCV and LCV (Lower Calorific Value) values, respectively under the conditions as defined on Table 2: Steam Boiler Data above.

$$\mathbf{HCV} = \mathbf{19605 - 196.05}\ (\boldsymbol{moisture}\ \%\ \boldsymbol{in\ bagasse}) - \mathbf{196.05}\ (\boldsymbol{ash}\ \%\ \boldsymbol{in\ bagasse}) - \mathbf{31.14}\ (\boldsymbol{brix}\ \%\ \boldsymbol{in\ bagasse})$$ [17]

Similarly:

$$\boldsymbol{HCV} = \mathbf{196.05\ x\ (100} - \boldsymbol{Ww} - \boldsymbol{Wa}) - \mathbf{31.14\ x}\ \boldsymbol{Wrds}$$ [18]

$$= 196.05\ (100 - 51.41 - 4.52) - 31.14\ x\ 1.49$$

$$= 196.05\ (44.07) - 46.34$$

$$= \mathbf{8549.51}\ \boldsymbol{kJ/kg}$$

Also: Lower Calorific Value (LCV) of the bagasse is given by:

$$\boldsymbol{LCV} = \mathbf{18260 - 207.01}\ \boldsymbol{Ww} - \mathbf{182.60}\ \boldsymbol{Wa} - \mathbf{31.14}\ \boldsymbol{Wrds}$$ [18]

$$= 18260 - 207.01\text{x}51.41 - 182.60\text{x}4.52 - 31.14\text{x}1.49$$

$$= 18260 - 10642.38 - 825.35 - 46.39$$

$$= \mathbf{6745.88}\ \boldsymbol{kJ/kg}$$

Where:

- LCV *is the lower heating value whereby the latent heat of evaporation is subtracted from the HCV with the assumption that at the end of the combustion cycle, the water ends up as vapour.*

Enthalpies

Enthalpy is the amount of heat content used or released in a system at constant pressure. In simple terms, enthalpy is defined as the sum of the internal energy of the system plus the product of the pressure of the gas in the system and its volume [19]. The enthalpy values for the context of these calculations are calculated via the table below:

Inputs	Degrees Superheat and Specific Entropy of Steam (s)	
Output	Single Value	Table
Pressure	31	bar gauge
Superheat Temperature	400	°C
	Calculate	Reset
Saturation Temperature	237.521	°C
Degrees Superheat	162.479	°C
Specific Enthalpy of Water (h_f)	1025.49	kJ/kg
Specific Enthalpy of Evaporation (h_{fg})	1777.72	kJ/kg
Specific Enthalpy of Superheated Steam (h)	3227.31	kJ/kg
Density of Steam	10.7726	kg/m³
Specific Volume of Steam (v)	0.0928281	m³/kg
Specific Entropy of Water	2.67873	kJ/kg K

(s_f)		
Specific Entropy of Evaporation (s_{fg})	3.48114	kJ/kg K
Specific Entropy of Superheated Steam (s)	6.88723	kJ/kg K
Specific Heat of Steam (c_v)	1.71098	kJ/kg K
Specific Heat of Steam (c_p)	2.30265	kJ/kg K
Speed of sound	617.906	m/s
Dynamic Viscosity of Steam	2.43780E-05	Pa s
Isentropic Coefficient (k)	1.28473	
Compressibility Factor of Steam	0.956544	

Figure 4: Enthalpy of supersaturated steam calculation

From the table above, the calculated value using the spirax sarco software for the superheated steam is 3227.31kJ/kg [20]. This is an actual value using 31bar steam at 400 °C. It can be verified by using any standard superheated steam temperature steam table.

The enthalpy for the feed water is taken from the same calculation done via the spirax sarco software [20]. This also can be verified using the standard sub-saturated water region on a steam table. The figure is shown below:

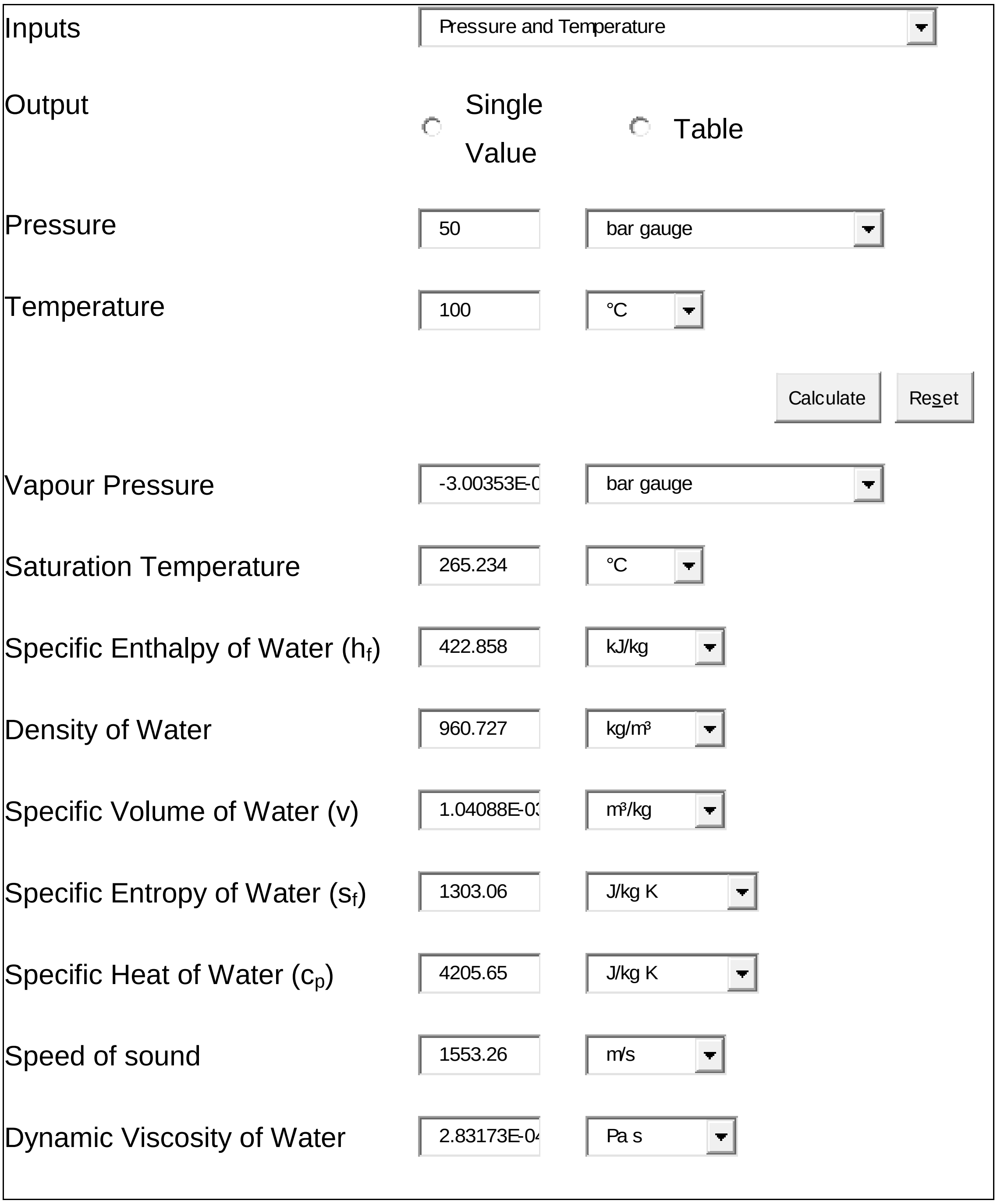

Figure 5: Enthalpy of feed water calculation

The enthalpy of the feed water is taken at 100 °C and 50bar (gauge). This pressure range is between 60 – 40 bar. At 0% valve opened, the feed water pressure is 60 bar and at 100% valve opened, the pressure is 40bar. The 50bar is taken as an average under normal operations.

The two values from the two tables above are:

Table 3: Enthalpy of Superheated Steam and Feed water

Enthalpy of superheated steam (h_{st})	3227.31 kJ/kg
Enthalpy of feed water (h_{fw})	422.86 kJ/kg

3.2.6 Boiler Efficiency

The boiler efficiency is calculated in two ways. There is a direct method and an indirect method. The direct method is an estimation method that does not take into consideration the losses during the combustion process and the indirect method takes into consideration all the heat losses during the combustion process. There is also an operational efficiency which is the ratio of the value of the efficiency achieved by direct method to the efficiency value achieved by the indirect method [17].

3.2.6.1 **Direct Method**

$$\boldsymbol{Boiler\ Efficiency} = \frac{(\boldsymbol{Mass\ of\ Steam} \text{ x } \boldsymbol{Enthalpy\ of\ Steam}) - (\boldsymbol{Mass\ of\ BFW} \text{x } \boldsymbol{Enthalpy\ of\ BFW})}{(\boldsymbol{Mass\ of\ Fuel} \text{ x } \boldsymbol{Calorific\ Value\ of\ Fuel})}$$

3.2.6.2 **Indirect Method**

$$\boldsymbol{Boiler\ Efficiency} = \frac{(\boldsymbol{Energy\ in\ Fuel} - \boldsymbol{Energy\ Losses})}{\boldsymbol{Energy\ of\ Fuel}}\ \boldsymbol{x\ 100}\%$$

Or

$$\boldsymbol{Boiler\ Efficiency = 100 - L1 - L2 - L3 - L4 - L5 - L6}$$

Where:

L_1 = Latent heat of the water formed by combustion of hydrogen in the bagasse

L_2 = Latent heat of the water contained in the bagasse

L_3 = Sensible heat of the flue gas leaving the boiler

L_4 = Losses in unburned solids

L_5 = Losses by radiation from the furnace and especially from the boiler

L_6 = Losses due to bad combustion of carbon giving CO instead of CO_2

Losses L_1 and L_2 are accounted for in the NCV formula and L_3 is given by the following formula:

$$\boldsymbol{Total\ Sensible\ Heat\ (q) = t(1-w)[1.4m + \frac{0.50}{1-w} - 0.12} \qquad [14]$$

Where:

q = sensible heat lost in flue gases in kcal/kg of bagasse

t = temperature of the flue gases in °C (taken as average)

w = moisture of bagasse relative to unity

m = ratio of weight of air used for combustion to weight theoretically necessary (1.5; [14])

Therefore:

$$\boldsymbol{Total\ Sensible\ Heat\ (q)} = [(\boldsymbol{1-w})(\boldsymbol{1.4m - 0.13}) + \boldsymbol{0.5}]\boldsymbol{kcal/kg}$$

$$= [(1-0.51)(1.4\text{x}1.5 - 0.13) + 0.5]\text{x } 205$$

$$= [(0.49)(1.97) + 0.5]x\ 205$$

$$= \boldsymbol{300.39\ kcal/kg}$$

Overall Boiler Efficiency can be calculated using the following formula:

$$\boldsymbol{q = {}^{Mv}/_{Ns}} \quad [14]$$

$$= \frac{\boldsymbol{Heat\ units\ transferred\ to\ the\ steam}}{\boldsymbol{Gross\ Carolific\ Value\ of\ the\ bagasse}}$$

Where:

GCV is the same as the above calculated HCV of 8549.51 kJ/kg. Heat unit transferred to the steam is given by M_v in the following formula:

$$\boldsymbol{Mv} = (\mathbf{4250} - \mathbf{4850}\boldsymbol{w} - \boldsymbol{q})(\boldsymbol{\alpha\beta\eta}) \qquad [14]$$

Where:

M_v = heat transferred to steam per kg of bagasse burnt in kcal

q = sensible heat of flue gasses in kcal/kg

α = solid unburned and is approx. 0.99 [14]

β = radiation losses – ranges between 0.90 – 0.95 depending on the lagging of the boiler [14]

η = losses due to incomplete combustion – ranges between 0.99 – 0.8 [14]

Q can be approximated as 1.5*t*; however, the actual calculated value of 300.39 kcal/kg will be used for further calculations. Heat unit transferred to the steam is given by M_v:

$$\boldsymbol{Mv} = (\mathbf{4250} - \mathbf{4850}\boldsymbol{w} - \boldsymbol{q})(\boldsymbol{\alpha\beta\eta})$$

$$= (4250 - 4850x0.51 - 300.39)(0.99x0.95x0.90)$$

$$= (1476.11)(0.846)$$

$$= 1249.45\ kcal/kg$$

$$= 1249.45\frac{kcal}{kg}\text{x}\frac{4.1868}{kcal}\ kJ/kg$$

$$= \mathbf{5231.19}\ \boldsymbol{kJ/kg}$$

Therefore, the overall boiler efficiency given by ὴ can be calculated as follows**:** [14]

$$\grave{\eta} = \frac{\boldsymbol{Mv}}{\boldsymbol{Ns}}$$

$$= \frac{Heat\ units\ transferred\ to\ the\ steam}{GCV\ of\ the\ \ bagasse}$$

$$= \frac{5231.16}{8549.51}\text{ x }100\%$$

$$= \mathbf{61.18}\ \%$$

This thus implies that the boiler in this context operating at the given values has an efficiency of 61.18 %

The next stage was to calculate the quantity of steam in tons generated per ton of fuel consumed. This is given by the formula: [15]

$$\boldsymbol{X = \frac{\eta B x HCV}{Hst - Hfw}}$$

$$= \frac{61.18 \text{ x } 8549.51}{3227.31 - 422.86}$$

$$= 186.51$$

$$= \mathbf{1.87} \ \boldsymbol{tons\ steam/\ ton\ bagasse}$$

The amount of bagasse produced per ton of cane crushed can be estimated at approximately 0.275tons. [21]. The amount of steam generated per ton of cane crushed can be calculated as follows: [15]

$$\boldsymbol{Y = \frac{X\ (F\%C - FibreLost\%C)}{F\%B}}$$

F%C = fibre content of the cane in percent less the fibre lost in juice and the fibre lost in the mud filters

FibreLost%C = fibre lost in juice

F%B = fibre content of the bagasse in percent

$$\boldsymbol{Y} \quad = \frac{\boldsymbol{X\ (F\%C - FibreLost\%C)}}{\boldsymbol{F\%B}}$$

$$= \frac{1.87\ (15 - 0.08)}{(100 - 51.41 - 4.52 - 1.49)}$$

$$= \frac{1.87\ (15 - 0.08)}{42.58}$$

$$= \mathbf{0.66}\ \boldsymbol{tons\ steam\ per\ tons\ cane}$$

The amount of carbon dioxide produced by this system can be calculated as follows: [17]

$$\boldsymbol{CO2} = \frac{\mathbf{1.762\ (1-w)}}{\mathbf{5.67\ (1-w)m+1}}\ \boldsymbol{x}\ \mathbf{100}\%$$

$$= \frac{\mathbf{1.7629(1-0.51)}}{\mathbf{5.67(1-0.51)1.5+1}}$$

$$= \mathbf{16.7}\%\ \boldsymbol{by\ mass}$$

3.2.7 Results and Discussion

The following table contains the important values that were calculated during the boiler efficiency calculation in the sections above;

Table 4: All calculated quantities

QUANTITY	**VALUE**
Higher Calorific Value, HCV	8549.51 kJ/kg
Lower calorific Value, LCV	6745.88 kJ/kg
Superheated Steam Enthalpy, H_{st}	3227.31 kJ/kg
Feedwater Enthalpy, H_{fw}	422.86 kJ/kg
Total Sensible Heat Lost, q	300.39 kcal/kg
Heat Unit Transferred to the Steam, Mv	5231.19 kJ/kg
Overall Boiler Efficiency, ὴ	61.18 %
Tons Steam Generated per Ton Bagasse	1.87 Ton
Tons Bagasse Generated per Ton of Cane crushed	0.275 Ton
Tons Steam generated per Ton of Cane Crushed	0.66 Ton
CO2 Emission under these conditions	16.7 % by mass

The table above is intended to highlight the relationship between the main quantities of a bagasse fired boiler.

3.2.8 Results Conclusion

Looking at the results, the efficiency of the boiler under evaluation is within the theoretical efficiency of 50 – 65%. The overall boiler efficiency is affected by a number of quantities. The main quantities are the steam produced, feed water used and the fuel used. By changing just the moisture of the feed fuel, the calorific value would change, thus changing the overall efficiency of the boiler. In summary, a factory that crushes 6000 tons of cane per day would make 750 tons of sugar (assuming standard 8/1 cane to sugar ratio), 1650 tons of bagasse based on the calculations above, and will be capable of producing 3085.5 tons steam.

The intention of this section of the research was to introduce the reader to the main area of concentration before moving forward. The intent of the entire research is to evaluate a system that uses a bagasse gasification plant as compared to the conventional direct combustion boiler. The steam boiler evaluated was the boiler with the quantities as calculate above. In the next section, the following was considered:

- The overall energy efficiency of the steam and power generation plant, assuming using the boiler with the quantities as calculated above.

3.3 Current System HP Steam Consumption

3.3.1 Introduction

In the energy efficiency calculations of a system, the first step was to determine the efficiency of the main equipment that the system comprises. These were the boilers as per the preceding chapter. This chapter entails the current steam consumption of the factory, concentrating on the steam and power generation system equipment steam consumption. The turbo-alternators and any other steam consuming equipment will be considered as these determine the amount of exhaust steam available for process operations.

3.3.2 Outcome Objective

The outcome expected from this chapter was the understanding of the operational steam consumption of the current system. This detailed the steam consumption per steam turbine used in the factory for both the power generation via the turbo-alternators and the mechanical load for any steam turbine driven machinery.

3.3.3 Procedure

As the intent of this chapter is to report on the basic calculations involved in determining the steam consumption of a system, the approach was to discuss the general equipment/machinery that uses/consumes high pressure steam generated from the steam boilers in order to calculate the operational steam/energy efficiency as per the Rankine Cycle. The values used in the calculations are actual values from data collected from the factory operational quantities. The first step is to explain the layout of the factory.

3.3.4 Equipment Identification

The factory consists of two turbo-alternators with an installed capacity of 8.5MW. There are four other steam turbines for mechanical load used in the boilers. There are two boilers in total, one rated at 100MCR and the other at 50MCR. The four other steam turbines referred to above for the mechanical loads used in the boilers are the induced draft (ID) fan for each boiler, and the boiler feedwater pumps for each boiler. The process operations have a total of four steam turbines driving different mechanical loads. These are explained below. There are thus a total of ten steam turbines throughout the factory that utilize the HP steam to drive mechanical loads and generate exhaust steam for process operations.

Steam Turbines for Different Loads

For ease of understanding the layout, the section below will explain the usage and specification for each steam turbine.

- **Mill Number 1 and Mill Number 2 Drives**

Mill Number 1 is driven by an Elliot turbine which runs at approximately 3300rpm. The HP steam pressure to the turbine is 31bar and the nozzle box pressure ranges from 1000kPa to 1300kPa. The turbine drives a triple reduction David Brown gearbox which has a total reduction of 928:1. The primary reduction is 400:103, the intermediate is 148:25 and the final reduction is 105:26. The system is controlled by a Woodward Governor. Mill Number 2 is driven by a steam turbine similar to that of Mill Number 1. Mill Number 2 turbine, however, runs at a speed of approximately 2200rpm. The HP steam pressure is the same (31bar) and the nozzle pressure ranges from 1500kPa to 1900kPa.

Table 5: Mill 1 and Mill 2 Steam turbine specifications

Operating Specifications	
Power Output	746 kW
Speed	5500rpm
Temperature	385 °C
Inlet Pressure	29.9 kg/cm² = 29.322 bar
Outlet Pressure	1.05 kg/cm² = 1.029 bar
Trip Speed	6300 rpm
Design Specifications	
Speed	6000rpm
Inlet Pressure	49.2kg/cm² = 48.249 bar
Exhaust Pressure	5.5kg/cm² = 5.394 bar
1st Critical Speed	8560 rpm

- **2nd Cane Knives Drive and Shredder Drive**

These knives are used in the cane preparation process. The shredder is driven by the same turbine as that of the 2nd cane knives which is an Elliot turbine producing approximately 1800kW power at 4500rpm as shown below:

Table 6: 2nd knives and shredder driven steam turbines specifications

Operating Specifications	
Rated Speed	4400 rpm
Trip Speed	4700 rpm
Nozzle Box Pressure	2000kPA nozzle box pressure
Design Specifications	
Inlet Pressure	3103.45kPA
Inlet Temperature	400°C
Exhaust Pressure	103.45kPA
Maximum Continuous Speed	4500rpm
Trip Speed	4950rpm
1st Critical Speed	2100rpm
Power	
2nd Knives	1265 kW
Shredder	1790.4 kW
Speed	
2nd Knives	4400 rpm
Shredder	4400 rpm

- **Turbo-Alternator Number 1**

The steam turbine used as a prime mover is an APE Allen T5/52966 turbine, rated as follows:

Table 7: Turbo-alternator number 1 steam turbine specifications

Design Specifications	
Original manufacturer	W H Allen
Year of manufacture	1980
Type	SLC 22
Serial number	T5/52966
Configuration	Single Cylinder Back Pressure
Continuous maximum rating	5.0 MW
Inlet steam conditions	28.2 bar g / 324 °C
Exhaust steam conditions	1.03 bar g
Speed	6000 rpm
Operating Specifications (Averages)	
Inlet Steam Pressure	31bar
Inlet Steam Temperature	320 °C
Exhaust Steam Pressure	110 kPa
Exhaust Steam Temperature	135 °C

- **Turbo-Alternator Number 2**

The steam turbine used as a prime mover is an AEG A50G turbine, rated as follows:

Table 8: Turbo-alternator number 2 steam turbine specifications

Design Specifications	
Original manufacturer	AEG
Year of manufacture	1965
Type	A 50 G
Serial number	12585
Configuration	Single cylinder, backpressure
Continuous maximum rating	3.5 MW
Inlet steam conditions	30 bar g / 370 °C
Exhaust steam conditions	0.8 bar g
Speed	9346 rpm
Operating Specifications (Averages)	
Inlet Steam Pressure	31bar
Inlet Steam Temperature	320 °C
Exhaust Steam Pressure	140 kPa
Exhaust Steam Temperature	140 ^{o}C

- **Boiler Feedwater Turbines and ID Fans Steam Turbines**

Boiler Feedwater Turbines and ID Fans Steam Turbines each have steam turbines as follows:

Table 9: Boiler feedwater and ID fan turbines

Design Specifications	
Rated Speed	6000 rpm
Inlet Pressure	49.2kg/cm² = 48.249 bar
Exhaust pressure	5.5kg/cm² = 5.394 bar
1st critical speed	8560 rpm

3.3.5 Quantities Calculated

The following quantities first needed to be calculated before the final overall energy efficiency could be calculated.

- Steam consumption for each steam turbine
- Efficiency of each turbine
- Overall steam energy efficiency for the combined steam consuming equipment

The assumption was that the condensate generated equals the exhaust steam produced from the steam turbines. This is with the assumption that there are no losses during the factory process operations. All exhaust steam generated is used in the process operations, thus generating the same amount of condensate that goes back to the boiler feedwater condensate system.

3.3.6 Calculations

The steam consumption for each of the steam turbines running mechanical loads was calculated as per the following calculations:

There are three main similarities on the design specifications of the steam turbines used. These are the inlet pressure, inlet temperature and the exhaust pressure. These are similar due to the steam network design. All steam turbines share the same HP steam range at 3103.45 kPA with a temperature of 400°C and an exhaust pressure of 103.45kPA.

The complete data for each steam turbine is shown on the table below.

Table 10: Steam turbines design specifications

Equipment Name	**Power Rating (kW)**
2^{nd} Knives	1265
Shredder	1790.4
Mill Number #1	746
Mill Number #2	746
Induced Draft Air Fan #1	1265
Induced Draft Air Fan #2	336
Boiler feed Water Pump Number #1	300
Boiler feed Water Pump Number #2	300

Turbo-Alternators are the main components of the factory that uses HP steam. They use steam to drive the steam turbines that in turn drive the alternators that produce electrical power. In order to determine the steam consumption of the turbine, the steam consumption was calculated based on the steam consumption per kWh produced.

The formula used was: [22]

$$\boldsymbol{Q'} = \frac{\mathbf{860}}{(\boldsymbol{\lambda} - \boldsymbol{\lambda'})\ \boldsymbol{\mu}\ \mathbf{x}\ \boldsymbol{\rho m}\ \mathbf{x}\ \boldsymbol{\rho r}\ \mathbf{x}\ \boldsymbol{\rho g}}$$

Where:

Q' = steam consumption of the turbo alternator set, in kg/kWh

λ = total heat of the steam at the nozzle-chest in kcal/kg

λ' = total heat of the steam at the exhaust, in kcal/kg

η = thermodynamic efficiency of the turbine

ρm = mechanical efficiency of the turbine

ρr = efficiency of the reduction gearing, if it is a geared turbine

ρg = efficiency of the alternator or generator

- Value of ρm is approximately 0.985
- Value of ρg varies with power between 0.94 – 0.985
- Value of ρr varies from 0.97 to 0.985

The value of η, the thermodynamic efficiency of the turbine, depends on:

- The mechanical standard of construction
- Its power; the more powerful the turbine, the higher the efficiency
- The adiabatic heat drops; the higher the drop, the better the efficiency

The table below may be used for referencing the thermodynamic efficiency based on the type of the turbine used [22]:

Table 11: Mean thermodynamics efficiencies

Types of turbines	**Mean Values of Thermodynamic Efficiency (%)**
Impulse back-pressure turbines with reduction gear and double wheel	65
Back-pressure = 43 – 100 p.s.i.g	65 – 70
Back Pressure = 7 – 43 p.s.i.g	70 – 72
Condensing reaction turbines	75 – 80
Condensing turbines 3 – 8MW	80
Condensing turbines 20 MW	82

In order to obtain the actual steam consumption, the losses are added to the calculated steam consumption. These losses are as follow [22]:

- For losses through condensation: 3 – 5%
- For losses by leaks: 2 – 3 %

The efficiency of the complete power plant is thus, taking the normal average values:

- Efficiency of the turbine:

$\boldsymbol{\rho m} \times \boldsymbol{\rho r} \times \boldsymbol{\rho g} \times \boldsymbol{\eta}$ = 0.985 x 0.98 x 0.95 x 0.7 = **0.642**

- Losses: ρp = **0.936**

Therefore:

Efficiency x Losses = 0.642 x 0.936 = 0.600

Taking into account auxiliary equipment (feed pump, air heater, draught fan) which takes its power from the turbine to allow it to function, without direct use in the factory, we also included coefficient ρa which equals to 0.935.

We then obtained the useful energy that is contained in the steam:

$$\rho v \quad = \boldsymbol{Efficiency} \text{ x } \boldsymbol{Losses} \text{ x } \boldsymbol{Coefficient\ of\ auxiliary\ equipment}$$

$$= 0.600 \text{ x } 0.935$$

$$= \ 0.562 \ \text{ x } 100\%$$

$$= \mathbf{56.2}\%$$

3.3.7 Steam Turbines Steam Consumption

- **Turbo-Alternator Number 1**

Assumptions:

λ = total heat of the steam at the nozzle-chest in kcal/kg = 3043 kJ/kg = 726.80 kcal/kg [23]

λ' = total heat of the steam at the exhaust, in kcal/kg = 2720 kJ/kg = 649.66 kcal/kg [23]

$$\boldsymbol{Q'} = \frac{\mathbf{860}}{(\boldsymbol{\lambda} - \boldsymbol{\lambda'})\ \boldsymbol{\mu} \text{ x } \boldsymbol{\rho m} \text{ x } \boldsymbol{\rho r} \text{ x } \boldsymbol{\rho g}}$$

$$= \frac{860}{(726.80 - 649.66) \text{ x } 0.642}$$

$$= \mathbf{17.36}\ \boldsymbol{kg/kWh}$$

Turbo-Alternator Number 2

Assumptions:

λ = total heat of the steam at the nozzle-chest in kcal/kg = 3043 kJ/kg = 726.80 kcal/kg [23]

λ' = total heat of the steam at the exhaust, in kcal/kg = 2734 kJ/kg = 653.00 kcal/kg [23]

$$Q' = \frac{\mathbf{860}}{(\boldsymbol{\lambda} - \boldsymbol{\lambda}')\ \boldsymbol{\mu}\ \boldsymbol{x}\ \boldsymbol{\rho m}\ \boldsymbol{x}\ \boldsymbol{\rho r}\ \boldsymbol{x}\ \boldsymbol{\rho g}}$$

$$= \frac{860}{(726.80 - 653.00) \text{ x } 0.642}$$

$$= \mathbf{18.15}\ \boldsymbol{kg/kWh}$$

Average steam consumption for the turbo-alternators under operating conditions is as follows:

Table 12: Average turbo-alternators steam consumption

Turbo-alternator load (%)	**Steam Consumption in Tons Per Hour (TPH)**
5MW Turbo-Alternator Number 1	
10	9.075
25	22.68
50	45.37
75	68.06
100	90.75
3.5MW Turbo-Alternator Number 2	
10	6.076
25	15.19
50	30.38
75	45.57
100	60.76

Under normal operations, TA Number 1 produces approximately 3.5MW and TA Number 2 about 2 MW equating the factory load to 5.5 MW. For simplicity, we will assume that TA Number 1 is constantly loaded at 75% and TA Number 2 at 60%, thus:

$$\boldsymbol{Average\ Total\ Steam\ Consumed\ by\ both\ TAs}$$
$$= \boldsymbol{TA\#1\ steam\ consumed + TA\#2\ steam\ consumed}$$
$$= 68.06 + (60\%\ \mathrm{x}\ 3.5\ \mathrm{x}\ 17.36)$$
$$= 68.06 + 36.456$$
$$= \boldsymbol{104.516\ TPH}$$
$$say\ 105\ TPH$$

- **Steam Consumption of Turbines Driving Mechanical Load**

The formula for calculating the steam consumption of the mechanical load driving turbines is as follows: [15]

$$\boldsymbol{Ms = \frac{P}{Hhp - Hlp}}$$

Where:

M_S = Total steam consumption at operating power

P = Operating power

H_{hp} = The specific enthalpy of the steam at the turbine inlet

H_{lp} = The specific enthalpy of the steam at the turbine exhaust

Assumptions:

- Isentropic efficiency = 1
- Turbine operating at 100% Full Load
- Specific enthalpy at the turbine exhaust pressure after isentropic expansion from the HP conditions equals the specific enthalpy of the steam at the turbine exhaust

H_{hp} = 3043 kJ/kg = 726.80 kcal/kg

H_{lp} = 2675 kJ/kg = 638.91 kcal/kg

- **2nd Knives and ID Fan Number 1**

$$\boldsymbol{Ms} \quad = \frac{\boldsymbol{P}}{\boldsymbol{Hhp - Hlp}}$$

$$= \frac{1265}{(3043 - 2675)}$$

$$= \mathbf{3.43}\ \boldsymbol{TPH/Turbine}$$

- **Shredder**

$$\boldsymbol{Ms} \quad = \frac{\boldsymbol{P}}{\boldsymbol{Hhp - Hlp}}$$

$$= \frac{1790.4}{(3043 - 2675)}$$

$$= \mathbf{4.86}\ \boldsymbol{TPH/Turbine}$$

- **Mill Number 1 and Number 2**

$$\boldsymbol{Ms} \quad = \frac{\boldsymbol{P}}{\boldsymbol{Hhp - Hlp}}$$

$$= \frac{746}{(3043 - 2675)}$$

$$= \mathbf{2.03}\ \boldsymbol{TPH/Turbine}$$

- **Boiler Feedwater Pump Number 1 and Number 2**

$$\boldsymbol{Ms} \quad = \frac{\boldsymbol{P}}{\boldsymbol{Hhp - Hlp}}$$

$$= \frac{300}{(3043 - 2675)}$$

$$= \mathbf{0.82}\ \boldsymbol{TPH/Turbine}$$

- **ID Fan Number 2**

$$\boldsymbol{Ms} \quad = \frac{\boldsymbol{P}}{\boldsymbol{Hhp - Hlp}}$$

$$= \frac{336}{(3043 - 2675)}$$

$$= \mathbf{0.91}\ \boldsymbol{TPH/Turbine}$$

Total Steam Consumption by Turbines Driving Mechanical Load (M_{ST})

$$\boldsymbol{Mst} = (\mathbf{3.42x2}) + \mathbf{4.86} + (\mathbf{2.03x2}) + (\mathbf{0.82x2}) + \mathbf{0.91}$$
$$= 6.86 + 4.86 + 4.06 + 1.64 + 0.91$$
$$= \mathbf{18.33}\ \boldsymbol{TPH}$$

Therefore, Total Steam Consumption by all turbines onsite (M_{ST_T})

$$\boldsymbol{Mst_t} = \mathbf{18.33} + \mathbf{104.516}$$
$$= 122.846\ TPH$$
$$= \boldsymbol{say}, \mathbf{123}\ \boldsymbol{TPH}$$

3.3.8 Results Discussion

With the two boilers rated at 100 MCR and 50 MCR respectively, the current steam consumption as calculated above is 123 TPH. This excludes any other losses not stated on the calculations. The steam plant, therefore, operates at 82% of its capacity. The results show that the two turbo-alternators consume an average of 17.755 kg/kWh of high pressure (HP) steam. It must be noted that this is taking into consideration the turbine efficiency, gearbox efficiency, and the alternator efficiency.

3.3.9 Conclusion

Considering the amount of power generated, a case study was thus utilized to calculate the difference in steam consumption to determine whether a more efficient system should be used. With a similar amount of kWh produced, a more efficient system will theoretically consume less HP steam. The bulk of the HP steam consumption in the factory is by the turbo-alternators. This therefore implies that if the turbo-alternators were to increase their efficiency, the overall steam plant efficiency would change significantly. The direct combustion boilers configuration of steam or power generation plant efficiency depends mostly on the following aspects:

- Fuel type and quality
- Boiler efficiency
- Steam consuming equipment efficiency

3.4 Current System Efficiency

3.4.1 Introduction

In calculating the energy efficiency of a system, the first step is to determine the efficiency of the main equipment of the system. In this case, these were the boilers as per the preceding chapter. In this chapter, the context entails the current energy efficiency of the factory in terms of steam and power generation. The focus was on the steam and power generation system equipment. The turbo-alternators and any other steam consuming equipment were considered, as these determine the amount of exhaust steam available for process operations.

3.4.2 Outcome Objective

The outcome expected from this chapter is the understanding of the operational energy efficiency of the current system.

3.4.3 Procedure

To calculate the energy efficiency of a plant/factory, one needs to understand the amount of steam generated and the amount of steam used for useful work, such as power generation and mechanical load driving. These were explained in detail in the preceding chapter. This chapter focuses on the overall energy efficiency, taking into consideration the steam and power generation plants.

3.4.4 Calculations

To simplify the calculations of the current system, a simplified Rankine Cycle approach was used to represent the factory steam system. The calculations were based on the diagram below:

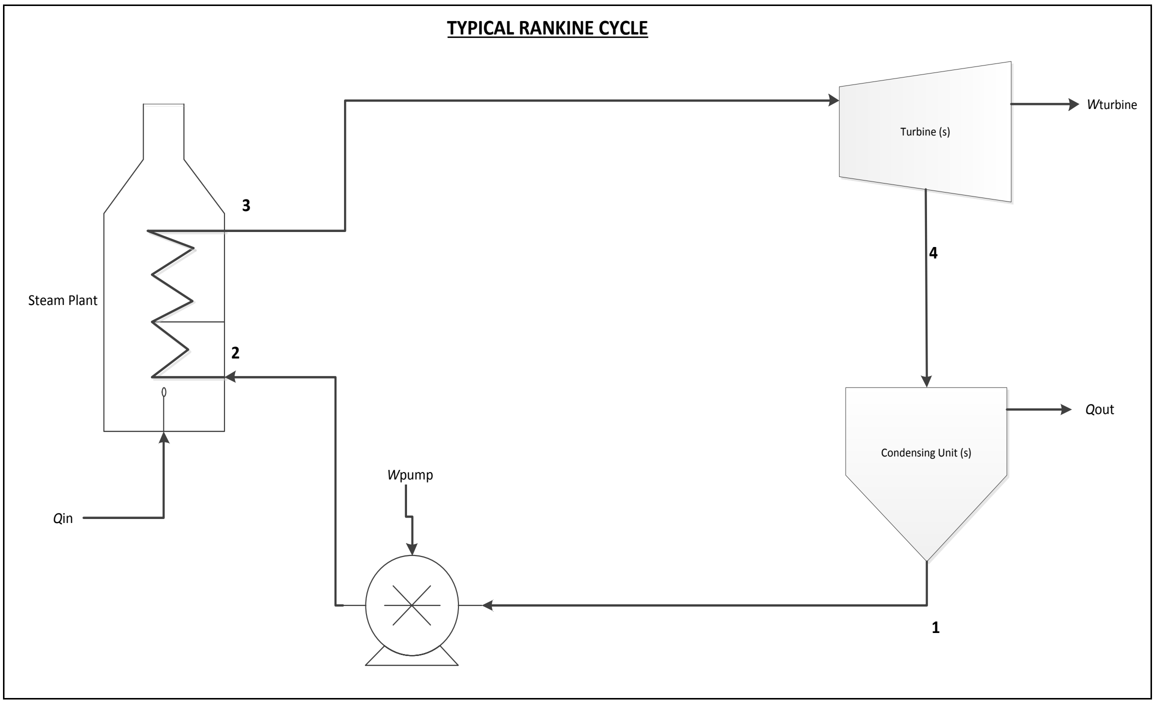

Figure 6: Typical Rankine Cycle

3.4.5 Thermal Efficiency

The data used for the calculated is tabled below:

Table 13: Enthalpy data used

DESCRIPTION	**CALCULATED QUANTITY (kJ/kg)**
Enthalpy into the boiler (h_2)	422.86
Enthalpy out of the boiler to the turbine (h_3)	3227.31
Enthalpy of exhaust (h_4)	2675.00

The thermal efficiency was calculated based on the simplified Rankine Cycle as shown on figure 3.

$$\boldsymbol{\mu\ thermal} = \frac{\boldsymbol{W\ thermal - W}}{\boldsymbol{Q\ in}} \approx \frac{\boldsymbol{W\ turbine}}{\boldsymbol{Q\ in}}$$

And:

$$\frac{\boldsymbol{Qin}}{\boldsymbol{m}} = \boldsymbol{h3} - \boldsymbol{h2}$$

Where:

h_3	= Enthalpy out of the boiler to the turbine
h_2	= Enthalpy into the boiler
m	= Mass flow
Q_{in}	= Heat flow rate

From preceding reports:

h_2 = Feed water enthalpy	= 422.86 kJ/kg
h_3 = Superheated steam enthalpy	= 3227.31 kJ/kg
m = Mass flow	= 123 tph

$$\frac{\boldsymbol{Qin}}{\boldsymbol{m}} = \boldsymbol{h3} - \boldsymbol{h2}$$

But:

$$\boldsymbol{Qin = 3227.31\frac{kJ}{kg} - 422.86\frac{kJ}{kg}}$$

$$\boldsymbol{Qin = 2804.45\frac{kJ}{kg}}$$

And:

$$\frac{\boldsymbol{Wturbine}}{\boldsymbol{m}} = \boldsymbol{h3 - h4 \ \approx (h3 - h4)\mu \ thermal}$$

Where:

h_4 = Enthalpy of exhaust = 2675 kJ/kg

Therefore:

$$\boldsymbol{Wturbine = h3 - h4}$$

$$Wturbine \ = 3227.31kj/kg - 2675 \ kj/kg$$

$$Wturbine = \mathbf{552.31}\ \boldsymbol{kj/kg}$$

Using…. (3) and … (5) on …. (1)

$$\mu\ thermal = \frac{W\ thermal - W}{Q\ in} \approx \frac{W\ turbine}{Q\ in}$$

$$\mu\ thermal = \frac{552.31}{2804.45}\ x100\%$$

$$\mu\ thermal = \mathbf{19.69}\ \%$$

3.4.6 Results Discussion

Using the knowledge and information calculated based on the current system; the overall thermal efficiency represented by a simplified Rankine Cycle was calculated to be **19.69 %.** Theory dictates that on average, a typical Rankine Cycle will have a thermal efficiency of between 22 – 24 %. The 19.69% result as calculated for this system shows that the efficiency is even lower than the typical Rankine Cycle efficiency. This is due to the fact that the typical efficiency referred to in theory in the research is average based while the calculated thermal efficiency was based on actual data taken as an average for the system under evaluation.

3.4.7 Conclusion

The calculations entailed in this chapter demonstrate what most scholars say [24], that, on average, the Rankine Cycle thermal efficiency is between 22 -24 % assuming complete combustions (no losses). During this research and calculations, the overall factory thermal efficiency represented by the Rankine Cycle was calculated to be 19.69%.

The intent of this research was to either prove or disprove the theory that states that a bagasse gasification system has a higher total thermal efficiency as compared to the direct combustion system. This is either proved or disproved through comparison of the current system of direct combustion and a typical bagasse gasification system using similar quantities as calculated based on the current system configuration. The system is based on taking the quantities of inputs used for the chapters up to this point and comparing the outputs to the use of a bagasse gasification system.

3.5 Gasification System Design

3.5.1 Introduction

For one to understand the gasification system as a replacement for the current direct combustion system, one needs to understand the main components that make the bagasse gasification unique. The gasifier has been defined in the preceding chapters. The one other system component that is critical in the overall system are the gas turbines that would utilize the produced syngas.

3.5.2 Understanding Gas Turbines

Regarding the variation of environment, the standard conditions used by the gas turbine industry are 59 ^{o}F/15 ^{o}C, 14.7 psia/1.013bar and 60% relative humidity which are established by the International Standards Organization (ISO) [25] and are frequently referred to as ISO conditions

3.5.3 Normal Gas Turbine System

The figure below represents a standard gas turbine system.

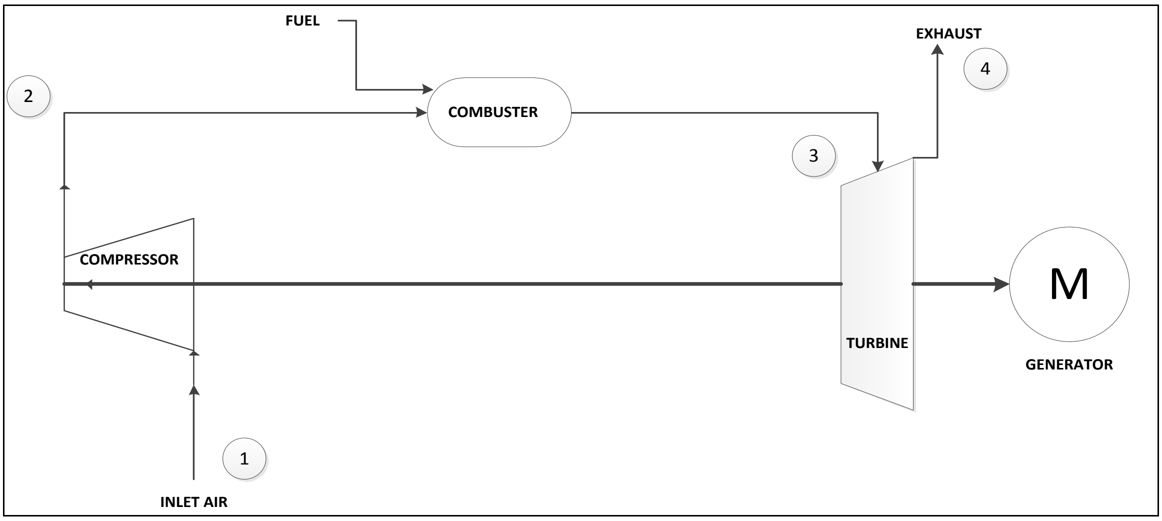

Figure 7: Normal gas turbine system

Typically, more than 50% of the work developed by the turbine sections is used to power the axial flow compressor.

3.5.4 The Brayton Cycle

This is the thermodynamic cycle of all gas turbines. The cycle is an open cycle. The main points are the Pressure Ratio and the Firing Temperature. The pressure ratio can be determined using the formula below:

$$\textit{The Pressure Ratio} = \frac{\textit{Compressor Discharge Pressure}}{\textit{Compressor Inlet Pressure}}$$

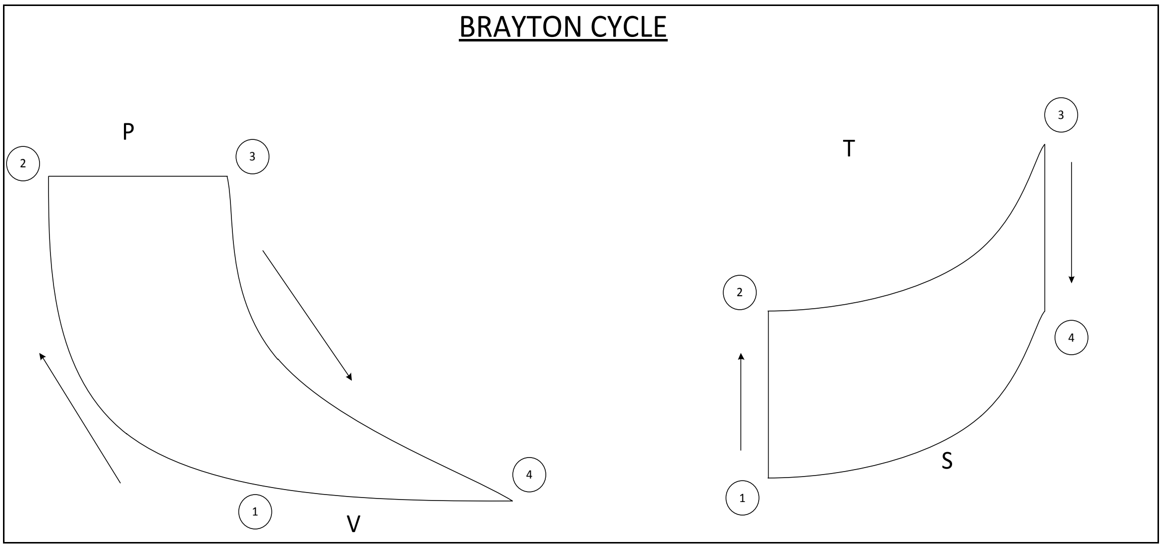

Figure 8: Brayton cycle representation

Also:

$$\boldsymbol{The\ Pressure\ Ration} = \frac{\boldsymbol{Pressure\ at\ Point\ 3}}{\boldsymbol{Pressure\ at\ point\ 4}}$$

Methods of Determine the Firing Temperature

Thermodynamic Analysis [26] state that there are two components that are important in determining the firing temperatures. These are:

- Output per pound of airflow which is important since the higher this value, the smaller the gas turbine required for the same output power, and
- The thermal efficiency which is important because it directly affects the operating fuel costs.

NB: Higher temperatures means more power

3.5.5 Combined Cycle

A typical simple-cycle gas turbine will convert 30% to 40% of the fuel input into shaft output. All but 1% to 2% of the remainder is in the form of exhaust heat [25]. Combined cycle has heat-recovery steam generators (HRSG) in the exhaust, producing steam for a steam turbine generator, heat-to-process or a combination thereof. Combined cycle producing electrical power is in the 50-60% thermal efficiency range using the more advanced gas turbines [26].

3.5.6 Factors Affecting Gas Turbine Performance

- Air temperature and site elevations
- Humidity
- Inlet and exhaust losses
- H_2O pressure drop. E.g.:
    - 4inches (10bar) H_2O inlet drop produces:
        - 1.42% power output loss
        - 0.45% heat rate increase
        - 1.9^oF (1.1^oC) exhaust temperature increases
    - 4inches (10bar) H_2O exhaust drop produces
        - 0.42% power output loss
        - 0.42% heat rate increase
        - 1.9^oF (1.1^oC) exhaust temperature increase

Work done

Work from a gas turbine can be defined as the product of mass flow, heat energy in the combusted gas (C_p) and temperature differential across the turbine.

3.5.7 Design Calculations of Downdraft Gasifier

Engine Selection

For the purpose of the calculations, the engine to be used is an engine with known properties. It is an engine with the following characteristics [27]:

Table 14: Gas engine specifications

Type: GE's Jenbacher Type 6 Twin-Turbo Engine: Type J624S	Value
Number of Cylinders (N) /arrangement	24 / 60°
Combustion	Lean burn principle
Bore (D)	190 mm
Stroke (S)	185 mm
Speed (RPM)	1500 RPM
Dimensions	11600 mm (Length) 2000 mm (Width) 2500 mm (Height)
GenSet Weight	43000 kg
Volumetric Efficiency	80 %
Displacement	Calculated below:

The engine displacement was calculated as follows:

- Engine Displacement Calculation

$$\boldsymbol{Displacement} = \frac{\boldsymbol{\pi}}{\boldsymbol{4}} \mathbf{x}\, \boldsymbol{Bore}^{2} \mathbf{x}\, \boldsymbol{Stoke}\ \mathbf{x}\ \boldsymbol{Number\ of\ Cylinders}$$

$$= 0.7854 \text{ x } 19cm^{2} \text{ x } 18.5\ cm \text{ x } 24$$

$$= 125887\ cc = 126\ l\ (= \mathbf{0.126}\boldsymbol{kl})$$

- Downdraft Gasifier Reactor Calculation

Engine Type: *as per Table 14 above*

  - Required Gas Production Rate

Engine swept volume is calculated as:

$$\boldsymbol{Vs} \quad = \frac{\mathbf{1}}{\mathbf{2}} \mathbf{x}\ \boldsymbol{RPM}\ \mathbf{x}\ \boldsymbol{N}\ \mathbf{x}\ \frac{\boldsymbol{\pi}}{\mathbf{4}}\ \boldsymbol{D}^{2}\ \mathbf{x}\ \boldsymbol{S}$$

$$= 0.5 \text{ x } 1500 \text{ x } 24 \text{ x } \frac{\pi}{4}\ (0.19^{2}) \text{x } 0.185$$

$$= 3330 \text{ x } 0.0283 = 94.42\ m^{3}/s = \mathbf{5664.90}\ \boldsymbol{m}^{3}/\boldsymbol{h}$$

- For an air-fuel (gas ratio) of 1.1:1.0, the air requirements for m^3 of gas is 1.1, thus V_g is the gas intake rate. The air + fuel intake will be $2.1V_g$. Volumetric Efficiency is taken as 80%.

Hence:

$$\boldsymbol{Vg = f \text{ x } \frac{Vs}{2.1}}$$

$$= 0.8 \text{ x } \frac{5664.90}{2.1}$$

$$= \mathbf{2158.05}\ \boldsymbol{m}^3/\boldsymbol{h}$$

- For maximum hearth load G_h of $0.9Nm^3/h\ cm^2$, the Throat Area (A_t) is given as:

$$\boldsymbol{At = \frac{Vg}{Gh\ max}}$$

$$= \frac{2158.05}{0.9}$$

$$= \mathbf{2397.84}\ \boldsymbol{cm}^2$$

Therefore: The throat diameter d_t for circular cross-section is:

$$\boldsymbol{dt = \sqrt{\frac{4 \text{ x } At}{\pi}}}$$

$$= \sqrt{\frac{4\ x\ 2397.84}{\pi}}$$

$$= 55.26\ cm = \mathbf{552.6}\ \boldsymbol{mm}$$

- The height (h) of the nozzle plane above the throat cross-section can be determined as below [28] :

$$\frac{h}{dt} = 0.4$$

$$h = 0.4 \text{ x } 552.5 \quad = \mathbf{221}\ \boldsymbol{mm}$$

- The diameter of the firebox (d_f) and the diameter of the nozzle top ring (d_n) can be determined as follows [28]:

$$\boldsymbol{\frac{df}{dt} = 2.0}$$

$$df = 552.5 \text{ x } 2.0$$

$$= \mathbf{1105}\ \boldsymbol{mm}$$

$$\boldsymbol{and\ \frac{dn}{dt} = 1.7}$$

$$dn = 552.5 \text{ x } 1.7$$

$$= \mathbf{939.25}\ \boldsymbol{mm}$$

- Assuming that 15 nozzles are used for supplying the required amount of air for gasification and noting the ratio of 100(A_m/A_t) as 4.8 for calculated throat diameter (d_m), the nozzle diameter can be calculated as follows:

$$\boldsymbol{100\left(\frac{Am}{At}\right) = 4.8}$$

$$100\ x\ Am = 4.8 \text{ x } 2397.84$$

$$Am = \mathbf{115.09}\ \boldsymbol{cm}^2$$

Therefore:

$$\boldsymbol{dm = \sqrt{\frac{4 \text{ x } Am}{\pi}}}$$

$$dm = \sqrt{\frac{4 \text{ x } 115.09}{\pi}}$$

$$dm = 12.1\ cm = \mathbf{121.06}\ \boldsymbol{mm}$$

- The air blast velocity U_m is taken as 36m/s (assumption)

- Biomass Consumption Gasifier [29]
  - The thermal efficiency of the gasifier is taken at 80%

- Thermal power consumption (full load): $P_g/0.8$ = 7312.5 kW (assuming P_g = 5850 kW = equivalent to current running value)
- Heating value of biomass (30% moisture content based on brix-free moisture content):

$$\mathbf{HCV} = \mathbf{19605} - \mathbf{196.05}\ (\boldsymbol{moisture}\ \%\ \boldsymbol{in\ bagasse}) - \mathbf{196.05}\ (\boldsymbol{ash}\ \%\ \boldsymbol{in\ bagasse}) - \mathbf{31.14}\ (\boldsymbol{brix}\ \%\ \boldsymbol{in\ bagasse})$$

$$HCV = 19606 - 196.05\ (30) - 196.05\ (4.52) - 31.14\ (1.49)$$

$$HCV = \mathbf{12790.96}\ \boldsymbol{kJ/kg}$$

Therefore:

$$Biomass\ Consumption\ Gasifier\colon \frac{7312.5}{12790.96}$$

$$= 0.5716\ kg/s$$

$$= \mathbf{2058.09}\ \boldsymbol{kg/h}$$

Thus, the installation under consideration uses ***5850/2058.09 = 2.84 kg*** biomass to produce ***1kWh*** of electricity.

3.5.8 Calculation of the Power Output of a Producer Gas Engine

The gasifier can be designed for an engine of the following specifications

- Bore = 190 mm
- Strokes = 185 mm
- Displacement (D) = 126 *L*
- The maximum air/gas intake is calculated as follows:

$$\boldsymbol{Max\ {}^{air}/_{gas}\,intake} = \frac{\mathbf{\frac{1}{2}}\ \mathbf{x}\ (\boldsymbol{rpm})\mathbf{x}\ \boldsymbol{D}}{\mathbf{60\ x\ 1000}}\quad \boldsymbol{m^3/s}$$

$$= \frac{(0.5 \text{ x } 1500 \text{ x } 126)}{60 \text{ x } 1000}$$

$$= \mathbf{1.575}\ \boldsymbol{m}^3\boldsymbol{/s}$$

- Air/gas ratio (assuming: stoichiometric of): 1.1: 1.0

$$\boldsymbol{Max\ gas\ intake}: \frac{\mathbf{1.0}}{\mathbf{2.1}} \mathbf{x\ 1.575} = \mathbf{0.75} \boldsymbol{m^3/s}$$

- The real gas intake is $\mathbf{0.75\ x}\ \boldsymbol{f}$, in which, *f* = volumetric efficiency (%) of the engine and is dependent on:
  - RPM of the engine
  - Design of the air inlet manifold of the engine
  - Fouling of the air inlet manifold of the engine

At 1500rpm, for a well-designed clean air inlet manifold ***f*** can be taken as 0.85

Therefore:

- The real gas intake is: 0.75 x 0.85 = **0.64 m^3/s**
- The heat value of the gas is taken as 5500kJ/m^3 [30]

3.5.9 Prediction of the Gas Composition

Introduction of the water-gas equilibrium concept provides the opportunity to calculate the gas composition theoretically from a gasifier which has reached equilibrium at a given temperature [28].

The procedure is to derive from mass balances of the four main ingoing elements (carbon, hydrogen, oxygen & nitrogen), an energy balance over the system and the relation given by the water-gas equilibrium. By further assuming that the amounts of methane in the producer gas per kg of dry fuel are constant (as is more or less the case of gasifiers under normal operating conditions), a set of relations becomes available, permitting the calculation of gas composition for a wide range of input parameters (fuel moisture content) and system characteristics (heat losses through convection, radiation and sensible heat in the gas). Theoretically calculated gas compositions are given in [28]. . Generally, a reasonably good agreement with experimental results is found. The composition of gas from commercial wood and charcoal gasifier is given in table 15 below [28]:

Table 15: Gas composition gas from commercial gasifier

Composition of Gas from Commercial Wood and Charcoal Gasifier		
	Wood Gas Vol.%	**Charcoal Gas Vol.%**
Nitrogen	50 – 54	55 – 65
Carbon Monoxide	17 – 22	28 – 32
Carbon Dioxide	9 – 15	1 – 3
Hydrogen	12 – 20	4 – 10
Methane	2 – 3	0 – 2
Gas Heating Value (kJ/m³)	5000 – 5900	4500 – 5600

3.5.10 Gasification Efficiency

A definition of the gasification efficiency of the gas used for engine application is given by:

$$\boldsymbol{\mu m} = \frac{\boldsymbol{Hg} \text{ x } \boldsymbol{Qg}}{\boldsymbol{Hs} \text{ x } \boldsymbol{Ms}} \text{ x } \mathbf{100}\%$$

Whereby:

μ_m = Gasification Efficiency

H_g = Heating value of the gas (kJ/m³)

Q_g = Volume flow of gas (m³/s)

H_s = Lower heating value of gasifier fuel (kJ/kg)

M_s = Gasifier solid fuel consumption (kg/s)

These quantities are as follows from preceding calculations:

$\boldsymbol{Hg} = 5500\ kJ/m^3$

$\boldsymbol{Qg} = 0.64\ m^3/s$

$\boldsymbol{Ms} = 0.5716\ kg/s$

$$\boldsymbol{Hs = 18260 - 207.01\,Ww - 182.60\,Wa - 31.14\,Wrds} \qquad [18]$$

$$= 18260 - 207.01\text{x}30 - 182.60\text{x}4.52 - 31.14\text{x}1.49$$

$$= 18260 - 6210.3 - 825.35 - 46.39$$

$$= \boldsymbol{11177.96\ kJ/kg}$$

Therefore:

$$\boldsymbol{\mu m = \frac{Hg \text{ x } Qg}{Hs \text{ x } Ms}}$$

$$= \boldsymbol{\frac{5500 \text{ x } 0.64}{11177.96 \text{ x } 0.5716} \text{ x } 100}\%$$

$$= \boldsymbol{55}\ \%$$

3.5.11 Conclusion

This chapter discussed the gasification system design and efficiency calculations. Gas turbines theory was discussed in order to understand the basic normal gas turbine system. Also the Brayton Cycle model was briefly discussed to give context to the thermodynamics cycle of gas turbines. A typical gasifier size was calculated in order to give context to the equipment that are used in a gasification system. Using a known gas engine details, the biomass or bagasse consumption was calculated to be 2058.09 kg/h. This meant that the biomass used to generate a 1kWH of electricity was calculated to be 2.84kg. This was based on a 5.85 MW gas engine. The overall gasification system thermal efficiency was calculated to be 55%. This means that the gasification system thermal efficiency is above that of the conventional system as the conventional system efficiency was calculated on chapter 5 as 19.69%.

3.6 Other Considerations

3.6.1 Introduction

The research objective was to establish whether a gasification system has higher thermal efficiency than the conventional direct bagasse combustion system. The process of steam and power generation using bagasse as the main fuel involves not only the process of just converting water to steam but other considerations need to be considered during the study of such systems. These are considerations such as the impact of bagasse moisture on the system, currently known issues with bagasse handling, the economic consideration as every project should have returns on investment and the safety considerations are amongst the other considerations on such a system. The safety consideration takes into account the hazards associated with fire, the explosion hazards and the environmental hazards. Bagasse moisture can be controlled through bagasse drying. This can be done in two main approaches, the direct bagasse drying or the indirect bagasse drying. These two are also discussed in this chapter.

3.6.2 Bagasse Moisture

Bagasse moisture plays a pivotal role on the overall system thermal efficiency. As seen in the calculation of the HCV, it is evident that minimum moisture will result in maximum HCV if all other quantities remain constant. It is therefore critical to ensure that means of reducing bagasse moisture are explored. This would in turn increase the overall HCV and thus the thermal efficiency of the system.

3.6.3 Bagasse Drying

The bagasse can be dried out using one of two drying methods. These are indirect or non-contact dryers and direct or contact dryers.

3.6.3.1 Indirect Bagasse Drying

The indirect bagasse drying units are also called non-adiabatic units, where the heat transfer medium is separated from the product to be dried by a metal wall. In bagasse drying, the heat transfer is only through conduction and forced convection.

3.6.3.2 Direct Contact Bagasse Drying

In this system, the heat is directly transferred onto the bagasse. The bagasse is dried by evaporating the moisture via heating. The advantages of this system are that there is short residence time and the drying process is uniform.

The bagasse drying process would be simpler in the case of the gasification process, as the resulting tar is at higher temperatures and can be used for this purpose.

3.6.4 Some Issues with Bagasse Handling

Bagasse is generally available in bulk quantities in most sugar factories that do not sell it to other companies such as the paper industry. The problem, however, arises when evaluating the gasification system designs. Unlike the current direct combustion boilers, which are merely a large chamber where bagasse is just thrown in and burnt, the gasification system uses gasifiers. Bagasse gasifier designs that are currently available utilize enclosed cylindrical reactors. This calls for a properly controlled feed system into the gasifier. The current belt conveyors may not necessarily work; instead, tubular conveyors may be required to direct the bagasse into the gasifier. This also requires a very dry bagasse to prevent chokes. The consideration of the bagasse handling system still needs to be investigated further. Also, the sustainability of the bagasse supply needs to be investigated further especially in the case of co-generation since the downtime due to bagasse shortages would not be acceptable and the national grid would not accept constant power dips in their system.

3.6.5 Economic Baseline Assumption

The economical evaluation in this context was to look at the average operational cost of the direct bagasse combustion as compared to the bagasse gasification operational cost. The economic evaluation will be assuming a labour wages in the ranges of between R50 – R160/hour with the price of bagasse being negligible. In the current direct bagasse combustion system, it was assumed that the boiler is attended by five personnel at an average cost of R100/hour each. This, therefore, would result in a labour wages of R500/hour total cost. This would equate to R84 000/week. Reducing the number of operators to three would reduce the overall weekly labour cost by R29 600/week. The five versus three employees were based on operational needs. Regarding the conventional operations, one would require an operator on the ground floor, the firing floor, the feeder chutes floor, a control operator, and an overall bagasse handling attendant, while on the bagasse gasification system one would require the control operator, the gasifier feed attendant, and the output product attendant.

- The capital cost
    - This is the initial expenditure that would be required for a new system. The context of this research did not undergo comprehensive cost study. This can be attended to on a feasibility study of a particular project.
- Service and maintenance cost
    - The service and maintenance costs would also be covered if a comprehensive study of a particular project was to be conducted.

3.6.6 Safety

With any system design, it is critical to consider safety. In the context of this section, a few hazards were highlighted.

3.6.6.1 Fire Hazards

There were a few causes of fire hazards identified for consideration. These are:

- High surface temperature
- Risk of spark during refuelling
- Flames through gasifier air inlet on refuelling lid

The precaution measures to be taken for the above are as follows:

- Insulate hot parts,
- Double sluice filling device, and
- Installation of back-firing valve in the inlet of a gasifier, respectively

3.6.6.2 Explosion Hazards

Explosion hazards in a gasification plant are possible if enough air/fuel mixture is reached under certain conditions. The causes of this may be due to the following:

- Air leakage into the gas system
- Air penetration during refuelling
- Back firing from the exhaust burner when the system is filled with mixture
- Air leakage into a cold gasifier still containing gas which subsequently ignites

3.6.6.3 Environmental Hazards

Ash does not contain any substance that may be environmentally hazardous. Disposal can therefore be done in a normal but controlled manner.

The properties of exhaust emissions from engines run on producer gas are generally considered to be acceptable, comparable to those of diesel engine, thus there are no significant environmental hazards to the gasification system if all emitted gases are controlled.

3.6.7 Conclusion

The other considerations chapter introduced bases of further studies in this field. Some of these considerations directly affect the feasibility of using the bagasse gasification. The main aspect of these considerations being is the bagasse moisture. Although the direct bagasse combustion is affected by the moisture in bagasse, the gasification system may be affected even more due to the design of the system. For instance, the bagasse gasification system fuel feed is through pipes instead of conveyors and chutes. These pipes may block or choke if the bagasse moisture is not adequately controlled. The presence of gas in the system introduces other safety hazards which need to be identified and mitigated against during the system design. Safety, fire and environmental hazards should be thoroughly considered during the system design.

CHAPTER FOUR: Results and Analysis

4.1 Introduction

The study entailed in this research paper has taken different routes. On one hand, it was meant to give an understanding of the efficiencies of the current system which uses direct combustion boilers and on the other hand, it was trying to use a known system to analyze the efficiencies if the system was to either be converted into a standalone gasification plant or incorporating the gasification plant into an existing system as an IGCC system. It is, therefore, critical to review all the important values that would assist in the conclusion which would either prove or disprove the theory that states that gasification plant efficiency is higher than conventional system.

4.1 Boiler Efficiency

The boiler efficiency was calculated in chapter 4 using known actual values and was found to be 61.18%. This is the value that all succeeding calculations were based on.

4.2 Steam Generated Per Ton of Bagasse

It is critical to know the amount of steam that can be generated based on the values used on the calculations. The values used were averages of actual data from an actual working system. This value was found to be 1.87 tons steam per ton bagasse

4.3 Tons Bagasse per Ton Cane

The analysis were based on a cane sugar manufacturing factory, it was thus important to understand the relationship between the amount of bagasse produced by crushing a ton of cane. This was determined to be 0.275 tons bagasse per ton of sugar cane crushed. This value was based on research.

4.4 Steam Generated Per Ton of Cane Crushed

The steam generated can be related to the amount of bagasse used. However, it is also advantageous for the understanding of sugar factory operations to directly relate the amount of steam generated to the tons of cane crushed. This was found to be approximately 0.66 tons of steam generated per ton of cane crushed. This value was based on actual data based on the condition of an actual working factory.

4.5 Environmental Considerations

To consider the environmental impact, the system has, the CO_2 produced was calculated to be 16.7% by mass.

4.6 Steam Consumption

The total steam consumption was calculated to be an average of 123 tons per hour based on the data used. This value has taken into consideration the average produced electrical power which is produced at 17.36 kg of steam per kWh and 18.15 kg of steam per kWh for Turbo-Alternator 1 and Turbo-Alternator 2 respectively.

Average Steam Consumption by the Turbo-Alternators

The two turbo-alternators are operated at different averages quantities. In this case, for the ease of understanding the calculations, Turbo-Alternator Number 1 was taken at 75% of its designed capacity and Turbo-Alternator Number 2 was taken at 60% of its designed capacity. These values are based on known normal operations.

75% of TA Number 1 refers to 75% of 5MW which equates to 3.75 MW and 60% of TA Number 2 refers to 60% of 3.5 MW which equates to 2.1 MW. 5MW and 3.5 MW are the rated capacity of TA Number 1 and TA Number 2 respectively.

The total steam per TA is thus simply calculated as follows:

$$\mathbf{3.75}\ \boldsymbol{MW}\ \mathbf{x}\ \mathbf{17.36}\ \boldsymbol{TPH} = \mathbf{65.1}\ \boldsymbol{TPH\ steam\ for\ TA}\mathbf{1}$$

$\mathbf{2.1}\ \boldsymbol{MW}\ \mathbf{x}\ \mathbf{18.15}\ \boldsymbol{TPH} = \mathbf{38.115}\ \boldsymbol{TPH\ steam\ for\ TA}\mathbf{2}$

$The\ total\ of\ which\ is\ 65.1 + 38.115 = \mathbf{103.215}\ \boldsymbol{TPH\ steam\ on\ average}$

The average power produced by the TAs is:

$$= 3.75 + 2.1$$

$$= 5.85\ MW$$

$$= \mathbf{5850}\ \boldsymbol{kW}$$

Therefore:

$\boldsymbol{The\ average\ steam\ consumption\ by\ the\ power\ generation\ plant}$:

$$= \frac{103.215\ TPH}{5.85\ MW}$$

$$= \mathbf{17.64}\ \boldsymbol{TPH/MW}$$

In summary, the above implies that for the generation of 75% of TA Number 1 full capacity and 60% of TA Number 2 full capacity, the average steam used to produce 1MWh is 17.64 TPH.

4.7 Exhaust Steam Generated

Since the sugar processing plant requires exhaust steam for sugar processing, it is important to take into consideration the amount of exhaust steam that this current system generates. Assuming a perfect system, the exhaust generated equals the total HP steam produced. In this context, that is 123TPH.

4.8 Thermal Efficiency

The overall thermal efficiency of the current direct combustion system was calculated using the concept of representing the entire system as a single Rankine Cycle system. The calculated total efficiency for the system was found to be 19.69 **%.** This implies that any other system that would have a thermal efficiency of 19.70 % or above (under identical conditions) can be considered to be more efficient than the current system.

4.9 Gasification Plant Efficiencies

It is vital to analyze the known efficiencies for the gasification plant in order to conclude on proving or disproving the theory that states that the gasification system is more efficient than the current direct combustion system.

4.10 Gasifier Thermal Efficiency

Similarly to the boiler in the direct combustion system, the gasifier is the main component of a gasification system, thus its efficiency is critical. The efficiency of the gasifier on its own was taken as 80%. This was based on scholarly research.

4.11 Bagasse Consumption by the Gasifier

The bagasse consumption by the gasifier was calculated to be 0.5716 kg/s based on the gasifier specifications calculated in Chapter 7. This equates to 2058.09 kg/h.

This therefore implies that to produce a 1MWh of power, 2.84 TPH of bagasse is required.

4.12 Gasification Efficiency

The total gasification system efficiency was calculated to be 55 %

4.13 Summary

From the conventional system, one requires 9.549 Tons of bagasse to produce 1 MWh of electrical power as compared to the 2.84 tons of bagasse required to produce the same amount (1MWh) in a gasification system. This is based on the previous calculations that showed that one 1 ton of steam is produced from 0.5347 tons of bagasse which was calculated in chapter 3 that stated that 1.87 tons of steam is generated per ton of bagasse. The data above is represented by the table below:

Table 16: Final Data Analysis

Quantity	**Value**
Boiler efficiency	61.18%
Steam generated per ton of bagasse	1.87 tons
Tons bagasse per ton of crushed cane	0.275 tons
Steam generated per ton of cane crushed	0.66 tons
Carbon Dioxide emitted	16.7%
Total steam consumption	123TPH
Total steam consumed by the power generation plant	17.64 TPH/MW
Thermal Efficiency	19.69%
Gasification efficiency	55%
Gasification Thermal Efficiency	80%
Bagasse consumption by the gasifier	2.84 TPH/MW
Summary:	
Conventional System	9.549 Tons bagasse consumed per 1MWH of Electrical Power produced
Gasification System	2.84 Tons bagasse consumed per 1MWH of Electrical Power produced.

4.14 Conclusion

The final analysis chapter presented the summation of all the calculations entailed in this dissertation. This chapter summarized all the data used for the conclusion of the dissertation. This includes amongst others, the boiler efficiency, the steam generated per ton of bagasse, the tons of bagasse produced per ton of sugar cane crushed, the steam generated per ton of sugar cane crushed, steam consumption and the thermal efficiencies of both the conventional direct combustion system and the bagasse gasification system.

4.15 Heat Recovery Steam Generator

4.15.1 Introduction

The sugar industry is a business that produces sugar as its main product. All other products are considered downstream products. Although these products may increase the company revenue, they are, however, a secondary operation. Thus, any changes in the system need to cater for the primary operation, which is sugar production.

The gasification system is a system that concentrates mainly on improving the power generation efficiency by allowing the system to produce more electricity with the same amount of fuel as compared to the direct combustion system. As the steam required is also reduced in a bagasse gasification system, the savings or benefit are also in that less water (BFW) is required when there is a gasification plant integrated into an existing factory.

It is thus important to ensure that if one incorporates a gasification system into an existing system, one considers the factory steam requirements. The sugar processing process uses exhaust steam in its operation. The system under evaluation requires this steam to remain at an average of 123TPH at approximately 130kPa (gauge). If a gasification plant is to be incorporated as an IGCC system, a heat recovery steam generator is critical.

4.15.2 Heat Recovery Steam Generator

An HRSG is an energy recovery heat exchanger that recovers heat from a hot gas stream. It produces steam that can be used in a process such as in the case of a cogeneration plant or used to drive a steam turbine to further increase the electrical power generated and generate exhaust steam for other operations such as sugar processing in a sugar factory.

4.15.3 Major Components of a Heat Recovery Steam Generator

There are ideally three major components in an HRSG that are critical. These are the economizer which uses the exit flue gases to preheat the feed water entering the system, the evaporator which is where the actual water to steam conversion takes place and the super heater that superheats the steam from the evaporator.

4.15.4 Integration into the current system

The current system that uses the direct combustion boiler already has these main components. The difference is the configuration of which instead of firing the bagasse in the furnace, the furnace would be replaced by the ducting from the gas outlet stream of the gas engine. This gas would perform a similar function as that performed by the furnace.

Depending on the application required, the ducting can be controlled into different streams. If only the direct heating is required, a different stream can be used to direct the gas heat to that area. The heat also can be controlled to work in conjunction with the current direct combustion system. In this case, the furnace would still remain but the internal heat would be buffered by the gases while the system can still be run with minimum or no gases through a direct combustion operation in the boiler furnace.

The system can easily be integrated by substituting or linking the hot gases to the currently installed forced draft air or secondary air that currently is coming from an air heater at much lower temperatures than the gas from a gas engine gas exit point.

4.15.5 Requirements for the System

The system must fulfill the following requirements:

- Allow the ease to change over to the current direct bagasse combustion system as every new system takes time to be fully trusted to work as a standalone system.
- Be able to run from cold start at the same or quicker time than the current system
- Consume less fuel (bagasse) for the same kWh generated
- Still ensure sufficient steam to the process department for sugar processing is available.

4.15.6 Conclusion

The importance and composition of the heat recovery system was discussed in this chapter. Since the system is designed for the sugar manufacturing factory, the core business of the sugar manufacturing organization is to produce sugar. Therefore, this chapter identified the requirements of the system in order to ensure that it is in line with the core business of the sugar industry. These considerations were noted on section 9.5 under the topic of “requirements for the system”.

The consideration of the heat recovery system is also crucial in order to determine how the bagasse gasification system can be adopted to fit within the current direct bagasse combustion system. The integration of a bagasse gasification system into the current direct combustion system would be advantageous to the industry as there would be ease of reverting back to the current system in the event of adverse impact on operations during the early stages of bagasse gasification integrated system as all new systems need to be learned.

CHAPTER FIVE: Conclusion and Recommendations

5.1 Conclusion

The steam turbine efficiency is determined using the Rankine Cycle. In the Rankine Cycle, the steam is used as the working fluid. The system can be summarized as follows:

The water is pumped into a high pressure (HP) steam boiler. The water is boiled and converted into HP steam at high temperatures by the addition of heat. This heat is obtained by a direct combustion of bagasse in the furnace. The steam expands in a steam turbine and after work done, it becomes exhaust steam. The exhaust steam is condensed (or sent to the process as required), into water and used as the boiler feed water. This completes the Rankine Cycle.

The net work done per cycle is the difference between the work produced by the steam as it expands and the work put from the external source to pump the water into the boiler. The higher the pressure and temperature of the steam in the boiler, the higher is the power output.

The gas turbine uses the Brayton Cycle. The working fluid in this cycle is a gas at high pressure and temperature. The system can be summarized as follows:

The working fluid is introduced into the gas turbine. The gas is allowed to expand inside the turbine blades, converting energy and producing work. The working fluid is then discharged as exhaust. The efficiency of the Brayton Cycle depends on the temperatures at which the working fluid is introduced and exhausted, and the compression ratio.

5.1.1 Comparing the Efficiencies between the Two Systems

The Brayton Cycle is said to be more efficient than the Rankine Cycle as it has been mentioned that a gasification system produces gas at very high temperatures that can go up to 1000°C. The other advantage of the Brayton Cycle is that the exhaust gas from the gas turbine has enough energy to operate a Rankine Cycle (in a combined cycle).

5.1.2 Problems with Bagasse Gasification

Although studies have shown that the gasification process is more efficient than the current direct combustion process, there are a number of obstacles that need attention before the system can be widely implemented. Some of these obstacles are the feeding and operation of high capacity pressurized gasifiers, the gas cleaning with complete tar cracking, separation of alkali and particles from the gas produced, modification of gas turbines for using the syngas, and obtaining the high performance comparable to other gas turbines. Another major obstacle is the capital and operational costs involves. The gas produced during gasification may contain large quantities of methane and other light carbons. There should be an option to convert these compounds into CO and H_2 at high temperatures and in the presence of a catalyst such as nickel. [*Sugarcane bioethanol, SBESD, Brazil, 2008*[15]

The major concern about this technology is the inaccessibility of documented results that would attract investors to invest in practical trials in South Africa.

5.1.3 Challenges Encountered During the Research

The research idea included practical experiments at the beginning, however, as the research proceeded, it was clear that conclusive practical experiments would be challenging to undertake as it was difficult to find a working prototype of a bagasse gasifier in South Africa. The research has thus ended taken a theoretical approach to the problem.

5.2 Recommendations

Research shows that bagasse gasification systems are more efficient than the current direct bagasse combustion systems. The inaccessibility of practical medium scale prototypes is one of the limitations in the progression of testing and evaluating the system for industrial adoption. The following still warrants further investigation:

- Building relationship with countries such as China, who has tested systems using different fuel feeds such as rice husks so that prototypes can be designed to accommodate bagasse as the feed.
- Bagasse handling and drying needs to form part of the feasibility study as it plays a vital role in the process of bagasse gasification. The moisture content of the bagasse needs to be as low as possible.
- Generated gases need to be thoroughly analysed to ensure they are within acceptable levels by the Department of Environment Affairs in the country.
- A full scale prototype needs to be built within the country that would allow further practical analysis to be undertaken. This can be done through institutions such as the Sugar Milling Research Institute.

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