TYPICAL BAGASSE BOILER EFFICIENCY

Distribution at your own risk

September 2014

Soft Copy: http://www.hailienene.com/personal-library.php

CONTENT PAGE

Title **Page**

TABLES

1. INTRODUCTION

It is vital to understand the basic efficiency calculation approach for a conventional bagasse fired HP steam boiler before any studies of new systems can be undertaken. The content of this report entails details on 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 are actual data courtesy of ISL: Eston Factory Data (LIMS, 2014).

2. OUTCOME OBJECTIVE

The outcome expected from this report in the understanding of the operational efficiency of a bagasse fire steam boiler using the conventional direct combustion method as the fire combustion method.

3. PROCEDURE

As the intent of this report is to report on the basic calculations involved in determining the boiler and/or energy efficiency of a system, the approach will be 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.

4. 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 (Hugot, 1986):

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

From the contents above, to reduce it down to actual values in a sugar factory, these can be explained as follows:

- The water (45 – 50%) is referred to a bagasse moisture
- The insoluble are refers to the ash content in the bagasse
- The substances in the water are refers to pol percent in bagasse
    - Whereby 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) (Engineers, 1999)

5. QUANTITIES TO BE CALCULATED

The following quantities will be first need to be calculated in order to calculate 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

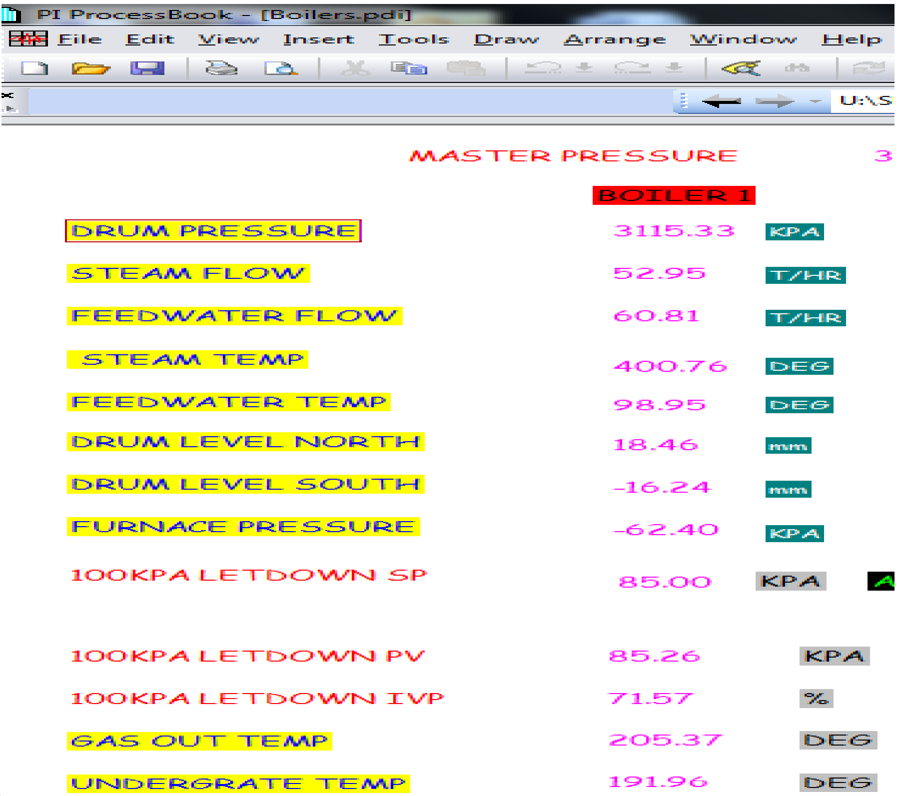
The overall boiler efficiency will then be calculated based on the higher calorific value (HCV).

6. CALCULATIONS

[Actual Data taken on (to date average): 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	350 °C
Feedwater 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

Table 1: Steam Boiler DATA



MASTER PRESSURE 3

BOILER 1

DRUM PRESSURE	3115.33	KPA
STEAM FLOW	52.95	T/HR
FEEDWATER FLOW	60.81	T/HR
STEAM TEMP	400.76	DEG
FEEDWATER TEMP	98.95	DEG
DRUM LEVEL NORTH	18.46	mm
DRUM LEVEL SOUTH	-16.24	mm
FURNACE PRESSURE	-62.40	KPA
100KPA LETDOWN SP	85.00	KPA
100KPA LETDOWN PV	85.26	KPA
100KPA LETDOWN IVP	71.57	%
GAS OUT TEMP	205.37	DEG
UNDERGRATE TEMP	191.96	DEG

(System, 2014)

Table 2: Screen shot of boiler quantities_PI System

6.1. Higher Calorific Value (HCV) of the bagasse

The HCV or GCV is the theoretical value of which is it 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 (Hugot, 1986). The following are the HCV the LCV values, respectively under the conditions as seen on Table 1: Steam Boiler DATA above.

HCV = 19605 – 196.05 (moisture% in bagasse) – 196.05(ash% in bagasse) – 31.14 (brix% in bagasse) (Lawler, 2011), similarly,

HCV $= 196.05 \times (100 - W_w - W_a) - 31.14 \times W_{rds}$ (Rein, 2007)

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

$= 196.05\ (44.07) - 46.34$

= 8549.51 kJ/kg

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

LCV $= 18260 - 207.01w_w - 182.60w_a - 31.14w_{RDS}$ (Rein, 2007)

$= 18260 - 207.01*51.41 - 182.60*4.52 - 31.14*1.49$

$= 18260 - 10642.38 - 825.35 - 46.39$

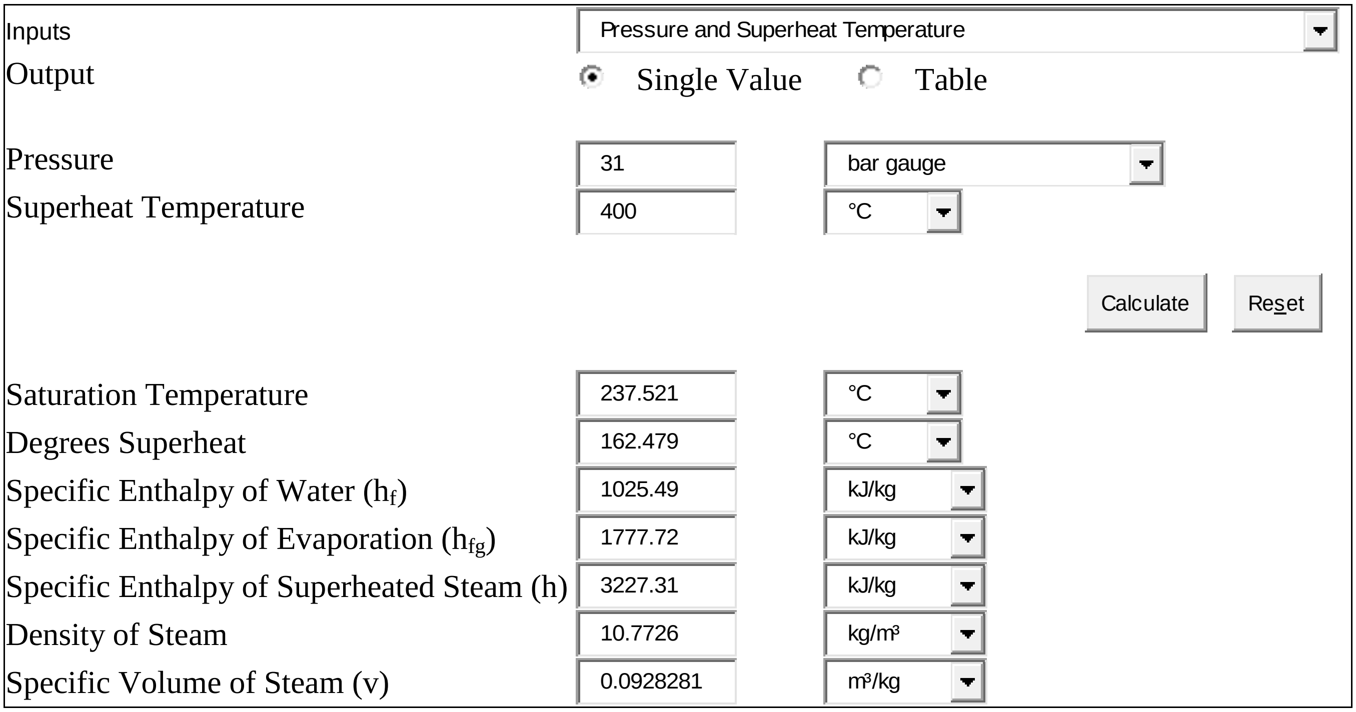
= 6745.88 kJ/kg

Where:

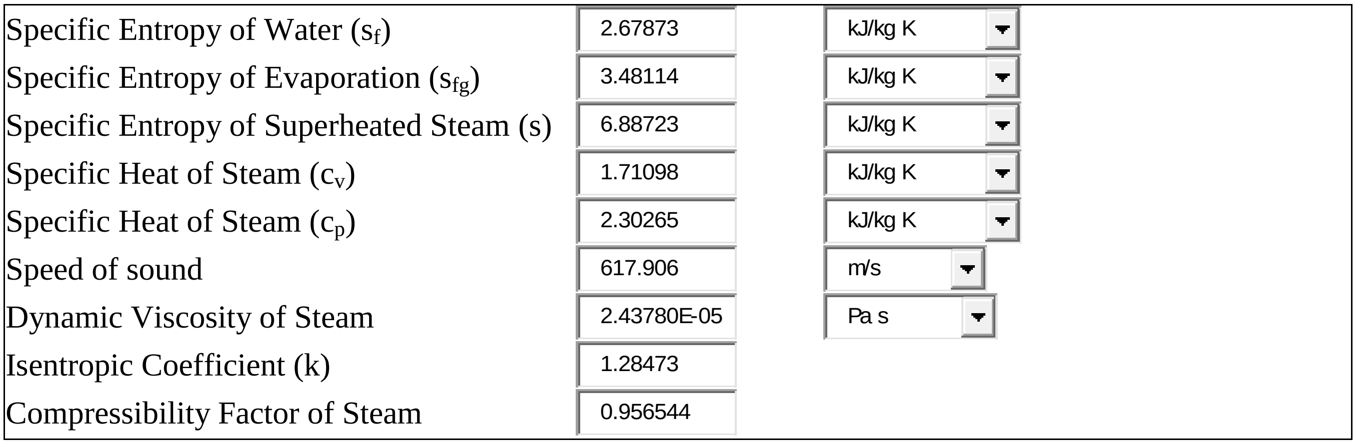
- LCV *is the lower heating value whereby the latent heat of evaporation is subtracted from the HCV with the assumption that at the end of the combustion cycle, the water ends up as vapour.*

6.2. 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. (Department of Chemistry, 2014). The enthalpy values for the context of these calculations are calculated via the table below:



Inputs	Pressure and Superheat Temperature	
Output	● Single Value	○ Table
Pressure	31	bar gauge
Superheat Temperature	400	°C
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



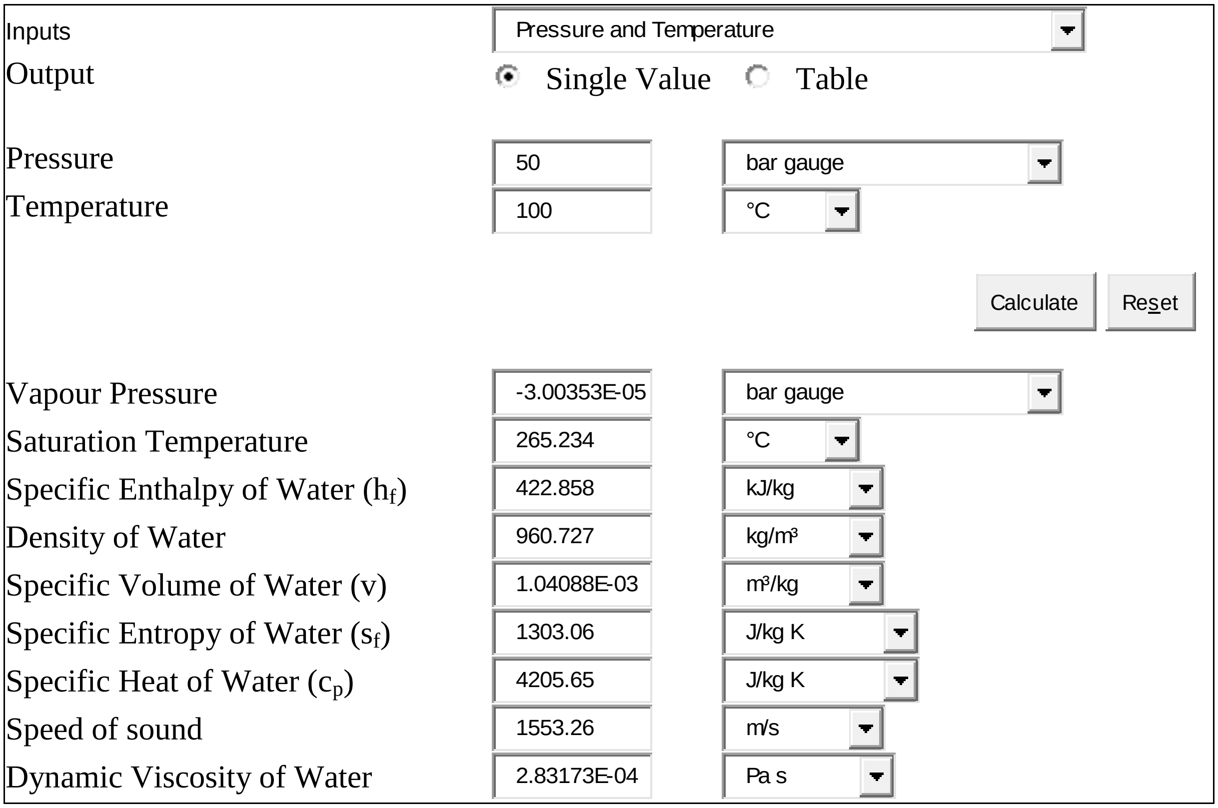
Specific Entropy of Water (s_f)	2.67873	kJ/kg K
Specific Entropy of Evaporation (s_{fg})	3.48114	kJ/kg K
Specific Entropy of Superheated Steam (s)	6.88723	kJ/kg K
Specific Heat of Steam (c_v)	1.71098	kJ/kg K
Specific Heat of Steam (c_p)	2.30265	kJ/kg K
Speed of sound	617.906	m/s
Dynamic Viscosity of Steam	2.43780E-05	Pa s
Isentropic Coefficient (k)	1.28473	
Compressibility Factor of Steam	0.956544	

(Spirax Sarco Limited, 2014)

Table 3: Enthalpy of Superheated Steam Calculation

From the table above, the calculated value using the spiraxsarco software for the superheated steam is 3227.31 kJ/kg. Table 3: Enthalpy of Superheated Steam Calculation. 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 spiraxsarco software Table 4: Enthalpy of Feed Water Calculation. This also can be verified using the standard sub saturated water region on a steam table.



Inputs	Pressure and Temperature	
Output	● Single Value	○ Table
Pressure	50	bar gauge
Temperature	100	°C
Vapour Pressure	-3.00353E-05	bar gauge
Saturation Temperature	265.234	°C
Specific Enthalpy of Water (h_f)	422.858	kJ/kg
Density of Water	960.727	kg/m^3
Specific Volume of Water (v)	1.04088E-03	m^3/kg
Specific Entropy of Water (s_f)	1303.06	J/kg K
Specific Heat of Water (c_p)	4205.65	J/kg K
Speed of sound	1553.26	m/s
Dynamic Viscosity of Water	2.83173E-04	Pa s

(Spirax Sarco Limited, 2014)

Table 4: 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:

Enthalpy of superheated steam (hst)	3227.31 kJ/kg
Enthalpy of feed water (hfw)	422.86 kJ/kg

Table 5: Enthalpy of Superheated Steam and Feed Water

6.3. 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 achieved by the indirect method

Direct Method

$$\text{Boiler Efficiency} = \frac{(\text{Mass Steam} \times \text{Enthalpy Steam}) - (\text{Mass BFW} \times \text{Enthalpy of BFW})}{(\text{Mass Fuel} \times \text{CV Fuel})}$$

(Lawler, 2011)

Indirect Method

$$\text{Boiler Efficiency} = \frac{(\text{Energy in Fuel} - \text{Energy Losses})}{(\text{Energy of Fuel})} \times 100$$

OR

Boiler Efficiency = 100 – L1 – L2 – L3 – L4 – L5 – L6

Where:

L1 = Latent heat of the water formed by combustion of hydrogen in the bagasse

L2 = Latent heat of the water contained in the bagasse

L3 = Sensible heat of the flue gas leaving the boiler

L4 = Losses in unburned solids

L5 = Losses by radiation from the furnace and especially from the boiler

L6 = Losses due to bad combustion of carbon giving CO instead of CO_2

Losses L1 and 2 are accounted for in the NCV formula.

Loss L3 is given by the following formula:

The formula to be used for these calculations is the indirect approach which is more realistic and more accurate than the direct method. Overall Boiler Efficiency can be calculated using the following formula:

$$q = Mv / Ns$$ (Hugot, 1986)

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

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

$$\mathbf{M_v} = (4250 - 4850w - q)(\alpha\beta\eta)$$ (Hugot, 1986)

Where:

Mv = 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 (Hugot, 1986)

β = radiation losses – ranges between 0.90 – 0.95 depending on the lagging of the boiler (Hugot, 1986)

η = losses due to incomplete combustion – ranges between 0.99 – 0.8 (Hugot, 1986)

Total Sensible Heat Lost (q) = t(1-w)[1.4m + (0.50)/(1-w) – 0.12] (Hugot, 1986)

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; (Hugot, 1986))

Therefore:

Total Sensible Heat Lost (q) = [(1 – w) (1.4m – 0.13) + 0.5] t kcal/kg
= [(1 – 0.51)(1.4*1.5 – 0.13) + 0.5] 205
= [(0.49)(1.97) + 0.5]205
= 300.39 kcal/kg

Q can be approximated as 1.5t; however, we will use the actual calculated value for further calculations. Heat unit transferred to the steam is given by $M_{v:}$

M_v **=** (4250 – 4850w – q)(αβη)
= (4250 – 4850*0.51 – 300.39)(0.99*0.95*0.90)
= (1476.11)(0.846)
= 1249.45 kcal/kg
= (1249.45 kcal/kg x 4.1868/kcal) kJ/kg
= 5231.19 kJ/kg

Therefore the overall boiler efficiency given by q can be calculated as follows:

$\dot{\eta}$ = Mv / Ns (Hugot, 1986)

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

= (5231.16 / 8549.51) x 100
= 61.18 %

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

Now the next stage is to calculate the quantity of steam in tons generated per ton of fuel consumed. This is given by the formula:

X = $\dot{\eta}$B*HCV / (Hst – Hfw) (Engineers, 1999)
= 61.18 * 8549.51 / (3227.31 – 422.86)
= 523059.02 / 2804.45
= 186.51
= 1.87 ton steam/ton bagasse

The amount of bagasse produced per ton of cane crushed can be estimated at approximately 0.275tons. (Busiso Mtunzi, 2012). The amount of steam generated per ton of cane crushed can be calculated as follows:

$$Y = x\,(F5C - FibreLost\%C)/F\%B \qquad \text{(Engineers, 1999)}$$

Where:

- F%C is the fibre content of the cane in percent less the fibre lost in juice and the fibre lost in the mud filters
- FibreLost%C is the fibre lost in juice
- F%B is the fibre content of the bagasse in percent

$$\begin{aligned} Y &= x\,(F5C - FibreLost\%C)/F\%B \\ &= 1.87\,(15 - 0.08) / (100-51.41-4.52-1.49) \\ &= 1.87\,(15-0.08) / 42.58 \\ &= \mathbf{0.66\ ton\ steam/ton\ cane} \end{aligned}$$

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

$$CO_2 = 100 \times \frac{1.762\,(1 - w)}{5.67\,(1 - w)\,m + 1} \qquad \text{(Lawler, 2011)}$$

$$= 100 \times \frac{1.762\,(1 - 0.51)}{5.67\,(1 - 0.51)\,1.5 + 1}$$

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

7. RESULTS AND DISCUSSION

The following table, Table 6: All calculated quantities tables the important values that were calculated during the boiler efficiency calculation in the sections above

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

Table 6: All calculated quantities

The table above, Table 6: All calculated quantities, is intended to highlight the relationship between the main quantities of a bagasse fired boiler

8. 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. Summing up the numbers, in a factory that crushes 6000tones of cane per day, it 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 boiler to be evaluated will be the boiler with the quantities as calculate above. On the next reporting, the following will be considered:

- The overall energy efficiency of the steam and power generation plant, assuming using the boiler with the quantities calculated above. This will be with the knowledge that the reader already understands the efficiency calculation of the boiler itself.

9. REFERENCES

1. Busiso Mtunzi, N. M. E. M. W. M., 2012. Bagassed-based co-generation at Hippo Valley Estates sugar factory in Zimbabwe. *Journal of Energy in Southern Africa,* 23(1), p. 2.
2. Department of Chemistry, 2014. *Texas A&M University.* [Online]

   Available at: https://www.chem.tamu.edu

   [Accessed 22 09 2014].
3. Engineers, S., 1999. *Sugar Factory Definitions.* [Online]

   Available at: http://www.sugartech.co.za

   [Accessed 20 September 2014].
4. Hugot, E., 1986. Handbook of Cane Sugar Engineering. In: *Handbook of Cane Sugar Engineering.* Netherlands: Elsevier Science Publishers B.V, pp. 907-920.
5. Index Mundi, n.d. *Commodities.* [Online]

   Available at: http://www.indexmundi.com

   [Accessed 4 June 2014].
6. Lawler, W., 2011. *Boilers and Co-Generation,* Durban: SMRI.
7. LIMS, 2014. *ISL: Eston Factory Daily Production Report,* Camperdown: ISL: Eston Factory.
8. Magasiner, N., 1966. *Boiler Design and Selection in the Cane Sugar Industry.* KZN, SASTA, p. 2.
9. Rein, P., 2007. Steam Generation. In: *Cane Sugar Engineering.* Berlin: Verlag Dr. Albert Bartens KG, pp. 620-621.
10. Spirax Sarco Limited, 2014. *Spiraxsarco.* [Online]

    Available at: http://www.spiraxsarco.com

    [Accessed 20 September 2014].
11. System, P., 2014. *Boilers pdi,* Eston: Pi ProcessBook.