BOILERS, BOILER FUEL AND BOILER EFFICIENCY

A WIENESE

Sugar Milling Research Institute, Durban 4041, South Africa

Abstract

This paper describes the modern boilers in the South African sugar industry. A new equation for the calculation of the net calorific value (NCV) of bagasse is suggested and a distinction is made between boiler design efficiency and boiler operation efficiency. Methods to calculate fuel calorific values and boiler efficiencies from first principles are presented.

Introduction

In the past the fuel requirements for most sugar factories were easily met by the available bagasse, in fact some factories were in the rather embarrassing situation of having a surplus of bagasse. However, with an increase in alternative uses of bagasse, the operation of back end refineries and the move towards cogeneration, more and more factories find themselves short of bagasse and have to resort to the use of alternative fuel in the form of coal. This has led to an increasing interest in energy efficiency of which the boiler efficiency forms an essential part. The boiler efficiency does not only depend on the boiler configuration and operation but also on the fuel being used. This paper describes a typical sugar factory boiler, the analysis of boiler fuel and discusses the calculation of boiler efficiency. The figures that are used are generic and are not to be taken definitively.

Boilers

Typical modern boilers in the South African sugar industry produce superheated steam at a pressure of 3100 kPa (abs) and a temperature of 400°C. They are designed to burn bagasse, coal or a mixture thereof and are equipped with a full heat recovery system.

Boiler configuration

The main components of a modern boiler are: the grate, fuel feeders, combustion chamber or furnace, water or mud drum, steam drum, main bank, superheater, economiser, air-heater, scrubber, induced draught (ID) fan, forced draught (FD) fan, secondary air (SA) fan, boiler feed water pumps and some auxiliary equipment (Figure 1).

Grate: Bagasse burns in suspension and has a relatively low ash content of 4%, part of which leaves with the flue gases. The removal of bagasse ash is therefore rather simple and can be achieved by a dumping or pinhole grate (Misplon *et al,* 1996). Coal burns on top of the grate, has a much higher ash content of typically 11-16% forming clinker and requires a continuous ash discharge (CAD) stoker (Page *et al,* 2000). Under grate air temperatures should not exceed 250°C for bagasse or 150°C for coal fired boilers to prevent overheating of the grate. Boiler grates are typically designed for a heat release rate of about 3 MW/m^2 for bagasse and 1,5 MW/m^2 for coal.

Fuel feeders and spreaders: Modern boilers are fitted with tall bagasse chutes to give a stable feed to the furnace. The throughput is controlled by feeder rolls and spreading is pneumatic. Coal spreaders are either mechanical or pneumatic. Today, dual pneumatic distributors are used successfully provided secondary air is introduced in the right quantities (Magasiner and Naude, 1988). Feeder chutes must never empty since the fuel in the chute provides an air seal and prevents blow backs.

Combustion chamber or furnace: While the spaced tube and tile has been the main furnace construction for many years, it is being replaced by membrane walls combined with refractory tiles to give the thermal reserve needed for the ignition of bagasse. This welded wall design has the advantage of providing a gas tight enclosure and is less prone to slagging. The gas leaving the furnace must be at least 200°C below the ash fusion temperature and is approximately 950°C for bagasse and 1050°C for coal. The furnace heat release rate is in the order of 0,24 and 0,12 MW/m^3 for bagasse and coal respectively. A typical boiler gas temperature profile is given in Table 1.

Superheater: Because of the regular failure from overheating of non-drainable superheaters during start-up fully drainable superheaters have become the norm. Where not already present, superheaters are more and more converted to this type (Boshoff, 1995). Most boilers are equipped with temperature operated automatic superheater drain valves to provide extra steam flow

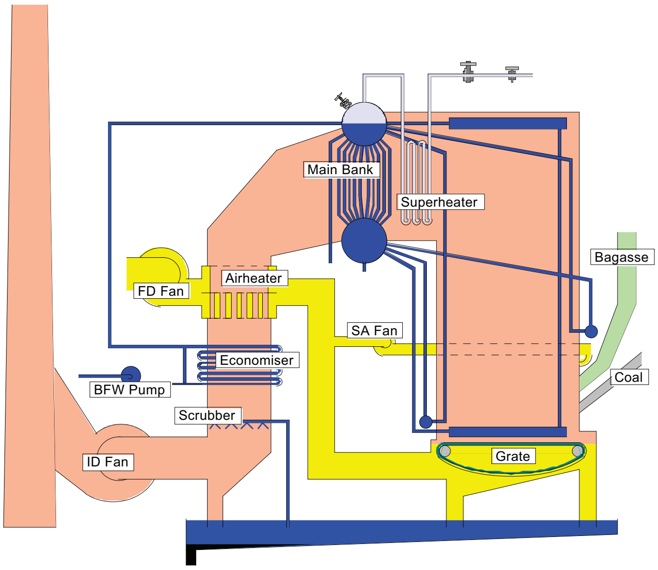

Figure 1. Boiler configuration.

Table 1. Boiler gas temperature profile.

	Bagasse °C	Coal °C
Under grate air	240	150
Furnace exit	950	910
Superheater exit	870	820
Main bank exit	440	380
Airheater exit	310	285
Economiser exit	190	165
Scrubber exit	75	55

for cooling at low loads. Gas velocities are between 8 to 10 m/s and should not exceed 12 m/s.

Water or mud drum: Continuously bleeding from the water drum should prevent the concentration and accumulation of chemicals in the boiler water. This boiler blow down is approximately 3-5% on steam.

Steam drum: Steam water separation is achieved by means of baffles, cyclones and other separation devices. These internals should ensure that the steam leaving the drum is dry and free of contaminants.

Main or generating bank: In the past most boilers were highly efficient multiple pass boilers. An increase in the ash (sand) content of bagasse resulted in a significant increase in tube erosion and now single pass boilers are favoured with main bank gas velocities not exceeding 15 m/s (Magasiner *et al,* 1984). Between 40 to 55% of the heat transfer takes place in the main bank, depending on the number of passes.

Airheater: In a bagasse fired boiler, the airheater is normally situated before the economiser. The air temperature is raised from ambient to the under grate air temperature which is about 250°C when burning bagasse and 150°C when using coal. Flue gas velocities are usually below 25 m/s.

Economiser: In the economiser the boiler feed water temperature is typically raised from 105°C to between 150 and 180°C. The exit temperature should be well below boiling point to prevent the concentration of solids. At the same time the flue gas temperature must not drop below its dew point to minimise corrosion. Economisers are designed for gas velocities not exceeding 15 m/s.

*Scrubbe*r: The main pollutants in the flue gas are particulate matter, NOx and SOx, the latter only when coal is being burnt. Legislation only makes mention of the emission of particulate matter which must be below 200 mg/m^3 measured under standard conditions. Scrubber types are wet scrubbers, cyclonic scrubbers, bag filters and electrostatic precipitators. While electrostatic precipitators are probably the most effective, wet scrubbers are much cheaper and they do meet the statutory requirements (Boshoff and Yeo, 1999).

Induced draught (ID) fan: Because erosion is more troublesome than corrosion, wet ID fans (downstream of the scrubber) are preferred to dry ID fans (upstream of the scrubber). In addition wet fans absorb less power because of the cooler and therefore denser gas. Table 2 shows a typical gas velocity profile.

Table 2. Boiler gas velocity profile.

	Bagasse m/s	Coal m/s
Superheater	9,0	3,7
Main bank	12,0	4,8
Airheater	20,0	7,7
Economiser	13,0	4,8

Forced draught (FD) fan: The temperature of the FD air plays an important role in cooling the grate and is controlled by airheater bypass dampers. The balance between ID and FD air should be such as to provide a furnace pressure just below atmospheric.

Secondary air (SA) fans: Secondary air provides the necessary turbulence in the furnace and is about 10% of the total air required for combustion. There is some discussion about whether this air should be pre-heated or not.

Boiler feed water pumps: It is common practice to have at least one boiler feed water pump which is turbine driven and can operate independently of electrical power.

Auxiliary equipment: Most boilers are fitted with a deaerator to remove oxygen from the boiler feed water. The steam used for deaeration is usually exhaust steam. Coal fired boilers require soot blowers to periodically clean the tubes. This can be done by steam or ultrasound. Controlling of the superheat temperature becomes important above 420°C (Magasiner, 1987) and is normally not done in the sugar industry. Boilers should have at least one safety valve, a crown valve and a non return valve in that order.

Boiler control

A boiler is the single most expensive item in a sugar factory. Because of the high operating pressure and temperature, it is also one of the potentially most dangerous pieces of equipment. For these reasons alone proper boiler control is imperative. There are normally three main control loops to provide this control, a water level control, a master pressure control and a furnace pressure control (Figure 2).

Water level control. The water level in the steam drum is maintained by a three element controller. The feed water into the boiler is regulated by the steam flow while corrected for sudden changes in water level. The steam drum diameter has a significant effect on this control (Moor, 1985).

Master pressure control. The steam pressure controls the combustion rate by altering the speed of the fuel feeders. At the same time a ratio controller maintains a constant air to fuel ratio by adjusting the air supply by the FD fan. It is common practice to monitor the oxygen levels in the flue gas and trim the air to fuel ratio when necessary. Acceptable oxygen levels are between 4 to 6% on a dry volume basis.

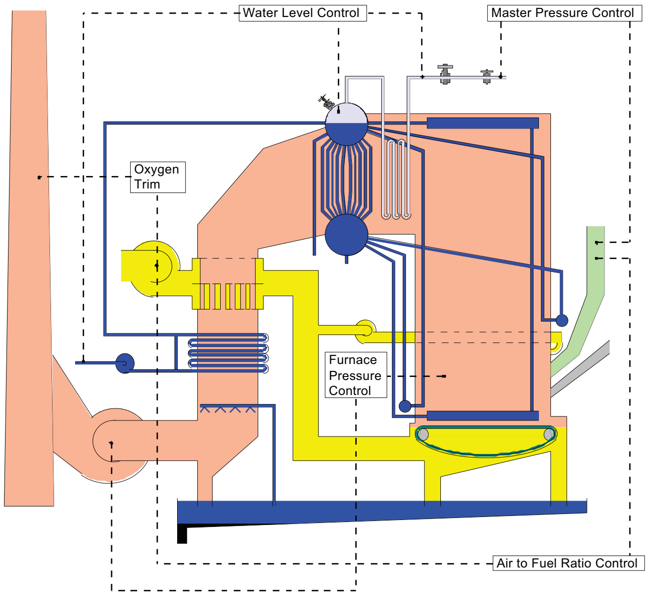

Figure 2. Boiler control.

Furnace pressure control. The furnace pressure is controlled by altering the speed of the ID fan. Both a positive and a negative pressure reduce boiler efficiency. Ideally the pressure should be just below atmospheric.

Note: In some boiler installations the air to fuel ratio control operates on the ID fan while the furnace pressure is regulated by the FD fan. It is not clear what the advantages are of the one system compared with the other.

Boiler fuel

In the cane sugar industry the predominant boiler fuel is bagasse, the residue of the cane plant after extraction. In South Africa, coal is the main auxiliary fuel when there is a shortfall of bagasse. The composition of the fuel plays a major part in assessing its calorific value and calculating boiler efficiencies.

Fuel analysis

The fuel components are usually divided into ash, moisture and other constituents. The different analyses such as physical, proximate and ultimate analyses concentrate on these other constituents.

Physical analysis: A physical analysis describes the fuel components in terms of their quantities. It is particularly used to calculate the calorific value. The composition of bagasse is usually expressed in terms of its fibre, brix and moisture content. For the purpose of analysing bagasse as a boiler fuel, it is important to separate the fibre component into vegetable fibre and ash. Coal can similarly be separated into dry, ash free coal, ash and moisture. Typical analyses of bagasse and coal are given in Table 3.

Table 3. Physical analysis of bagasse and coal

	Bagasse %	Coal %
Coal (dry, ash free)	-	80
Fibre (vegetable)	44	-
Brix	2	-
Ash (insoluble)	4	12
Moisture	50	8
	100	100

Proximate analysis: The proximate analysis defines that part of the fuel that gasifies below 750°C, called the volatiles, in relation to the fixed carbon. It provides an indication of its combustion properties especially the combustion stability. This property is particularly important for coal and is used to a lesser extent for bagasse. A proximate analysis for bagasse and coal is given in Table 4.

Ultimate analysis. The ultimate analysis is the analysis of the fuel into its basic chemical elements. This analysis is used to obtain the theoretical air needed for combustion based on the stoichiometric equations of the various elements. It also provides a means to determine the quantity and composition of the flue gases. Finally, it forms the corner stone in the calculation of the boiler efficiency using the 'loss method'. Table 5 gives a typical ultimate analysis for bagasse and coal.

Ash analysis: An important analysis with regards to the combustion characteristics of a fuel is the analysis of ash. It is well known that not only the concentration but also the composition of the ash has a major affect on boiler performance (Magasiner *et al*, 2001). Combustion problems related to ash are clinker formation, corrosion, slagging, erosion, gaseous emission, bird nesting, blockage and reduced heat transfer. Al-

Table 4. Proximate analysis of bagasse and coal

	Bagasse %	Coal %
Volatiles	35	24
Fixed carbon	11	56
Ash	4	12
Moisture	50	8
	100	100

Table 5. Ultimate analysis of bagasse and coal.

	Bagasse %	Coal %
Carbon	22,16	67,20
Hydrogen	2,84	4,00
Oxygen	21,00	6,00
Nitrogen	0,00	1,80
Sulphur	0,00	1,00
Ash	4,00	12,00
Moisture	50,00	8,00
	100,00	100,00

though all these problems are important and need attention, ash analysis falls out of the scope of this paper.

Calorific value

There are two different calorific values, a gross calorific value (GCV) and a net calorific value (NCV). The GCV is the total energy released during the combustion process and can only be accurately determined by using a bomb calorimeter. The NCV is the GCV minus the latent heat of the water formed by the combustion process and is obtained by calculation. The experimental procedure and method of calculation are laid down in ISO 1928 (Anon 1995).

Bagasse. In South Africa most of the work on the calorific value of bagasse was done by Don *et al* (1977). They measured the GCV of the bagasse from various cane varieties using a bomb calorimeter. No meaningful differences were found in the GCVs of cane stalks and tops on a brix-free, moisture-free and ash-free basis. The GCVs of the leaves were however significantly higher than those of the stalks and tops. The results excluding leaves are summarised in Table 6.

Eliminating the fibre content results in an equation for the GCV of bagasse as a function of the moisture (M), brix (B) and ash (A).

$$GCV = 19605 - 196{,}05 * M - 31{,}14 * B - 196{,}05 * A$$

The experiments by Don *et al* (1977) were however not carried out in accordance with the standard procedure for the determination of calorific values as laid down in the ISO standard. The temperature was 20°C as opposed to 25°C and no conversion was made from a constant volume to a constant pressure value. Fortunately the difference is well within the experimental error and the above equation for the GCV can be used with reasonable confidence. They subsequently derived from the GCV a formula for the NCV. This familiar equation, commonly used in the sugar industry, is again based on a bagasse temperature of 20°C and a hydrogen content of 5,91% on a dry basis.

Table 6. Calorific value of bagasse at 20°C.

	Bagasse Mass %	Bagasse GCV kJ/kg
Fibre (vegetable)	44	19605
Brix	2	16491
Ash (insoluble)	4	0
Moisture	50	0
	100	7107

$$NCV = 18309 - 207{,}63 * M - 31{,}14 * B - 196{,}05 * A$$

Although the deviation from the standard temperature of 25°C is negligible in determining the GCV it does have a small effect on the calculation of the NCV. In order to compare the NCV of bagasse with that of other fuels it is necessary to use the same reference temperature. At the same time the above equation for the NCV can be improved by expressing the hydrogen content not only on a dry basis but on a dry ash free basis. Ash levels during the original experiments were 2,08%. At that level a hydrogen concentration of 5,91% on a dry basis equates to 6,17% on a dry ash free basis. This results in the following formula for the NCV of bagasse:

$$NCV = 18260 - 207{,}01 * M - 31{,}14 * B - 182{,}60 * A$$

Coal. The same theory that applies to bagasse holds equally for coal. However, the GCV of dry, ash free coal varies significantly from one coal grade to another and has to be experimentally determined for each grade. If however no experimental data is available the GCV may be estimated from the ultimate chemical analysis of the fuel and the enthalpy of combustion or GCV of the relevant compounds (Table 7) (Perry and Chilton, 1973).

The calculation of the GCV of coal based on the GCV of its chemical components is a very rough approximation and can be out by as much as 5%. Although true for pure carbon, hydrogen and sulphur it ignores the form in which these elements are present in the fuel and it does not take into consideration any heat of combination or dissociation. The resulting equation is a variant of the Dulong formula (Pratt, 1965). As a function of the carbon (C), hydrogen (H_2) and sulphur (S) it takes the following form:

$$GCV = 327{,}78 * C + 1417{,}91 * H_2 + 92{,}66 * S$$

Given the GCV and the composition of the coal, it is again possible to derive a formula for the NCV by subtracting the latent heat. The equation for the NCV, at a temperature of 25°C and as a function of the GCV, the moisture content (M) and the hydrogen concentration (H_2) is as follows:

$$NCV = GCV - 24{,}41 * M - 218{,}13 * H_2$$

Table 7. Calorific value of coal at 25°C.

	Coal Mass %	Coal GCV kJ/kg
C (solid) + O_2 (gas) = CO_2 (gas)	67,2	32778
H_2 (gas) + $1/2O_2$ (gas) = H_2O (liquid)	4,0	141791
S (solid) + O_2 (gas) = SO_2 (gas)	1,0	9266
Others	27,8	0
	100,0	27791

Boiler efficiency

The efficiency of a boiler is the energy imparted to the boiler feed water in its conversion to superheated steam as a percentage of the energy in the fuel. It can be expressed either in terms of the net or gross calorific value. Because the latent heat in the flue gas is not normally recovered, only the boiler efficiency on NCV is of practical value and the one commonly used. For the purpose of boiler calculations, calorific values must be corrected to ambient temperature. One of the standards for determining boiler efficiencies is BS 845 (Anon 1987) but there are other methods being practiced, often with different results. Whichever way it is done it is based either on the 'direct method' or the 'indirect or loss method'.

Direct method

In the direct method, the boiler efficiency is defined as the difference between the energy in steam and the energy in boiler feed water as a percentage of the energy in fuel. In equation form:

$$\text{Boiler Efficiency} = \frac{\text{Energy Steam - Energy BFW}}{\text{Energy Fuel}} * 100$$

or

$$\text{Boiler Efficiency} = \frac{\text{Mass Steam * h * Steam - Mass BFW * h * BFW}}{\text{Mass Fuel * CV Fuel}} * 100$$

The greatest advantage of the direct method is that it is easy. In addition, it can cover any period of time. It takes into account any losses occurring during the period under consideration and reflects the actual steam generation and fuel consumption for that period. The mass of steam is usually taken at the crown valve which means that auxiliary steam such as deaerator steam, steam used for boiler fans and feed water pumps or any other steam related to the boiler operation is included. The boiler feed water may or may not exclude boiler blow down.

Indirect or loss method

The definition of boiler efficiency is the same irrespective of the method being used. The difference is in the approach. While the direct method concentrates on the energy made, the 'loss method' focuses on the energy lost. In equation form:

$$\text{Boiler Efficiency} = \frac{\text{Energy Fuel - Energy Losses}}{\text{Energy Fuel}} * 100$$

or

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

where L1 to L5 are the various losses as a percentage of the total energy of the fuel.

L1 = Latent heat loss in flue gas (applies only to GCV)

L2 = Sensible heat loss in flue gas

L3 = Loss due to unburned carbon

L4 = Radiation loss

L5 = Other losses

In order to determine these losses it is necessary to first do a combustion calculation. This combustion calculation is a stoichiometric calculation of the combustible elements in the fuel. These elements are carbon ($C+O_2=CO_2$), hydrogen ($2H_2+O_2=2H_2O$) and sulphur ($S+O_2=SO_2$). The latter is only present in minor quantities in coal. The stoichiometric calculation determines the theoretical air required for combustion and the products of combustion. To ensure complete combustion allowance must be made for additional or excess air. This excess air is about 25% for bagasse and 30% for coal. Only with a full knowledge of the products of combustion, is it possible to calculate the various losses and the boiler efficiency. An example is given in Appendix I with bagasse as fuel. Below follow some comments on the calculation.

Latent heat loss. The vapour in the flue gas is derived from the moisture in the fuel, water formed through the combustion of hydrogen in the fuel and moisture in the air. Only the contribution from the fuel must be considered as a latent heat loss. The moisture in the air both enters and leaves the boiler in the vapour form and does not form a latent loss. If this was otherwise the NCV would be a function of the moisture content of the air. It is also important to use the latent heat at ambient temperature and not at the final flue gas temperature or else the NCV would depend on the combustion process.

Sensible heat loss. The sensible heat loss is the total flue gas mass times the mean specific heat multiplied with the temperature difference between the final flue gas temperature (before the scrubber) and the ambient temperature. The mean specific heat of the flue gas can be calculated from the mean specific heat of the individual gases which in turn can be derived from the specific heat of these gases, which are virtually linear with temperature (Hugot, 1986), by integration (Table 8).

Unburned carbon loss. The calculation of the heat loss due to unburned carbon is based on the carbon content in boiler ash. Assuming that the boiler ash consists of the ash in fuel plus the unburned carbon it is possible to determine the amount of unburned carbon. This unburned carbon represents a loss of about 3320 kJ/kg. The problem is to obtain a representative sample of boiler ash which is particularly difficult with a bagasse fired boiler. It is estimated that the loss due to unburned carbon on GCV ranges from 3 to 6% for coal and 1,5 to 3% for bagasse.

Radiation loss. Radiation losses are rarely measured in practice. It is however estimated that for a modern well insulated boiler this loss lies between 1 and 2% on GCV.

Table 8. Specific heat of combustion gases as a function of Temperature (°C).

	Specific heat kJ/kg
Water vapour	1,960 + 0,001302 * T
Carbon dioxide	0,834 + 0,000682 * T
Sulphur dioxide	0,595 + 0,000151 * T
Nitrogen	1,030 + 0,000168 * T
Oxygen	0,897 + 0,000151 * T

Other loss. Other losses include incomplete combustion, heat in boiler ash, boiler blow down, inflow of cold air and out flow of hot gases. This loss is estimated at about 1 to 2% on GCV. If however any auxiliary steam would be included, this figure could be much higher.

The boiler efficiency calculated by the 'loss method' is a snapshot in time and can be considered an equipment or design efficiency. The boiler efficiency by the 'direct method' on the other hand, is normally lower, contains a design element as well as an operational element and is only equal to that of the 'loss method' under steady state conditions. The ratio between the 'direct method' and the 'loss method' shows the effect of process variation and multiplied by one hundred might be called the boiler operation efficiency.

$$\text{Operational Efficiency} = \frac{\text{Efficiency by the direct method}}{\text{Efficiency by the loss method}} * 100$$

Summary

With a growing usage of coal to supplement bagasse as boiler fuel, boiler efficiency and fuel calorific value become increasingly important. The differences between bagasse and coal have major effects on boiler design and operation.

The most important difference between bagasse and coal is the cost. While bagasse is free, coal costs about R200 per ton but this price varies depending on location and coal grade. Then there are of course the differences in appearance and physical properties. Some of these differences are best illustrated with typical figures (Table 9).

Table 9. Some differences between bagasse and coal.

	Bagasse	Coal
GCV (kJ/kg)	8956	27791
NCV (kJ/kg)	7116	26723
Moisture	50	8
Ash	4	12
Sulphur	0	1

Table 10. Boiler parameters on bagasse and coal.

	Bagasse	Coal
GCV boiler efficiency (%)	62,90	82,59
NCV boiler efficiency (%)	79,15	85,89
Mass of steam (t/h)	100,00	69,39
Mass of fuel (t/h)	49,10	8,23
Mass of air (t/h)	163,20	96,64
Mass of flue gas (t/h)	209,68	103,55
Steam temperature (°C)	400,00	375,00
Under grate air temperature (°C)	240,00	140,00
Final flue gas temperature (°C)	190,00	165,00
Grate heat release (MW/m2)	3,00	1,50
Furnace heat release (MW/m3)	0,24	0,12
Excess air (%)	25,00	30,00

One of the more noticeable effects resulting from these differences is that bagasse burns in suspension and coal on the grate. Furthermore, bagasse and coal require different ash removal systems. Some other effects are given in Table 10. The figures are again typical and based on a steaming rate of 100 t/h on bagasse.

The familiar formulas for the calorific values of bagasse used in the South African sugar industry contain some fundamental flaws. A new equation for the NCV of bagasse correcting these flaws is proposed:

$$NCV = 18260 - 207{,}01 * M - 31{,}14 * B - 182{,}60 * A$$

The boiler efficiency by the 'loss method' can be seen as a design efficiency while the 'direct method' contains both design and operational elements. A definition for operational efficiency is suggested:

$$\text{Operational Efficiency} = \frac{\text{Efficiency by the direct method}}{\text{Efficiency by the loss method}} * 100$$

Acknowledgment

The author would like to thank Tongaat-Hulett, Illovo, TSB, John Thompson and Babcock for their contribution to this paper and for the excellent papers on boilers produced by members from these organizations in the past which have been a valuable source of information.

REFERENCES

Anon (1995). *SABS ISO 1928. Solid mineral fuels - Determination of gross calorific value by the bomb calorimetric method, and calculation of net calorific value.* The South African Bureau of Standards, 45 pp.

Anon (1987). *BS 845. Methods for assessing thermal performance of boilers for steam, hot water and high temperature heat transfer fluids*. British Standards Institution, part I, 18 pp., part II, 39 pp.

Don, CE, Mellet, P, Ravno, BD and Bodger, R (1977). Calorific Values of South African Bagasse. *Proc S Afr Sug Technol Ass* 51: 169-173.

Boshoff, TL (1995). Improving older sugar mill boilers. *Proc S Afr Sug Technol Ass* 69: 122-124.

Boshoff, TL and Yeo, WH (1999). Reduction of stack particulate emission. *Proc S Afr Sug Technol Ass* 73: 251-253.

Hugot, E (1986). *Hand book of Cane Sugar Engineering*. Elsevier, 3^{rd} Edition, Amsterdam, pp. 932.

Magasiner, N (1987). The effect of fuel moisture content on the performance of a typical bagasse fired watertube boiler. *Proc S Afr Sug Technol Ass* 61: 86-89.

Magasiner, N and Naude, DP (1988). Pneumatic spreaders of fibrous fuels and coal in boiler combustion chambers. *Proc S Afr Sug Technol Ass* 62: 79-84.

Magasiner, N, Alphen C van, Inkson, MB and Misplon, BJ (2001). Characterising fuels for biomass - coal fired cogeneration. *Proc S Afr Sug Technol Ass* 75, in press.

Magasiner, N, Naude and McIntyre, P (1984). Operating experience on single and three pass boilers in the cane sugar industry with particular reference to erosion and drum water level stability. *Proc S Afr Sug Technol Ass 58*, pp. 123-129.

Misplon, BJ, Verbanck, H and McIntyre, P (1996). Pinhole grate conversions of two 30 t/h boilers at South Nyanza sugar company, Kenya. *Proc S Afr Sug Technol Ass* 70: 200-203.

Moor, BStC (1985). A reliable high efficiency sugar mill boiler. *Proc S Afr Sug Technol Ass* 59: 118-125.

Page, B, McIntyre, P and Verbanck, H (2000). Operating experience with high combustion efficiency continuous as discharge zoned stokers. *Proc S Afr Sug Technol Ass* 74: 290-294.

Perry, HP and Chilton, CH (1973). *Chemical Engineers' Handbook*. McGraw-Hill Kogakusha LTD, 5th Edition, Tokyo, pp. 3/137.

Pratt, AD (1965). *Principles of combustion in the steam boiler furnace.* Babcock & Wilcox LTD, London, pp. 24.

APPENDIX I: Boiler efficiency

Description		Description	
GCV (kJ/kg)	8956,02	NCV (kJ/kg)	7116,78

Description		Description	
Nitrogen content air (%)	76,24	Air temperature (°C)	25,00
Oxygen content air (%)	22,77	Air pressure (kPa(abs))	100,00
Moisture content air (%)	1,00	Air relative humidity (%)	50,00

	Fuel	Air	Flue	H_2O	CO_2	SO_2	N_2	O_2
	%	kg	kg	kg	kg	kg	kg	kg
Carbon	22,16	2,59	2,80	0,03	0,76	0,00	1,98	0,04
Hydrogen	2,84	0,99	1,02	0,26	0,00	0,00	0,75	0,00
Oxygen	21,00	-0,92	-0,71	-0,01	0,00	0,00	-0,70	0,00
Nitrogen	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Sulphur	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Ash	4,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Moisture	50,00	0,00	0,50	0,50	0,00	0,00	0,00	0,00
Excess air	25,00	0,66	0,66	0,01	0,00	0,00	0,50	0,15
Total		3,32	4,27	0,79	0,76	0,00	2,53	0,19

Description		Description	
Flue Temperature (°C)	190,00	Unburnt C in Ash (%)	25,00

Description	Loss kJ/kg	GCV %	NCV %
Loss latent heat in flue	1839,24	20,54	0,00
Loss sensible heat in flue	853,14	9,53	11,99
Loss unburnt carbon in ash	450,93	5,03	6,34
Loss radiation	89,56	1,00	1,26
Loss unaccounted	89,56	1,00	1,26
Loss total	3322,43	37,10	20,85
Boiler efficiency	5633,59	62,90	79,15