CALORIFIC VALUES OF SOUTH AFRICAN BAGASSE*

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Abstract

When gross calorific values (GCV's) on a moisture-free, brix-free and ash-free basis were determined on varieties of S.A. bagasse, no significant differences were found when age, time of harvest, source, fibre, pith, cane stalk or cane tops were considered. Only cane leaves gave higher values. Since ash exerts a significant influence, a formula including ash % sample as an independent variable was developed to predict the GCV. Using a hydrogen content of 5,91% (dry basis) for bagasse, an equation to predict net calorific value (NCV) of bagasse was developed which also includes ash % sample as an independent variable. The equation predicts NCV defined at 20°C.

Introduction

Accurate assessment of the calorific value of bagasse is of economic importance, yet the only methods of assessment presently available are direct laboratory analysis of calorific value or the use of calculation formulae derived for specific conditions elsewhere in the world.

In spite of considerable differences in appearance between varieties of cane, the gross calorific value (GCV) of dry bagasse varies only about two percent for bagasse from different countries, and a universal value, as quoted by Hugot[1] (based on values from several different authors) has therefore been adopted for the GCV of dry bagasse, i.e. GCV = 19 256 $kJ.kg^{-1}$.

Many formulae[1, 2, 3, 4, 5, 6] have been proposed to determine the calorific value of wet bagasse; among the better known are those of von Pritzelwitz van der Horst[2] of Java and Hessey[3] of Australia.

The ultimate analysis of bagasse is used to calculate net calorific values (NCV's) from GCV's[1, 7, 8, 9]. The NCV equations used therefore depend on the percentage of net hydrogen in bagasse which varies from country to country, and the general value of NCV for dry bagasse being used, viz. 17 791 $kJ.kg^{-1}$, is not very precise.

The effects of various parameters on the calorific value of South African bagasse have been tested including variety of cane, age at harvesting, source, moisture content, sucrose and non-sucrose contents. The variations of calorific values between cane leaves, cane stalk, cane tops, pith and fibre were measured. The ultimate analysis of bagasse was also experimentally determined.

Experimental

Preparation of samples

Most samples were obtained from the Mount Edgecombe Experiment Station and it was ensured that all samples fairly represented the particular cane being tested. Details of all procedures and results are given in the original work[10]. Normally about eight to ten sticks of cane were collected from the field for each sample. The cane was sorted separately into cane leaves, cane tops and cane stalks and the following procedure[11] was applied to all groups and samples.

The cane was cut into pieces 30 to 60 mm long and placed in a shredding machine to reduce the particle size so as to be suitable for direct analysis. If the samples were required free of brix, they were treated in a cold digester bowl.

Four different South African varieties were tested, two with average pith, N 55/805 and NCo 376, one high pith, N 50/211, and a low pith variety NCo 310. All four varieties tested were grown on dolorite soil and were twenty-four months old when cut. The varieties were chosen to obtain an average calorific value for some commonly grown South African canes and also, with the increasing demand for fibre as opposed to pith by the paper and particle board industries, to see if there was a significant difference between varieties with high and low pith contents. Samples were tested brix-free. Four samples of the N 55/805 variety which were of different ages when harvested were chosen to test the effect of age on calorific values. Samples of cane stalk which were 8, 10, 18 and 24 months old were prepared and tested brix-free.

Samples of N 55/805 stalk which were of the same age but which were grown on two different types of soil were tested. Samples grown on heavy soil (middle Ecca) and sandy soil (Clansthal sand) were chosen and tested brix-free and samples of pith and fibre were obtained using a similar apparatus to that used by Snow[12]. Samples of leaves, tops and stalk were prepared in the standard way.

Bagasse samples with up to 60° brix by mass in the sample were prepared and tested by partial extraction of brix and pol in the cold digester bowl. Ash determinations were done on all samples so that calorific values could be presented on an ash-free, brix-free and moisture-free basis.

To test the validity of the developed formulae and to compare the calorific values so obtained with actual determined values as well as with values obtained by existing formulae, five samples of final mill bagasse were obtained from Mount Edgecombe mill. The retention time of the tandem of mills was calculated so that the variety of final mill bagasse actually sampled could be identified with the aid of the mill yard operator. A sub-sample of about 300 g was taken from the sample collected by the Central Board for analysis and was placed immediately in a moisture teller and dried. This was done to minimise the breakdown of the sugars from the time the sample was collected to when it was actually tested in the bomb calorimeter. The sub-sample was milled finely and then the gross calorific value, moisture content and ash content were determined. The brix and pol percentages and moisture percentage of the bagasse were obtained from the Central Board laboratory. The five samples chosen were from the varieties NCo 310 and NCo 376 with low ash content, NCo 376 with a high ash content and NCo 376 fermented.

Bomb calorimeter

The gross calorific values of all the bagasse samples were measured using a Baird & Tatlock bomb calorimeter (1 520 kPa of oxygen pressure, 6 V circuit voltage, ca. 0,7 g of bagasse sample). Generally fresh bagasse samples were found

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to contain a negligible amount of sulphur. A correction was made for the formation of nitric acid during experiments.

Ultimate analyses

Nine samples were sent to the Butterworth Microanalytical Consultancy Limited in Middlesex, United Kingdom for analysis of C, H and N. They consisted of 5 samples of cane stalk, two samples of cane tops and a sample each of cane leaves and cane pith.

Results and discussion

Gross calorific values (GCV) on a dry basis

The relatively unknown effects of many different parameters on the GCV of South African bagasse were tested in this study by experimentation under controlled conditions. The GCV's were broken up into various groups which would isolate one or two controlled variables and a factorial analysis of variance (F-ratio test) was applied to the samples within the groups, corrected to a moisture-free and brix-free basis. Linear regression analysis was applied to calorific values versus moisture content and calorific values versus brix and pol content because the data suggested an obvious correlation between the dependent and independent variables. Results of F-ratio tests are given in Table 1.

TABLE 1

Summary of statistical tests on gross calorific values

Source of Variance	Calculated F Value	Tabulated F Value
1. Different varieties on non ash-free basis	1,16	3,49
2. Different varieties on ash-free basis	2,12	3,49
3. Analysis of pith and fibre of varieties on non ash-free basis (pith/fibre)	3,9	5,32
(varieties)	2,5	4,46
4. Analysis of pith and fibre of varieties on ash-free basis (pith/fibre)	1,23	5,32
(varieties)	1,75	4,46
5. Analysis of leaves, stalk and tops of different varieties on non ash-free basis (leaves, stalks, tops)	3,36	3,29
(varieties)	0,66	3,29
6. Analysis of leaves, stalk and tops of different varieties on ash-free basis (leaves, stalks, tops)	3,74	3,29
(varieties)	0,51	3,29
7. Analysis of leaves and stalk on ash-free basis	6,12	4,21
8. Analysis of stalk and tops on ash-free basis	0,13	4,2
9. Analysis of leaves and tops on ash-free basis	18,54	4,54
10. Different sources on non ash-free basis	0,04	4,84
11. Different sources on ash-free basis	0,63	4,84
12. Age at which cane is cut on ash-free basis	0,76	2,78

The only variables that produced a significant F-ratio test on a brix-free and moisture-free basis, but not ash-free, were the analyses of leaves, stalk and tops on cane. These data were further broken down into three groups and the F-ratio test applied between each pair of independent variables. The tests showed that the GCV's of cane tops and cane stalk were not significantly different on a brix-free, moisture-free and ash-free basis, but the GCV's of leaves were significantly higher than those of stalk and tops when also expressed on a brix-free, moisture-free and ash-free basis.

It can therefore be concluded that there is no significant difference of GCV's on a moisture-free, brix-free and ash-free basis for the different varieties tested, different ages of cane, different sources and between fibre, pith, cane stalk and cane tops. An average of all the non-significant GCV's (i.e. excluding leaves) on a brix-free, ash-free and moisture-free basis, gives:

$$GCV = 19\,605 \text{ kJ.kg}^{-1}$$

The average of the GCV's of all the leaf samples tested on a brix-free, ash-free and moisture-free basis yields a value of:

$$GCV = 19\,953 \text{ kJ.kg}^{-1}$$

Gross calorific values are normally quoted on a non ash-free basis and the above value, excluding leaves, on a brix-free, moisture-free but non ash-free basis gave:

$$GCV = 19\,424 \text{ kJ.kg}^{-1} \text{ (ash \%} = 1{,}28)\text{.}$$

The equivalent value for leaves is:

$$GCV = 19\,244 \text{ kJ.kg}^{-1} \text{ (ash \%} = 3{,}55)\text{.}$$

Thus the significant difference between leaves and stalk or tops is only partially caused by the ash content of the sample.

Various GCV's of bagasse on a dry basis, but with varying ash contents, have been reported[1] and some of them differ by up to 2% from the universally accepted value of 19 256 kJ.kg^{-1}. The value determined in the present study is only 0,87% different from this universal value. This produces further evidence that the universal value for GCV of dry bagasse can be used with an error of scarely more than 2%.

Linear regression analysis using GCV on an ash-free, moisture-free basis as the dependent variable and brix, pol and non-pol as independent variables yielded the following equations:

$$GCV = 19\,523 - 42{,}23 \text{ non-pol} - 20{,}78 \text{ pol kJ.kg}^{-1} \quad (1)$$

$$GCV = 19\,523 - 42{,}23 \text{ brix} + 21{,}45 \text{ pol kJ.kg}^{-1} \quad (2)$$

$$GCV = 19\,419 - 38{,}8 \text{ pol kJ.kg}^{-1} \quad (3)$$

$$GCV = 19\,514 - 28{,}66 \text{ brix kJ.kg}^{-1} \quad (4)$$

Statistical analyses of the above equations show that it is better to use the equation of GCV versus brix alone rather than use the independent variables brix and pol or non-pol and pol. Brix should also be preferred to pol as a term in the equation for GCV's of bagasse for two other reasons, viz. brix is the easier laboratory analysis and the brix co-efficient is less sensitive to variation in residual purity and combustible content of the pol-free brix material[14]. The "pooled" GCV for bagasse (excluding leaves) on a brix-free, ash-free and moisture-free basis was 19 605 kJ.kg^{-1}. When the data is force fitted through the point 19 605 kJ.kg^{-1}, a "method of least squares" fit gives an equation to predict GCV:

$$GCV = (19\,605 - 31{,}14 \text{ brix}) \text{ kJ.kg}^{-1} \quad (5)$$

Statistical evaluation of equations (4) and (5) showed that the two equations are not different on the 95% level of significance, thus the co-efficients from equation (5) can be used to predict the full GCV equation:

$$\text{GCV predicted} = \left[\left(1 - \frac{\%\text{ moisture}}{100}\right)\left(1 - \frac{\%\text{ ash*}}{100}\right)(19\,605 - 31{,}14\,(\text{brix \% sample})\right]$$

$$= [19\,605 - (31{,}14 \text{ brix \% sample}) - (196{,}05 \text{ moisture \% sample}) - (196{,}05 \text{ ash \% sample**})] \text{ kJ.kg}^{-1} \quad (6)$$

*ash % dry sample; **ash % sample

Therefore, the value predicted by this equation for a brix-free, moisture-free and ash-free sample is 19 605 kJ.kg^{-1}.

Gross calorific values of final mill run bagasse

The GCV formula as derived in this study (Equation 6) as well as formulae for GCV of bagasse as predicted by von Pritzelwitz[2] and Hessey[3] were applied to predict the GCV of some final mill run bagasse samples collected from the Mount Edgecombe Mill. Results are given in Table 2. In his experimental work von Pritzelwitz[2] assumed an average ash content of bagasse in Java to be 3% so his formula was used in the form:

$$\text{GCV predicted} = [19\,046 - 30{,}98 \text{ (brix \% sample)} - (190{,}46 \text{ moisture \% sample})] \text{ kJ.kg}^{-1} \quad (7)$$

Hessey[3] assumed an average ash content of dry bagasse in Queensland to be 2,7% so his formula was used in the form:

$$\text{GCV predicted} = [19\,406 - (34{,}12 \text{ brix \% sample}) - (194{,}06 \text{ moisture \% sample})] \text{ kJ.kg}^{-1} \quad (8)$$

TABLE 2

Comparison of GCV values of final mill bagasse, predicted by various formulae to actual measured values (kJ.kg^{-1})

Sample	Bx % sample	Moisture % sample	Ash % dry sample	(a) Measured GCV	(b) GCV present formu. (6)	(a-b) diff. %	(c) GCV equa. (9)	(a-c) Diff. %	(d) GCV equa. (8)	(a-d) Diff. %
NCo 376	6,29	4,25	2,69	18 375	18 071	−1,65	18 042	−1,81	18 366	−0,05
NCo 310	6,47	3,78	2,94	18 497	18 108	−2,10	18 126	−2,01	18 452	−0,24
NCo 376	5,62	3,59	14,29	16 209	16 025	−1,13	18 188	+12,21	18 518	+14,25
NCo 376	5,00	6,66	3,15	17 546	17 567	+0,12	17 622	+0,43	17 942	+2,26
NCo 376	4,16	3,65	10,76	16 750	16 727	−0,14	18 222	+8,79	18 555	+10,78

TABLE 3

Comparison of calculated GCV values (kJ.kg^{-1}) of final mill bagasse to actual measured values

Sample	Bx % sample	Moisture % sample	Ash % dry sample	(a) Measured GCV	(b) GCV present formu. (6)	(a-b) diff. %	(c) GCV equa. (9)	(a-c) Diff. %	(d) GCV equa. (10)	(a-d) Diff. %
NCo 376	6,24	4,25	2,69	18 375	18 071	−1,65	18 098	−1,50	18 369	−0,03
NCo 310	6,47	3,78	2,94	18 497	18 108	−2,10	18 134	−1,96	18 407	−0,40
NCo 376	5,62	3,59	14,29	16 209	16 025	−1,13	16 048	−0,99	16 290	+0,50
NCo 376	5,00	6,66	3,15	17 546	17 567	+0,12	17 592	+0,26	17 861	+1,80
NCo 376	4,16	3,65	10,76	16 750	16 727	−0,14	16 751	00,00	17 008	+1,54

When these formulae are used in practice they do not take account of the wide fluctuations in ash and extraneous matter in bagasse. When the bagasse contained an ash and extraneous matter higher than 3,0 and 2,7% respectively, as can be seen from the results in Table 2, the von Pritzelwitz's and Hessey's formulae overpredicted GCV's by an amount depending on the ash and extraneous matter percent.

However, if von Pritzelwitz's formula is modified to include ash % sample as an independent variable it becomes:

GCV predicted

$$= [19\,632 - (30{,}98\ \text{brix \% sample}) - (196{,}32\ \text{moisture \% sample}) - (196{,}32\ \text{ash \% sample})]\ \text{kJ.kg}^{-1} \qquad (9)$$

If Hessey's formula is modified to include ash % sample as an independent variable it becomes:

GCV predicted

$$= [19\,946 - (34{,}12\ \text{brix \% sample}) - (199{,}46\ \text{moisture \% sample}) - (199{,}46\ \text{ash \% sample})]\ \text{kJ.kg}^{-1} \qquad (10)$$

The recalculated values of GCV obtained using the above formulae for the five final mill bagasse samples are compared to the experimentally measured values and also to the values obtained using the present developed formula. The results are given in Table 3. It can be seen that the values obtained by von Pritzelwitz's and Hessey's modified formulae are very close to those found by the newly developed formula and all three formulae predicted values that are within about 2% of the actual determined values. Thus, the importance of including ash as an independent variable in the equation is obvious.

Net calorific value

An average of the ultimate analyses of the cane stalk bagasse samples tested has been calculated and is compared with values from other sources in Table 4.

TABLE 4

Values of the ultimate analysis of bagasse

Constituents	% C	Net % H	Net % O + N	% Ash
Tromp[7]	45,0	6,0	47,0	2,0
Magasiner[8]	45,0	6,0	46,0	3,0
Hugot[1]	47,0	6,5	44,0	2,5
Paturau[9]	46,47	5,88	44,71	2,94
This work	48,12	5,91	44,91	1,04

The value that is of particular interest to calculate NCV equations is the net % hydrogen. Statistical analysis of the hydrogen values for all the bagasse samples tested shows that there is no significant difference between stalk, leaves and pith using a confidence level of 95%. The overall average mean for all nine samples of 5,91% net hydrogen in bagasse was thus used to derive the NCV equations. There is statistically no difference when this value is compared with values derived by Magasiner[8], Tromp[7] and Paturau[9] but it is significantly different from the value used by Hugot[1].

It must be noted that predicted NCV equations differ from those reported in the original text[10] since further testing has been done on ultimate analyses of bagasse samples.

The bagasse tested had an average hydrogen content of 5,91% (dry basis) so the NCV for dry bagasse at 20°C (on a non ash-free but brix-free basis) can be taken as:

$$\text{NCV} = 19\,424 - 21\,936 \times 0{,}0591$$
$$= 18\,128\ \text{kJ.kg}^{-1}$$

This value differs less than 2% from the universal value[1] of 17 791 kJ.kg^{-1} due mainly to the lower hydrogen content determined in the present work. In developing an equation to predict NCV, ash % sample will have the same influence on NCV as on GCV, therefore the NCV equation developed contains ash as an independent variable. This predicted equation is:

$$\text{NCV moist} = \left[(\text{GCV})\ \text{predicted} - (24{,}53\ \text{moisture \% sample}) - \left(1\,296\left(1 - \frac{\text{moisture \% sample}}{100}\right)\right)\right]$$

$$= [(19\,605 - (196{,}05\ \text{moisture \% sample}) - (196{,}05\ \text{ash \% sample}) - 31{,}14\ (\text{brix \% sample}) - (24{,}53\ \text{moisture \% sample}) - 1\,296 + (12{,}96\ \text{moisture \% sample})]$$

$$= [18\,309 - (31{,}14\ \text{brix \% sample}) - (207{,}6\ \text{moisture \% sample}) - (196{,}05\ \text{ash \% sample})]\ \text{kJ.kg}^{-1} \qquad (11)$$

TABLE 5

Comparison of NCV values of final mill bagasse predicted by various formulae ($kJ.kg^{-1}$)

Sample	Bx % sample	Moisture % sample	Ash % dry sample	(a) NCV, present formula (11)	(b) NCV equation (12)	(a-b) Diff. %	(c) NCV equation (13)	(a-c) Diff. %
NCo 376 . . .	3,00	54,35	2,69	6 691	6 779	+1,3	6 840	+2,2
NCo 310 . . .	3,16	53,03	2,94	6 931	7 039	+1,6	7 105	+2,5
NCo 376 . . .	2,77	52,50	14,29	5 992	7 157	+19,4	7 227	+20,6
NCo 376 . . .	3,00	53,05	3,15	6 912	7 040	+1,8	7 106	+2,8
NCo 376 . . .	2,31	51,20	10,76	6 578	7 433	+13,0	7 510	+14,1

TABLE 6

Comparison of NCV values of final mill bagasse predicted by various formulae ($kJ.kg^{-1}$)

Sample	Bx % sample	Moisture % sample	Ash % dry sample	(a) NCV, present formula (11)	(b) NCV equation (14)	(a-b) Diff. %	(c) NCV equation (15)	(a-c) Diff. %
NCo 376 . . .	3,00	54,35	2,69	6 691	6 733	+0,6	6 842	+2,2
NCo 310 . . .	3,16	53,03	2,94	6 931	6 975	+0,6	7 086	+2,2
NCo 376 . . .	2,77	52,50	14,29	5 992	6 105	+1,8	6 205	+3,5
NCo 376 . . .	3,00	53,05	3,15	6 912	6 958	+0,6	7 068	+2,2
NCo 376 . . .	2,31	51,20	10,76	6 578	6 672	+1,4	6 780	+3,0

Von Pritzelwitz's[2] and Hessey[3] original equations to predict NCV values at 30°C are respectively:

$$\text{NCV moist} = [17\,791 - (30{,}98 \text{ brix } \% \text{ sample}) - (200{,}9 \text{ moisture } \% \text{ sample})]\ kJ.kg^{-1} \quad (12)$$

and

$$\text{NCV moist} = [18\,100 - (34{,}12 \text{ brix } \% \text{ sample}) - (205{,}3 \text{ moisture } \% \text{ sample})]\ kJ.kg^{-1} \quad (13)$$

The above formulae for NCV were applied to the five final mill bagasse samples collected from Mount Edgecombe factory. The results are given in Table 5 and show that the predicted values by all formulae compare well for those samples with low ash contents, as was the case with GCV values. However for samples containing high ash contents the values obtained by the present formula differed significantly from values as predicted by von Pritzelwitz's and Hessey's formulae.

If the latter two formulae are changed to include ash as an independant variable, they become respectively for von Pritzelwitz and Hessey:

$$\text{NCV moist} = [18\,335 - (30{,}98 \text{ brix } \% \text{ sample}) - (207{,}6 \text{ moisture } \% \text{ sample}) - (183{,}35 \text{ ash } \% \text{ sample})]\ kJ.kg^{-1} \quad (14)$$

and

$$\text{NCV moist} = [18\,603 - (34{,}12 \text{ brix } \% \text{ sample}) - (210{,}3 \text{ moisture } \% \text{ sample}) - (186{,}03 \text{ ash } \% \text{ sample})]\ kJ.kg^{-1} \quad (15)$$

The recalculated NCV values based on the above modified equations for the five mill bagasse samples, together with the values as predicted by the present formula are given in Table 6. It is now found that these values agree very well and that von Pritzelwitz's modified equation gave NCV values which differ by less than 2% and Hessey's modified equation gave values which differ by less than 3,5% from the NCV values as predicted by the present formula.

Summary and conclusions

It was found that there were no significant differences of GCV's on a moisture-free, brix-free and ash-free basis for bagasse from different cane varieties tested, from cane cut at different ages and from different sources, and between fibre, pith, cane stalk and cane tops. The data from these tests were therefore pooled into a single set. The GCV's of cane leaves were found to be significantly higher than those of fibre, pith, stalk and tops, on an ash-free, moisture-free and brix-free basis.

The final GCV equation predicted for clean cane (excluding leaves) was:

$$\text{GCV predicted} = [19\,605 - (196{,}05 \text{ moisture } \% \text{ sample}) - (196{,}05 \text{ ash } \% \text{ sample}) - (31{,}14 \text{ brix } \% \text{ sample})]\ kJ.kg^{-1}$$

The formulae by von Pritzelwitz van der Horst and by Hessey agree well with the values obtained by the present formula only if the ash content of the sample is low. As the ash content of bagasse increases the values derived by the von Pritzelwitz van der Horst and Hessey formulae move further and further away from the true values. The present developed formula, containing ash as an independent variable, is therefore preferred.

The ultimate analyses of some of the bagasse samples gave slightly higher carbon contents and lower hydrogen contents when compared to values used by other sources. The hydrogen content for dry bagasse gave an average value of 5,91%. This value is slightly lower than values quoted by other sources[1, 7, 8, 9]. The hydrogen content is used to calculate NCV's but the significant difference in hydrogen content measured has a very small effect on final NCV's of bagasse.

The NCV equation predicted was found by using the GCV predicted, the hydrogen content of the bagasse and the latent heat of vaporisation of water at 20°C. The equation thus predicts the NCV defined at 20°C. The equation predicted using H = 5,91% (dry basis) was:

$$\text{NCV moist} = [18\,309 - (31{,}14 \text{ brix } \% \text{ sample}) - (207{,}6 \text{ moisture } \% \text{ sample}) - (196{,}05 \text{ ash } \% \text{ sample})]\ kJ.kg^{-1}$$

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