THE DESIGN AND OPERATION OF BOILER PLANT UTILISING FURFURAL RESIDUE AS A FUEL

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Abstract

Bagasse is the fibrous waste which results from the processing of cane to produce sugar. Furfural can be produced from the bagasse yielding a waste product, furfural residue, which can be disposed of in a boiler for generating steam. While bagasse and furfural residue are waste materials from the same feedstock, the physical properties and combustion characteristics of the two fuels differ markedly. Boilers designed for burning furfural residue incorporate features to enable stable and continuous combustion of the fuel. Operating experience gained over a number of seasons has resulted in modifications to peripheral plant to enable the safe change over from one fuel to another. Comparison with the properties of bagasse leads to a formal approach which can be used to describe the combustion process.

Introduction

Sezela Sugar Mill is capable of crushing 440 t/h of cane and is one of the largest mills in the South African sugar industry. Steam requirements for the mill are supplied by four boilers noted as follows:

No. 1: 140 t/h three-pass with dump grate
No. 2: 57 t/h three-pass with travelling grate
No. 3: 57 t/h three-pass with travelling grate
No. 4: 130 t/h single-pass with travelling grate

At Sezela, the coarse fraction of mill bagasse is utilised in a by-products plant for producing furfural. Steam is required by this plant, and as a consequence, the additional process heat demand is made up by burning coal. Bagasse, furfural residue and coal were the fuels specified for generating steam when the No. 4 boiler was ordered. The specification required that each of the fuels be burnt individually or in combination with each other.

Limited experience is available on the combustion of furfural residue, in view of the limited number of mills at which furfural is produced from bagasse. At the time the boiler was designed, it was known that furfural residue had been burnt at Victorias Milling in the Philippines and Central Romana in the Dominican Republic.

Furfural Residue

Plant materials containing pentosans can be used as the feedstock for producing furfural. At Sezela, the coarse fraction of the bagasse is fed to reactors where furfural is produced in contact with steam. Paturau (1969) illustrated the production of furfural by the following simplified equation showing the hydrolysis of Xylan to Xylose, which subsequently loses three water molecules to form furfural:

$$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5 \rightarrow C_5H_4O_2 + 3H_2O$$

Xylan Xylose Furfural

The cellulose molecule loses two water molecules and as a consequence, the furfural residue has a higher carbon to hydrogen ratio and a higher carbon to oxygen ratio than bagasse. Typical analyses for both furfural residue and bagasse are given in Table 1, confirming the differences between the proportions of carbon, hydrogen and oxygen within the accuracy of the analysis.

Table 1

Chemical and physical characteristics of furfural residue and bagasse

		Furfural residue	Bagasse
Proximate analysis:			
Ash	(%)	2,9	2,0
Volatile	(%)	37,2	40,2
Carbon	(%)	8,0	5,8
Moisture	(%)	51,9	52,0
Ultimate analysis (daf):			
Carbon	(%)	56,2	48,6
Hydrogen	(%)	5,8	6,0
Oxygen	(%)	37,4	45,4
Nitrogen	(%)	0,5	—
Sulphur	(%)	0,1	—
Combustion:			
Gross calorific value	(kJ/kg)	9 800	8 740
Heat released per kg of air consumed	(kJ)	3 180	3 415
Theoretical maximum CO_2	(%)	19,9	20,6

Physical properties

The densities of bagasse and furfural residue differ markedly. Typically, furfural residue has a bulk density of 450 kg/m^3, compared with that for bagasse of approximately 140 kg/m^3. At Sezela, bagasse moisture contents are of the order of 51,5%, compared with furfural moistures of around 53%.

Size grading

The texture of furfural residue indicates a grading much finer than that of bagasse. Typical gradings of bagasse and furfural residue are represented in Figure 1. The bone dry residue shown in this figure indicates two distinct size fractions. The first is similar to bagasse where a large proportion of the sample has a size in excess of 1 mm. The second and larger fraction, is similar to the grading anticipated for bagacillo and has a size of between 105 and 185 microns. The size grading of wet furfural residue appears to be coarser due to the agglomeration of the wet particles. An explanation of the two distinct size fractions in the bone dry furfural residue sample could be ascribed to the physical breakdown of the bagasse in the reactors, where only part of the bagasse is broken down, with a smaller fraction remaining almost intact after processing.

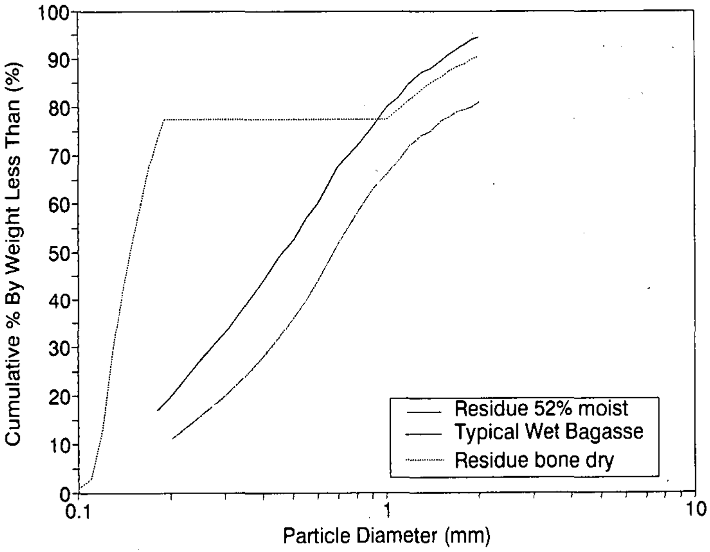

FIGURE 1 Typical size grading of bagasse and furfural residue.

Chemical analyses

The chemical analyses noted in Table 1 were used in defining the combustion characteristics of the two fuels. However, cognisance also has to be taken of the size grading and the matting propensity of the residue. As a consequence, stable combustion would generally only be achieved when the moisture content of the furfural residue does not exceed 53%, while for bagasse this limit would be 55%. Bagasse also contains more fibrous particles which increase the voidage, which would indicate that drying of the residue would be more difficult than bagasse.

Analysis of Combustion Properties

Thermo-gravimetric analysis (TGA) can be used as a combustion tool in analysing the combustion properties of various fuels. The work of Raman (1981) indicated that the pyrolysis of cellulosic materials is heat transfer controlled for particle sizes greater than 60 mm. For sizes between 2 and 60 mm, they contended that it is controlled by both heat transfer and chemical reaction, while for sizes less than 2 mm, the pyrolysis is reaction controlled. Shamsuddin (1992) has described the use of TGA in predicting the thermochemical conversion of biomass, and in particular, the devolatilisation of palm oil solid wastes which are similar to bagasse. A comparative analysis of bagasse and furfural residue, based on TGA techniques, was undertaken to provide information on differences in the combustion reaction of the two fuels. Samples of bagasse and residue were given to Falcon laboratories to undertake the TGA analyses.

Volatile release rate

The rate and extent of decomposition of the fuel can be seen from the volatile release profile shown in Figure 2. An inert atmosphere was maintained in the furnace with nitrogen to prevent combustion. Table 2 summarises the results of Figure 2, where the profile can be described as follows:

- The initial peak represents the moisture loss.
- The second peak represents the volatiles loss. The initial smaller peak in the bagasse curve may be due to the decomposition of the pentosans.
- The final peak occurring at about 440°C represents the remaining char.
- The volatile curves indicate a larger volatile release attributed to the bagasse, with a larger char release attributed to the residue.

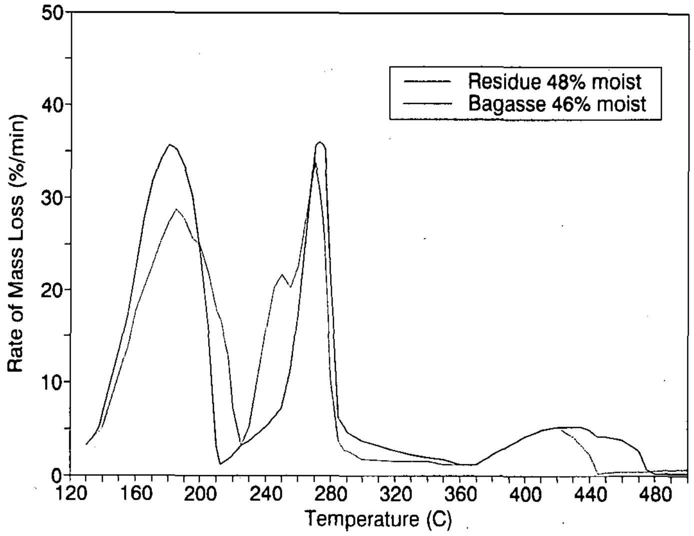

FIGURE 2 Volatile release profiles for bagasse and furfural residue at a constant heating rate of 45°C per minute in an inert nitrogen atmosphere.

Table 2

Volatile release rates

	Furfural residue	Bagasse
Volatiles from thermal decomposition (%)	26,9	31,0
Weighted mean activation energy (kJ/mol)	80,7	66,2

Combustion

The sample was heated at a rate of about 50°C per minute during the combustion tests. The results of the tests graphically presented in Figure 3 show an initial moisture release, followed by combustion. These results are summarised in Table 3, where the temperature at onset of combustion occurs 20°C earlier for bagasse than for residue. The activation energy to burn the residue is about 10% higher than for bagasse.

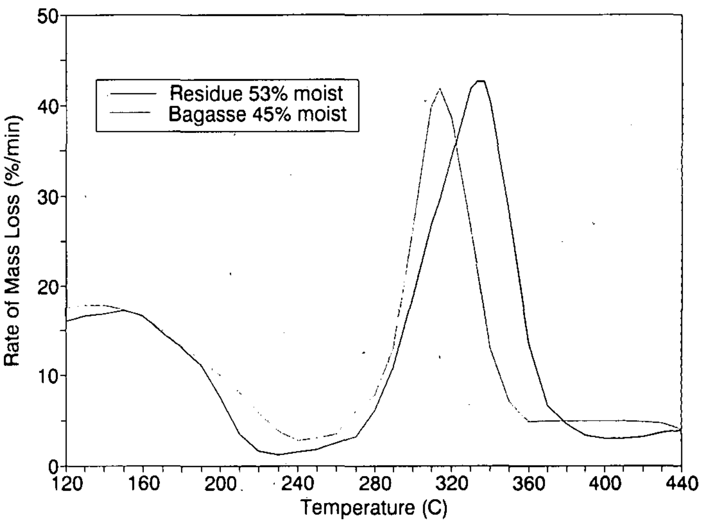

FIGURE 3 Combustion profiles for bagasse and furfural residue at a constant heating rate of about 50°C per minute in an atmosphere of air.

Table 3

Thermo-gravimetric analysis from the combustion profiles

	Furfural residue	Bagasse
Temperature at onset of combustion (°C)	249	228
Apparent activation energy to burn (kJ/mol)	109	101
Temperature at maximum mass loss (°C)	369	366

The difference in ignition temperatures can be attributed to the faster drying rate of the bagasse, where there is higher voidage due to the larger proportion of stringy fibrous material contained in the bagasse as opposed to the furfural residue.

The differences in the intensity and temperature of the combustion peaks for the bagasse sample are due to the difference in mean particle size and volatile contents.

Drying of the fuel

In the tests for measuring the volatile release rate and combustion characteristics, the sample was placed in the furnace at ambient temperature and then heated at a fixed rate to about 550°C. During this time the sample dried, caught fire and burned. Drying took between 4 and 5 minutes. This does not happen in normal practice.

A further series of tests was conducted with furfural residue with the furnace initially pre-heated to 500°C and secondly to 1 000°C. In the furnace pre-heated to 500°C, the sample dried out at about 430°C and ignited after about 36 seconds, while at 1 000°C preheat, ignition occurred after 15 seconds at 550°C.

These tests show that the residue can take a significant time to dry out when fed into a furnace. Fuel can fall on the grate, restricting the flow of air through the fuel, causing the fuel to smoulder, and in extreme cases, leading to loss of ignition.

This supports the need for undergrate air heating to promote combustion. Magasiner (1987) has reported on the cellulose nature of fibrous fuels which are difficult to dry by means of radiant heat. In an experiment to quantify the rate at which heat is transferred to a pile of bagasse by radiation, it was noted that after sixteen minutes the temperature at about 60 mm below the surface was less than 100°C. These experiments showed that drying could best take place by introducing hot air through the grate from below, rather than by radiation from above.

The fine nature of furfural residue and the results of the TGA analysis show that additional heat would be required in the combustion air to dry the furfural residue to obtain combustion performance similar to a typical bagasse.

Microscopic analysis of bagasse and furfural residue

A microscopic analysis of both the materials indicates that bagasse is largely fibrous, open celled, thin walled and very porous. Cell cavities are largely intact and uncompressed, with the cell walls relatively rigid. This leads to high internal voidage and a large internal surface area, much of which is well connected.

Furfural residue analysed under a microscope indicates a more compact structure with the cell walls less rigid. Pieces of the fibrous material are in the form of small grains in which the cellular cavities have been reduced. The cell walls are unevenly broken or massed together, leading to reduced natural porosity. Internal voids are smaller individually with fewer inter-connections than for bagasse. These conditions indicate a reduced internal voidage and a greater density of the material as a whole.

The study shows that care is necessary to ensure efficient combustion of furfural residue. The reduced porosity limits the diffusion of oxygen to the combustible matter. This is translated into an increased air to fuel ratio to compensate for reduced porosity when burning furfural residue than when burning bagasse.

Design Details

Fuel feeders

In designing plant for burning fibrous fuels, as much attention needs to be given to the handling of the fuel as to the combustion. It was recognised that feeding of furfural residue to the furnace may prove difficult. A further concern was the ability of the bagasse feeders to 'hold up' a column of furfural residue.

Tests were conducted to prove that the traditional three drum bagasse feeder was capable of handling the residue and of maintaining a head of this fuel. A draught was created below the test feeder with a view to inducing the flow of furfural residue through the unit.

The tests showed that, with a draught below the feeder, the unit was capable of maintaining a column of furfural residue without by-passing. The feed characteristic was linear, with a similar volumetric characteristic to that obtained with bagasse. The carding drum was arranged in a herring-bone pattern, rather than parallel to the shaft, to ensure that when feeding very wet fuel, the bagasse or furfural residue is sliced off uniformly, rather than being fed in lumps.

Combustion chamber

Boiler No. 4, i.e. the 130 t/h single-pass unit, is designed to burn bagasse, furfural residue and coal either individually or in varying mixed proportions. This boiler is described by Magasiner and Naudé (1988) and is illustrated in Figure 4 taken from their paper.

The most important component of a boiler in which different fuels have to be burnt is the furnace. While the design requirements for bagasse and coal are well known, data were extrapolated for a range of fibrous fuels to describe the combustion characteristics of furfural residue. In particular, the size grading and matting propensity of the residue was used in developing guidelines for the design. Normally, for bagasse firing, secondary air injection is incorporated low down on the rear wall, while the fuel is introduced pneumatically from the front wall with secondary air. Additional secondary air was introduced above the feeders on the front wall, as well as high up on the rear wall.

The boiler was designed with a sandwich wall construction. In this construction a tile is located between furnace wall tubes. The refractory tiles provide the thermal inertia required for stabilising combustion when burning the wet fibrous fuels, while furnace tubes provide cooling which reduces slagging when burning coal.

Operation

Initially, the No. 4 single pass boiler burnt a combination of furfural residue and bagasse. It was found that the fuels burnt well in the furnace with a controlled fuel to air ratio. However, as operation of the by-products plant increased, so the quantity of furfural residue increased. Field *et al.* (1992) reported that up to about 1986 the quantity of residue produced was insufficient to cause serious problems in the

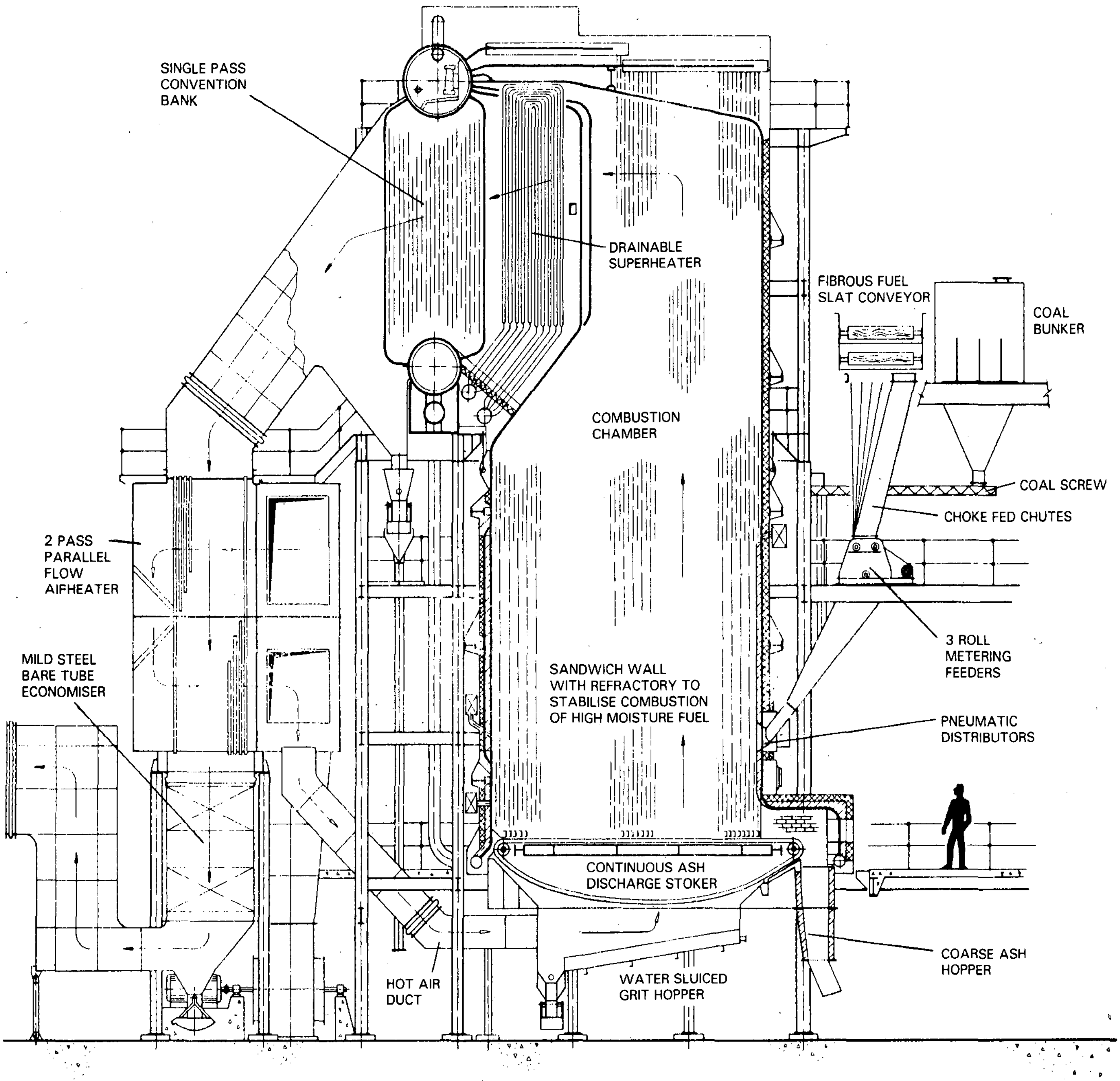

FIGURE 4 Boiler designed for burning bagasse, furfural residue and coal.

mill. From that time onward 'puffs' could occur when disturbances caused the fuel composition, and hence the density, to change rapidly. As the feeders were volumetric devices, the amount of fuel fed to the furnace was no longer in proportion to the air flow.

In analysing the problem, it was felt that 'puffs' could occur during start-up or transient operation. These two operating conditions can be considered separately.

Start-up

If the boiler is tripped during operation with furfural residue, then this fuel will remain in the system and, in particular, the chutes leading to the boiler will contain the residue. Without a supplementary fuel, it is necessary to utilise furfural residue as a means of establishing stable combustion during the re-start. However, any start which does not result in the immediate ignition of the furfural residue could lead to a 'puff'. Initially, it was thought that 'puffs' occurred due to wet furfural residue extinguishing the flame and then re-igniting. Current thinking is that, while the wet residue may extinguish the flame, the puff occurs as the result of the dry furfural residue re-igniting as a dust cloud.

Transient operation

Unstable furnace combustion conditions may take place due to deviations from the correct air to fuel ratio. This can occur through changes in fuel density. As the fuel feeders are volumetric flow units, changes in density may result in the introduction of more fuel to the furnace than anticipated. In the particular case where the density increases due to a changeover from bagasse to furfural residue, piling can occur on the grate. Once the fuel dries, a 'puff' may occur as additional air is introduced to the furnace when the load increases.

Experience in the Philippines indicated that 'puffs' were noted if the moisture content of the furfural residue fell below 44% (John Thompson Australia, personal communication). As a consequence, sprays were used above the conveyors to damp the residue.

Operation at constant density

At the installation in the Philippines, furfural residue and bagasse enter the boiler station on separate conveyors. A precaution taken to ensure stable combustion was to mix the bagasse and furfural residue in fixed proportions. The rate of production of the furfural residue was known and the bagasse flow was adjusted to match this rate by a variable speed bagasse conveyor. Both fuels were mixed in a bin above the feeders and fed into the boiler by conventional bagasse conveyors and pneumatic distributors. The proper mixing of the bagasse and residue in this bin was regarded as the best means of maintaining a constant fuel density, which had the effect of reducing the formation of 'puffs'.

A further precaution was the use of a base load oil flame. The rate of oil firing was commensurate with the smallest stable flame that could be maintained. A single burner was used with a 4:1 turndown.

Fuel density compensation

It became clear that at Sezela the sudden changeover from bagasse to furfural residue could not be avoided. A 'slug' of furfural residue could be introduced to the furnace, thereby changing the density of the fuel by a factor of three, and as a consequence, affecting the air to fuel ratio to the extent that ignition might be lost. Field *et al.* (1992) described the successful utilisation of density measurement at Sezela as a means of compensating for changes in density and overcoming the problem of incorrect fuel to air ratios with varying proportions of bagasse and furfural residue.

The use of fuel density compensation has been extended from the use of a single density probe to a multiple of probes on both boilers 1 and 4. The use of more than one probe improves the control by smoothing minor short duration changes in density.

While fuel density measurement does enable the changeover from one fuel to another without major deviations in the combustion conditions in the furnace, the volumetric fuel feeder is not ideally suited to the large variations in density that occur when changing from bagasse to furfural residue. The result is that when feeding residue the feeder speed is slowed down and the sensitivity of the feeder is impaired. Consideration has been given to including within the control logic means of reducing the number of feeders in operation when feeding high density fuel at part loads. Under these conditions, care has to be taken to ensure that an even spread of fuel is maintained with the reduced number of feeders.

Support fuel

It was noted that boilers 2,3 and 4 were less susceptible to 'puffs' than the No. 1 three-pass unit. The better operation of these units was attributed to combustion support offered by the coal bed maintained on their grates.

During a sudden mill stop, the bagasse carriers and feed chutes contain the last fuel which, due to the high rate of furfural production, is more likely to be furfural residue.

Coal firing has been introduced on to the No. 1 three-pass boiler, so that in the event of loss of ignition through a mill stop, ignition is re-established on the boiler by initially burning coal prior to introducing furfural residue. Alternatively, bagasse can be utilised as a start-up fuel.

Flame failure detection

Flame flicker monitoring systems will be incorporated into boilers 1 and 4 during the 1993 season to protect these units in the event of a flame-out. Precautions generally applied to pulverised fuel firing have also been implemented as an additional safety measure.

Conclusions

While furfural residue is a derivative of bagasse, the combustion properties of this fuel differ from that of bagasse. Major differences occur in the physical nature of the fuels, which affects the drying and hence combustion.

Operational experience has shown that care has to be taken, particularly during start-up and transient operation. This has been overcome at Sezela by introducing a support fuel to the boilers and by density compensation.

In assessing a fibrous fuel, it is useful to compare the properties of that fuel with an existing fuel for which design parameters have been established. In this instance, furfural residue, when compared to bagasse, can be described as follows:

Physical Properties:	Furfural residue has a higher density and a finer size grading.
Chemical Properties:	Furfural residue has a higher carbon to hydrogen and carbon to oxygen ratio, a higher calorific value and less heat is liberated per kilogram of oxygen consumed.
Combustion Properties:	Furfural residue is more difficult to dry due to its matting propensity, and to the lower voidage of the fuel. On a microscopic basis the fuel has a poorer voidage, making it more difficult for the diffusion of oxygen to the combustible material. Furfural residue has a higher activation energy, which would indicate the need for higher undergrate air temperatures.

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