The Sugarcane Industry : the Largest Global Thermal Renewable Sector
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Part I : Practical Implications of Thermodynamics for Generation and Cogeneration

Abstract

The sugarcane industry is gifted with abundant energy from 'bagasse', the fibrous component of the cane. It is used to raise the steam from which electricity is generated, the LP steam driving the sugar-making process thermally : i.e. cogeneration.

This paper provides an introduction to the industry and the implications for the power station equipment used, particularly the boiler. Although at first this seems irrelevant to the UK, in practice bagasse is typical of most renewable fuels to some extent or other so there are valuable lessons to be learnt.

Background

Sugarcane is a tall tropical grass which uses sucrose [sugar] to store energy in its stem in order to see it through periods of poor conditions :

Figure 1 : Manual Harvesting of Sugarcane

As with most commercial crops, there are many varieties of sugarcane around the world and there is always ongoing research to develop better varieties, whether that be to impart better disease resistance, higher sucrose content or higher fibre content [or some combination of those characteristics].

The composition of sugarcane is rather variable but ‘typical’ cane might be :

Sucrose :	10 - 12%
Fibre :	12 - 14%
Non-Sucrose Dissolved Solids :	2%
Water :	70%

[In practice sucrose varies from 8 to 18% and fibre from 10 to 20%.]

To produce sugar, the juice of the sugarcane is removed by counter-current extraction with hot water after mechanical disruption, the juice is then clarified and evaporated up before the sugar is crystallised out.

All of those processes require electrical and thermal energy. However, the sugarcane industry is blessed with a ‘free’ supply of energy in the form of the cane fibre : the ‘bagasse’ left over after juice extraction. There is, in fact, an embarrassment of bagasse energy which meant that factories – including their boilers – were originally deliberately designed to be energy inefficient in order to avoid bagasse disposal costs.

A conservative estimate of the global sugarcane crop is at least 2.2 billion tons per annum. At 12 to 14% fibre, that equates to 275 to 325 million tons of fibre per annum. A tiny proportion is diverted to board production but most is used as boiler fuel.

We do not have reliable data for installed capacity but there are at least one thousand bagasse fired power stations in the industry so maybe 50GW or more of installed capacity.

Bagasse

Just as sugarcane is rather variable in make-up, so is the fibrous residue, bagasse. In some ways it is very typical of fibrous ['renewable'] fuels but generalisations can be misleading.

As a boiler fuel, it is the Gross Calorific Value [GCV or HCV] that is of primary interest and that depends on its combustible content. The GCV of pure sugarcane fibre has been shown to be 19 605 kJ/kg when bone dry. From that, a formula for bagasse GCV was developed :

$$GCV = 19\,605\,(1 - m - a) - 3\,115\,b \quad \text{kJ/kg}$$

where	m	=	the moisture fraction of the fuel
	a	=	the ash fraction of the fuel
and	b	=	the brix [sucrose] fraction of the fuel

The first version of the formula ignored the sucrose but it was realised that, even though the sucrose content was low [after all the factory is designed to recover as much sucrose as economically possible from the sugarcane], it contributed to the GCV of the bagasse but didn't have the same GCV as fibre.

Bagasse supply is variable at both macro [global and regional] and micro [the factory] level :

- The fibre content of the sugarcane changes with variety [and a factory will process several varieties each crop period], during the crop and from year to year;
- The moisture of the bagasse can vary from minute to minute and certainly from shift to shift;
- The ash content will vary both with the weather [muddy fields meaning dirtier cane] and with the source of the cane [some fields will have stickier soils and manually harvested cane is cleaner than mechanically harvested cane];

Bagasse Moisture Content

It follows that the key characteristic of bagasse is its moisture content.

Bagasse is mechanically dried after the extraction process, passing through a large mill or mills [Figure 2, over]. Mills are notoriously difficult to photograph so, to put it into perspective, each roll in Figure 2 is two metres long and one metre in diameter and there are actually four rolls in the mill. Some factories use mills as the extraction equipment, other factories use a diffuser, followed by at least one mill to dry the bagasse.

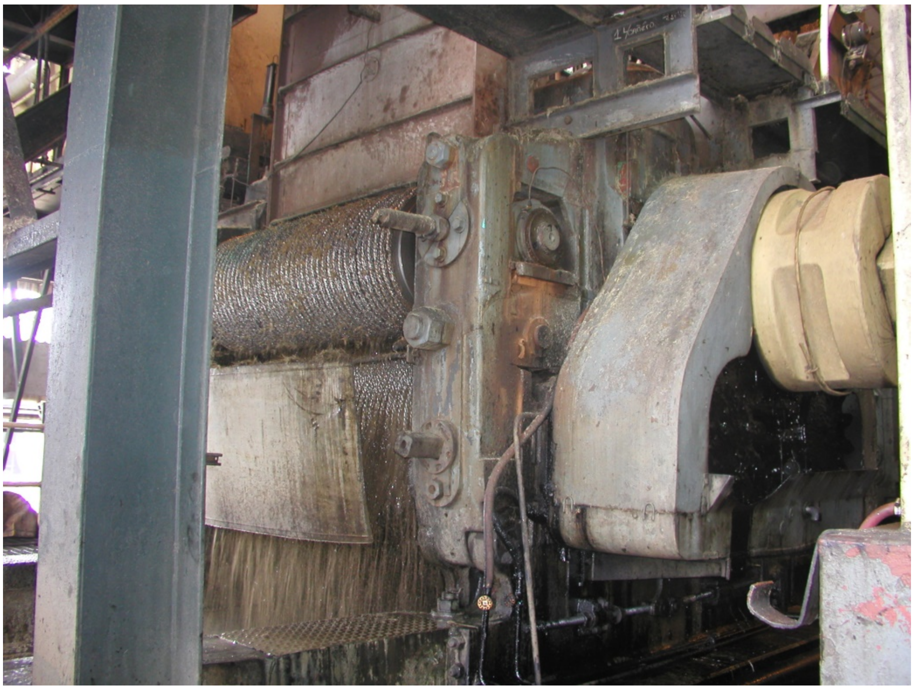

Figure 2 : Sugarcane Mill

Despite the cascade of juice seen in Figure 2, it is difficult to extract liquid from sugarcane because it is so springy and re-absorbs as soon as it is past the pinch point of the rolls. If there is a 'typical' value for bagasse moisture content it is 50% but a well-run factory will achieve 48, 47 or sometimes even 46% moisture and, equally, poorly run factories might only achieve 54, 55 or even 56% moisture.

It requires a lot of effort to achieve the lower moisture values so management is reluctant to do so unless the factory energy balance requires it or the bagasse energy is seen as a by-product and surplus energy is sold.

Bagasse Ash Content

The key characteristic of bagasse may be its moisture content but that doesn't mean that the ash content can be ignored. There are two types of ash – whether one is considering bagasse or any other fibrous fuel : the soluble ash and the extraneous ash. Soluble ash is typically the inherent ash of the fuel, i.e. derived from the plant material itself. Extraneous ash is typically ash such as grains of sand adhering to the fibre. [An important exception is the silica content of rice husks which is very high, it is not soluble but is inherent – and highly erosive, see below.]

Soluble ash usually affects problems like clinkering, slagging and fouling of the boiler. Which occurs depends on the elemental content of such ash, heavier metals leading to clinkering and/or slagging and lighter metals [sodium, potassium] leading to fouling. This is analysed as the ash fusion temperature, a science worthy of a paper in its own right.

Bagasse, of course, is the residue following aqueous extraction and therefore soluble ash tends to be insignificant. The problem arises when management wants to co-fire other, non-leached, fibrous fuels such as sugarcane leaves or sorghum with bagasse. In such situations we typically limit the co-firing to no more than 15 to 20% inclusion, depending on detailed analysis.

Extraneous ash and non-soluble inherent ash, tends to be discussed in terms of erosion within the boiler. It is an important consideration when engineering a boiler.

The More Physical Characteristics

There are other characteristics of bagasse that need to be considered : the more physical characteristics :

- it has a low bulk density : typically 125 kg/m³;
- it has a matting capability and has a negative angle of repose so quickly chokes a conventional fuel chute;
- it composts over time and can self-combust;
- it is essentially volatile, despite appearances;

Examination of the proximate analysis of a typical bagasse analysis shows the latter to be true :

FUEL			Bagasse
SOURCE OF SAMPLE			TES std
PROXIMATE ANALYSES (as received)			
Fixed carbon		%	5.99
Volatiles		%	42.01
Moisture (inherent)		%	0.00
Moisture (free)		%	50.00
Ash		%	2.00
	TOTAL	%	100
Brix		%	2.00
ULTIMATE ANALYSES (as received)			
Carbon		%	22.85
Hydrogen		%	2.83
Suphur		%	0.10
Nitrogen		%	0.86
Oxygen		%	21.36
Moisture		%	50.00
Ash		%	2.00
	TOTAL	%	100.00
GCV		kJ/kg	9,348
NCV (ISO)		kJ/kg	7,613

Figure 3 : Bagasse Analysis

Moisture is volatile in the furnace and so are the volatiles of course so the particular bagasse analysed is 92.01% volatiles.

Bagasse Energy Density

Energy density is an important parameter of fibrous fuels such as bagasse. They do not lend themselves to metering by weight [and metering is a given for efficient boiler operation] so they are metered by volume.

A typical bagasse will have an as-fired bulk density of ~125 kg/m³ with a GCV of ~8 000 kJ/kg so an as-fired energy density of 1 million kJ/m³. Waste wood, on the other hand, is likely to be 500 kg/m³ with a GCV of 16 000 kJ/kg so an as-fired energy density of 8 million kJ/m³.

That is a major difference in fuel characteristics for what are two, otherwise similar, fibrous fuels.

The Boiler

The boilers in the sugarcane industry range from the small [50 t/h] to the large [300 t/h] and from low pressure [21 bar] to high pressure [120 bar]. In general, it is the oldest units [50 years old!] which are small with low steam conditions and the newest which are large with high steam conditions.

Over that half century the industry has changed dramatically from deliberate energy inefficiency to high efficiency, selling electricity as a co-product. The design of bagasse fired boilers has also changed dramatically in the same period, from multiple drum hearth boilers to bi-drum or even single drum grated furnace units. Figure 4 shows the GA of a typical modern bi-drum bagasse fired boiler with feed system and heat recovery tower :

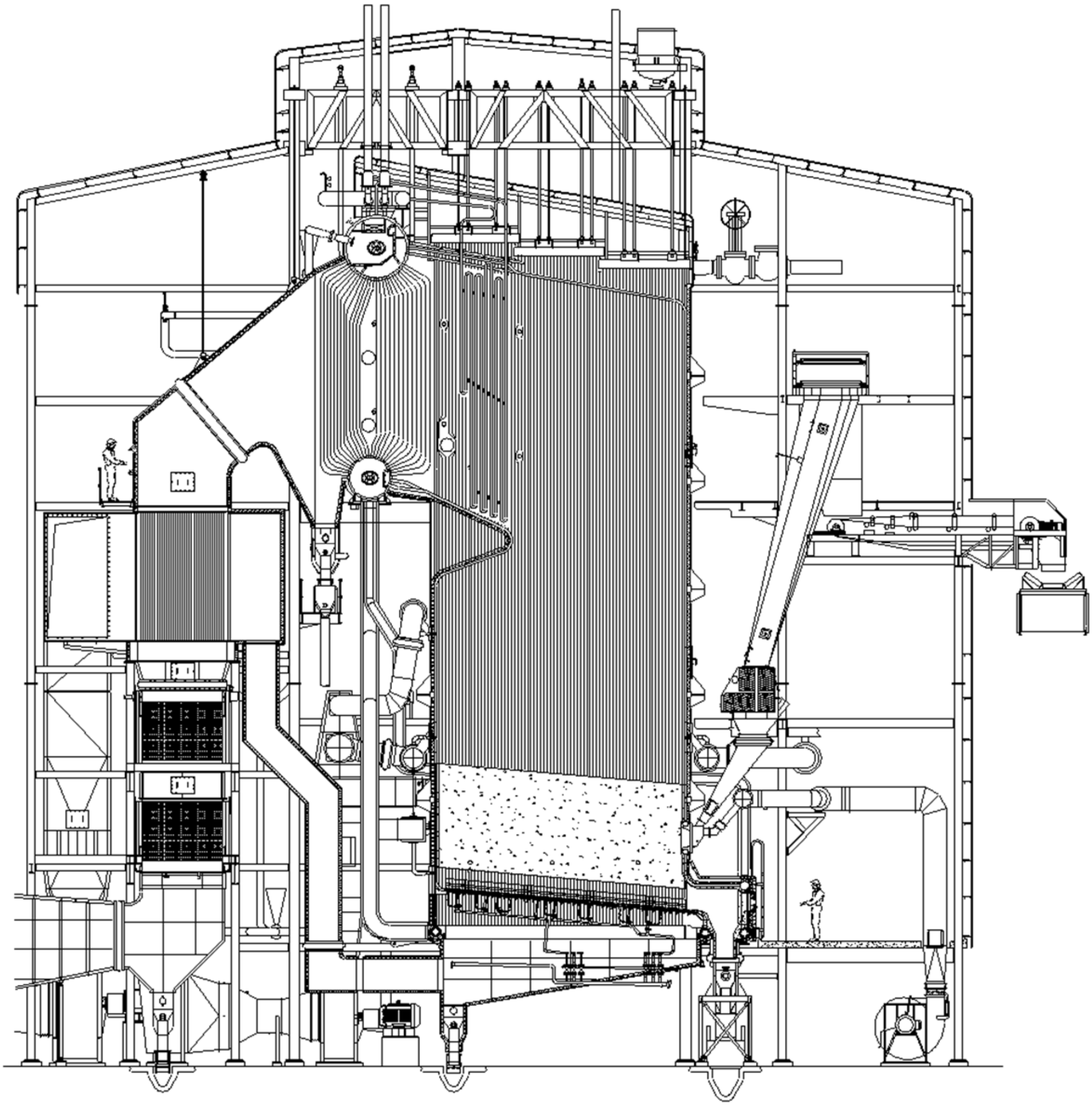

Figure 4 : A Typical Modern Bagasse Fired Boiler

The Grate

Knowing that bagasse is essentially a volatile fuel, it makes sense that it is fired in suspension and not on the grate. The grate is there to spread the primary air and to handle the ash.

The typical bagasse fired grate is a steam-swept pinhole grate, more often sloped but sometimes flat :

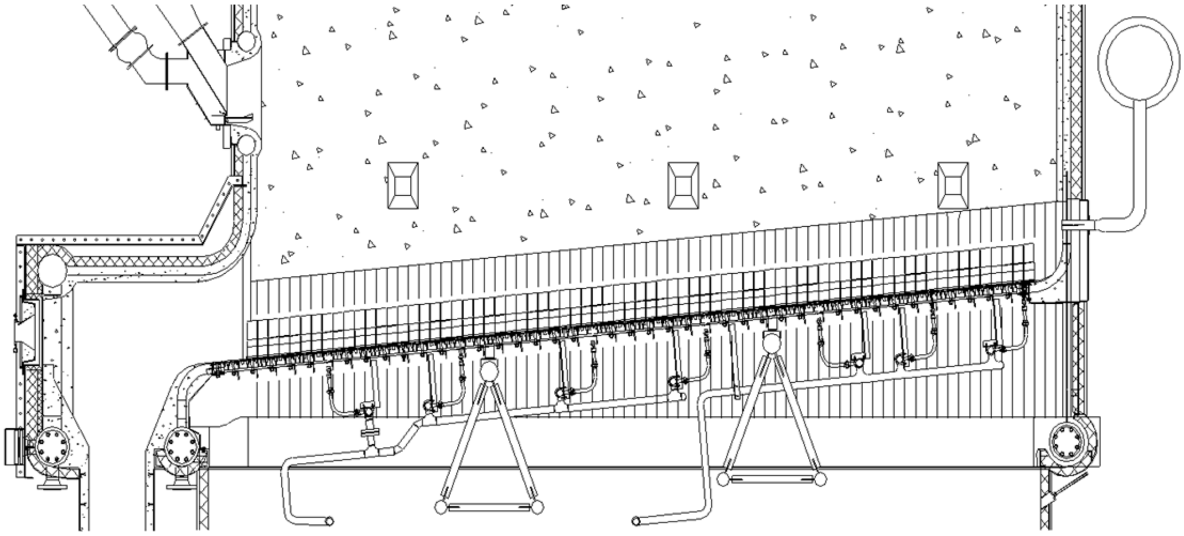

Figure 5 : A Sloping Steam-Swept Pinhole Grate

In high ash situations [some bagasse will have up to 8% extraneous ash or more], a continuous ash discharge [CAD] stoker is preferred :

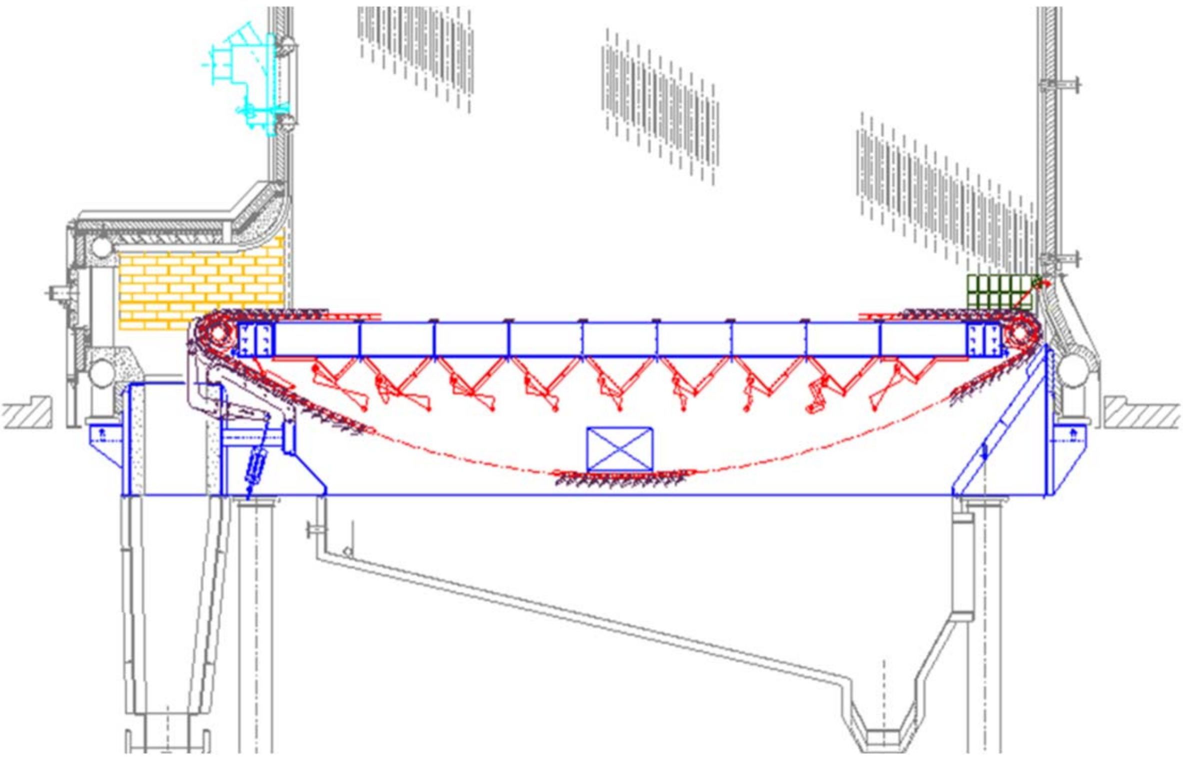

Figure 6 : A Continuous Ash Discharge [CAD] Stoker

Whatever type of grate is selected, the moist nature of bagasse requires that the primary air, fed into the furnace from below the grate, is hot. That is particularly useful when, during drying mill upset conditions, high moisture bagasse is fed into the boiler : it has a tendency to pile on the grate rather than burn in suspension.

Note too the refractory coating of the membrane walls shown in Figure 5. This also helps stabilise combustion during upset conditions.

Fuel Spreaders

Bagasse spreaders are pneumatic devices, powerful enough to spread not only bagasse but wood chips and the like, even 'washed pea' coal.

The fuel falls down from the feeder and on to a distribution plate from whence it is blown into the furnace with distribution air. The plate angle is adjustable so that the distributor can be tuned during commissioning. The objective is to throw the bagasse to the back of the furnace from where the lowest secondary air nozzles throw it forward again :

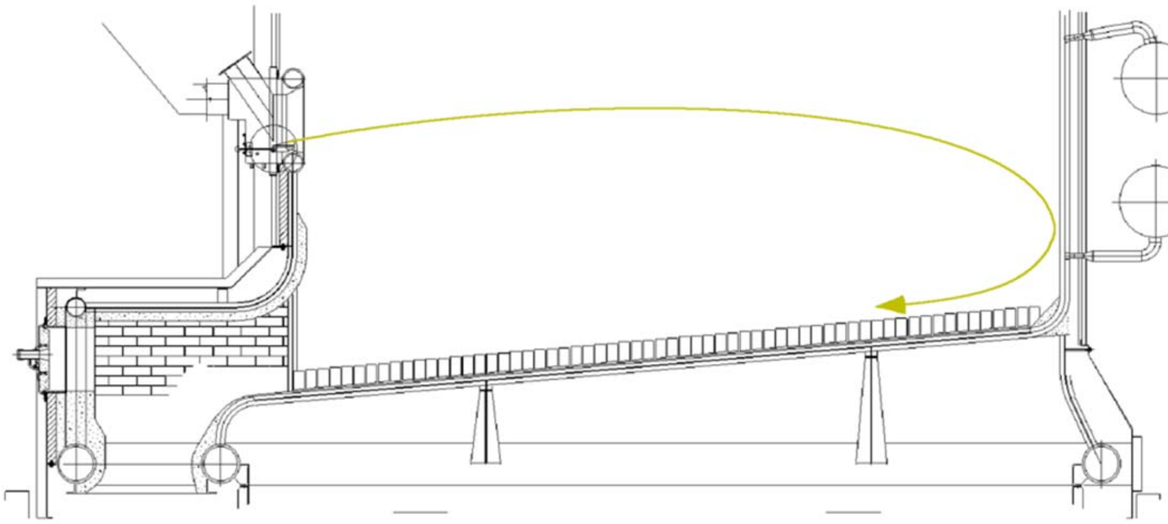

Figure 7 : Idealised Bagasse Trajectory

Once commissioned, the plates are normally locked in position. It should be noted that the distribution plates next to the sides of the furnace are different from the rest, having a bias inwards to avoid the walls.

The Main Bank

The other aspect of bagasse fired boilers that requires particular attention is the main bank and that is because of the erosive nature of the fly ash.

Erosion is, of course, related to gas velocity. Examination of the factors affected by gas velocity is very illuminating :

HT Coefficient	$\propto$	$v^{0.61}$
Pressure Drop	$\propto$	v^{2}
Power Absorbed	$\propto$	v^{3}
Erosion	$\propto$	$v^{3.5}$

In practical terms, that means that it pays to accept a lower heat transfer coefficient in order to gain on fan power and erosion despite the increase in capex. Halving the gas velocity increases the tube life eleven fold [$2^{3.5}$ = 11.314] but the HT coefficient only reduces by one quarter [$2^{0.61}$ = 1.526]. Clearly, a commercial optimisation is required.

Early designs were three-pass ones with internal baffles to improve the heat transfer. However, when diffusers were introduced for juice extraction the quantity and nature of the fly ash changed and serious erosion started to be an issue where the gas changed direction.
A change was made to single pass main banks, as shown in Figure 8 [over] :

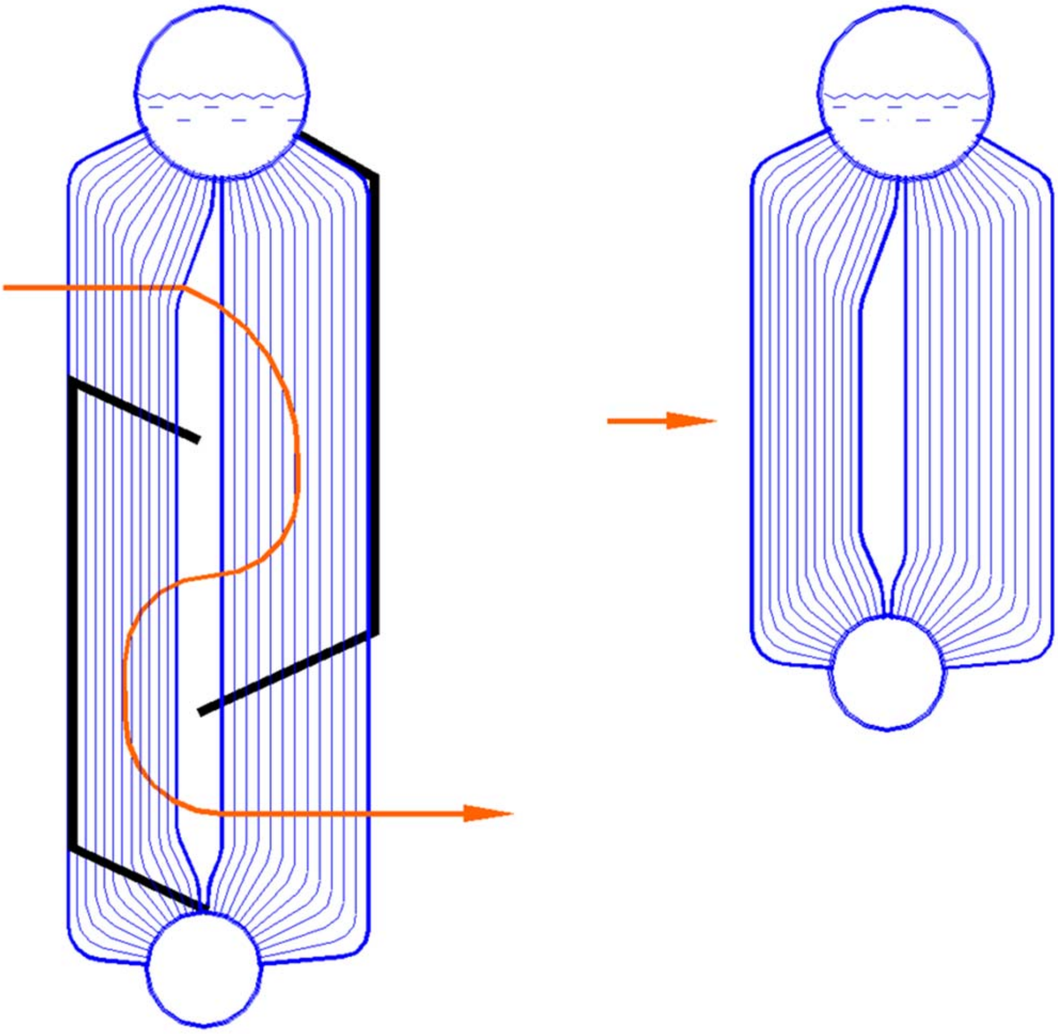

Figure 8 : Older Three-Pass and Modern Single Pass Main Banks

Peripherals

Fuel Feeding System

A typical large bagasse fired boiler might burn 100 t/h of fuel. At 125 kg/m^3 that is 800 m^3, a pile which might measure 12 x 12 x 5.5 metres. Such a typical large bagasse fired boiler will have eight fuel feeders so each chute takes 100 m^3/h of bagasse. With a typical cross section of 0.43 m^2 and a typical height of 5.0 m, the storage capacity is only 1 minute and 17 seconds.

There are also the issues of the negative angle of repose and the matting properties of the bagasse. Those require the storage chutes above the feeders to be diverging. An increase of cross section of only 25 mm in each direction is adequate but note that after the feeders the free flowing bagasse does not require a diverging chute.

The role of the fuel feeders is not only to meter the fuel into the boiler but also to seal the furnace against tramp air, the engineering team having taken great care in optimising the air supply.

Feeders tend to be either roller devices or screw units.

Roller feeders are low power devices able to cope with tall upper chutes. Figure 9 [over] shows one of our triple drum feeders. Two small top rolls do the metering and a single carding drum with a greater peripheral speed ensures that the bagasse does not clump. The drive is typically a 3 kW motor but the machine absorbs less than 1 kW.

Figure 9 : TES Triple Drum Feeder

We tend to limit the upper chutes to 10m height, which gives about 2½ minutes of fuel storage.

The feeder body can incorporate a secondary fuel inlet that by-passes the metering mechanism so that a separately metered stream of solid fuel such as wood chips or coal can be fed to the fuel spreader below.

Because of the requirement for tall upper fuel chutes, feeders have to shear the bagasse from the bottom of the chute. Roller feeders require minimum shear but large forces are needed to do this with screw or chain feeders. The latter must be of robust construction and with powerful drives greater than 10 kW.

The Heat Recovery Tower

Erosion is a particular problem in heat recovery towers on fibrous fuel boilers.

Economisers can be either plain tube or finned tube units but finned tube units are far less susceptible to erosion and provide greater performance for a given control volume [provided that they are designed correctly].

Fin profile and spacing is important – use robust rectangular set-on fins, do not use spiral finned tubes. The fins must be set in the same places on each tube so that they stack above each other and the tubes should be widely spaced as shown in Figure 10.

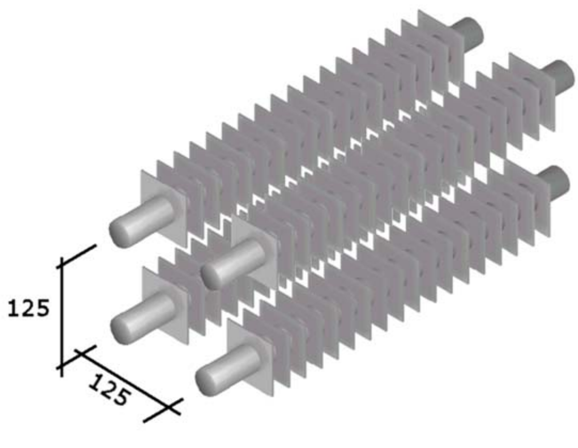

Figure 10 : Sketch of Economiser Section

One of the characteristics of boiler erosion is the segregation of the erosive particles caused by the inertia of the particles when the gas changes direction. The particles concentrate on the outside of the curve – one of the causes of the erosion seen in the three pass main banks discussed earlier.

One solution, to protect the economiser, is to use wall baffles at the start of the bank. Those in Figure 11 are made with galvanised grid flooring sections that can easily be replaced :

Figure 11 : Economiser with Entrance Baffles

Induced Draught System

Erosion is also a particular problem with the induced draught system and there are other issues too.

Modern boilers are usually fitted with electrostatic precipitators. The fly ash from fibrous fuels consists, in part, of activated carbon so is very flammable which means that the ESP must be kept under positive pressure so that oxygen-rich air does not ingress. That means that the ID fan must be placed before the ESP and, hence, is potentially exposed to the erosive gas.

Affordable cyclone separators are not very efficient so a scrubber is usually placed before the fan.

Using ID fan speed control rather than some form of damper system also helps with erosion management, not only for the fan but also for the dampers, if they were to be used.

The other issue for ID fans is that, inevitably, damp unburnt bagasse sometimes carries over. It is therefore wise to use a forward curved, radially tipped fan because it is the most self-cleaning of the possible designs.

Conclusions

Bagasse is the world's most used fibrous fuel with at least 50 GW of installed capacity. In some ways all fibrous fuels are similar but in other ways they are particularly dissimilar so always take care to evaluate the characteristics of fibrous fuels, the moisture, the specific energy density and the ash quality being the most important but don't neglect the physical characteristics.

Fibrous fuels are normally fired in suspension using pneumatic feeders and a steam-swept pinhole grate is best unless extraneous ash is high, in which case select a CAD stoker. Hot primary air helps flash off fuel moisture and a refractory coating to lower furnace walls helps stabilise combustion.

Erosion is an issue so use single pass main banks and optimise the gas velocity [with the knowledge that the HT coefficient is proportional to gas velocity raised to the power of 0.61 but erosion is proportional to gas velocity raised to the power of 3.5].

Fibrous fuels tend to create handling and storage problems so keep them moving once started into motion. It is necessary to accept that local storage will be minimal and combustion in suspension is short-lived which means that fuel handling must be robust and a suitable control philosophy must be adopted. The feeders must meter the fuel and also ensure that tramp air is excluded. Low energy roller feeders are preferred for fibrous fuels.

Both the heat recovery tower and the induced draft system need to be designed to manage erosion and the highly flammable nature of organic fly ash must be taken into consideration, especially when using dry separation equipment.