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INCLINED PERFORATED DRUM DRYER AND SEPARATOR FOR CLEANING AND DRYING OF SUGARCANE BAGASSE

LOKHAT D[1] AND BERNHARDT HW[1]

[1] *School of Engineering, University of KwaZulu-Natal, Durban 4041*

Lokhat@ukzn.ac.za, Bernhardth@ukzn.ac.za

Abstract

Sugarcane bagasse is a renewable energy source that has the potential to be used to generate electricity in sugar mills. The moisture content of bagasse as generated in the normal sugar extraction process is typically around 50 %. Its energy value could significantly be enhanced if the moisture content was reduced to 20 % or below. The bagasse contains a significant amount of pith, a fibrous component of the biomass that has a lower calorific value than the remaining constituents, as well as sand. In this work it was shown that pith and sand removal as well as drying of the bagasse could be effectively carried out using a perforated rotating drum dryer. Hot air passes counter-current through a rotating drum inclined a few degrees to the horizontal where bagasse moves down through the drum by gravity and heated air flows upward through the tumbling bagasse. The pith and sand are able to pass through the perforations in the drum whilst the remaining bagasse exits at the bottom end.

The extent of moisture and pith/sand removal were found to be dependent on the rotational speed of the drum, feed rate of biomass, angle of inclination, and flowrate and temperature of the air. The initial modelling study assumed plug flow of bagasse and a constant air temperature in the drum. The full model is able to adequately predict the performance of the dryer.

Keywords: sugarcane, drying, rotating drum, moisture ratio, inclined, bagasse

Introduction

Bagasse is the fibrous material remaining after sugarcane undergoes juice extraction. According to Anwar (2010), typical mill run bagasse consists of 43-52 % fibre, 46-52 % moisture and the remaining 2-6 % of soluble solids. Sugarcane bagasse is widely used as a source of fuel for boilers in sugar mills. Due to the seasonal production of bagasse, large quantities of the fuel need to be stored for use in steam and electricity generation during the off-crop period. Storage of bagasse for use during the off-crop period poses a problem due to the level of moisture in the bagasse and the propensity for decay. The high level of moisture also significantly decreases the gross calorific value of the fuel. Excess energy is used to evaporate the moisture present within the bagasse during the combustion process resulting in lower boiler efficiency. Reduction of bagasse moisture gives more efficient and stable operation of the boilers and lowers emissions as well as increases fibre preservation during storage. Various types of dryers have been utilised for the removal of moisture from bagasse. Fluidised-pneumatic dryers offer high efficiency but discharge more dust to the atmosphere. Rotary drum dryers use less energy than the pneumatic type but are generally less efficient and occupy a larger area on the plant floor (Ansari, 1986).

The soluble solids found in bagasse generally refers to the sand and dirt that is retained after the extraction process, as about 60 % of the dirt is picked up during harvesting of the sugarcane (Wright, 2003). The sand in bagasse causes wear to the boiler components such as tubes, grates and fans. Boiler efficiency is also negatively affected by soil and boiler fires are occasionally extinguished due to excessive soil. Sand removal is also critical for any briquetting or pelleting process for long term storage of bagasse, since the sand can cause wear to the pelleting dies.

Of the fibre present in bagasse, there exists a cellulosic constituent known as the central parenchymatous tissue or pith. The pith fraction is generally easier to compress whereas the remaining large straw-like fibres form open bridges and do not compress well. Separation of these fractions has been suggested as a means of controlling the pelletising/briquetting behaviour of the bagasse as well as improving overall usage efficiency.

In this work the combined drying, cleaning and separation of bagasse using an intensified rotating drum unit was investigated. The objective was to determine the technical feasibility of reducing the moisture (from 50 % to below 20 %) and sand content of the bagasse using a perforated rotating drum dryer that incorporates counter-current flow of bagasse and heated air.

Materials and Methods

Pith content of raw bagasse

The bagasse was obtained from the Tongaat Hulett Maidstone sugar mill in Durban, South Africa, and was used without further preparation. A wet abrasive technique reported by Lathrop *et al.* (1955) was used to determine the pith content of the raw bagasse. A well-mixed sample of the raw bagasse was weighed using a digital laboratory balance. The bagasse was transferred into a 500 ml beaker and water was added whilst simultaneously stirring the mixture using a glass rod, ensuring that all contents of the beaker were completely loosened and soaked. The beaker was placed on a hot plate stirrer assembly and the contents were heated between 38-45 °C under constant stirring. Once the imbibed liquid had completely loosened the bagasse fibres, the mixture was taken off the hot plate stirrer and allowed to cool. Once cooled, the sample was filtered under vacuum to remove all excess water before being left to dry overnight on absorbent tissue. Once the bagasse had completely dried it was vigorously rubbed together by hand to remove the pith cells that were attached to the fibre. It was essential to rub the bagasse along the fibre length instead of across it, as rubbing the fibre across its length causes the breaking down of fibres and reduces particle size. The bagasse was then sieved using a 325 μm aperture sieve to remove the pith. The pith, along with the de-pithed bagasse fibres, was then separately weighed.

Sand content of raw bagasse

A well-mixed sample of the raw bagasse was burnt on a stainless steel screen using a Bunsen burner. The residue was collected and weighed on a digital laboratory balance. In order to separate the bagasse ash from the sand, a dense medium separation technique was employed using water as the separating medium. Bagasse ash has a density of approximately 0.75 $g{\cdot}cm^{-3}$ and sand of approximately 1.6 $g{\cdot}cm^{-3}$. In order to achieve a sharp separation, the density of the water medium was modified by addition of sodium metatungstate hydrate. An appropriate amount of the salt was added to deionised water to give a density of 1.2 $g{\cdot}cm^{-3}$. The mixture was placed in a 100 ml measuring cylinder and the burnt residue was added. After gentle mixing the residue was left to separate overnight. The ash layer accumulated at the top of the cylinder and was carefully removed and dried. The sand at the bottom of the cylinder was vacuum filtered and dried. Both the ash and sand were weighed on the digital laboratory balance.

Experimental equipment and procedure for drying tests

The experimental work was conducted in a perforated rotary drum dryer that was fabricated specifically for this project. It consisted of a stainless steel drum with perforations large enough to achieve sand and pith removal. The perforations had a diameter of 4.9 mm on a square pitch of 3.3 mm. The drum was mounted on an axle and rotated by means of a motor using a pulley and belt system. The drum was inclined at 13 ° to the horizontal at its lowest level, and could be increased to 15 ° and 17 ° at its intermediate and high levels, respectively. This allowed for smooth flow of particles down the drum under gravity. The bagasse was introduced to the top of the drum using a Fritsch vibrating feeder. The air which was used was compressed air being fed from a gas line in the laboratory. This was fed to a cylindrical pipe that was 750 mm long and 60 mm in diameter, with four clamp on band heaters attached along the axis. The heating pipe was used to heat the air flowing through the pipe before it entered the drum. In order to allow for more uniform heat distribution within the pipe, it was packed loosely with glass rings. The air was then fed to the bottom of the rotating drum using a flexible stainless steel hose. The dried bagasse exited the drum via a chute located below it into a collection tray, whilst the sand and pith that fell through the drum perforations were collected in a removable tray located beneath the drum. The entire apparatus was housed in a Perspex box that was 1 200 mm long and 600 mm high and wide.

In a typical experiment, approximately 100 g of bagasse was weighed on a laboratory balance and the moisture content was determined using a Boeco BCO35 electronic moisture analyser. Approximately 2 g of bagasse was used for the moisture analysis. The remaining bagasse was subjected to the drying test by placing it in the vibrating feeder, activating the drum assembly and air feed at prescribed levels and collecting the dried bagasse for analysis after the run had been completed. The inlet air velocity was measured using a digital anemometer and the air temperature was determined using a calibrated temperature probe and handheld display. The moisture content of the collected sample was again determined using the electronic moisture analyser.

The effect of five operating variables on the performance of the cleaning and drying system was investigated. The chosen variables were inlet air velocity, air temperature, drum rotational speed, solids feed rate and the angle of inclination of the drum. In order to identify the effect of each variable on the extent of drying and cleaning achieved, a factorial experimental design was used where each variable was individually varied between three levels, namely low, intermediate and high, whilst the remaining variables were kept constant.

Results and Discussion

The raw bagasse used in this investigation had an initial moisture content of 38.35 % on a dry basis. This value was lower than the typical value of between 46-52 % reported by Anwar (2010), and the average value of 50.68 % for South African sugar mills reported by Smith *et al*. (2011). Nevertheless, the moisture content was deemed sufficiently high in order to carry out feasibility tests on the rotary drum dryer. Using the wet abrasive technique, the pith content was found to be 38.63 %. This value was between the 30 % reported by Hurter (2007) and 47 % reported by Anwar (2010) for the pith content of bagasse. The sand content of the raw bagasse, as determined by the combustion and dense medium separation test, was approximately 3.5 %. An 80 g sample of the raw bagasse was subjected to a sieve test. The results of this test, presented in Table 1, showed that almost 90 % of the bagasse consisted of particles greater than 500 µm. The moisture analysis of the different size fractions showed that most of the moisture was contained in the largest sized particles.

Table 1. Particle size distribution and moisture content of raw bagasse

Sieve size (µm)	Mass of bagasse (g)	Mass percentage (%)	Moisture content (%)
500	71.13	88.91	42.4
355	1.94	2.43	5.9
212	4.50	5.63	7.3
106	2.06	2.58	2.8
Pan (<106)	0.37	0.45	2.8
Total	80	100	38.4

In total, 17 drying experiments were conducted using the perforated drum apparatus. In each experiment an initial sample mass of 100 g was used. The base set of operating conditions were air temperature of 80 °C, air velocity of 2 $m{\cdot}s^{-1}$, drum speed 44 rpm, bagasse feed rate 0.106 $g{\cdot}s^{-1}$ and a drum angle of 13 ° to the horizontal. The air demand (volume of air required per gram of bagasse dried) was estimated from the volumetric flowrate of air and mass flowrate of bagasse. This value ranged between 2 and 15 $cm^3{\cdot}g^{-1}$. In an independent study it was shown that an air temperature of 70-80 °C could be obtained through solar heating in a duct, hence this served as the benchmark for the current investigation. The results of the experimental runs are presented in Table 2. The dimensionless moisture ratio at the exit was calculated according to Equation 1:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

where

$M =$ exit moisture content (% dry basis)

$M_e =$ equilibrium moisture content (% dry basis)

$M_0 =$ initial moisture content (% dry basis)

The equilibrium moisture content was estimated from the relative humidity of the air and the equilibrium data of Duggal *et al*. (1988).

Figure 1 shows the effect of drum rotational speed on the exit moisture ratio, with all other operating variables held constant. There was no definite trend in the data, with the highest level of drying obtained from the base set of operating conditions. It was observed that the rotational speed had an influence on the residence time of the bagasse within the drum as well as the nature of the flow of solid material through the drum. At the lowest rotational speed there was very little cascading of the solid material within the drum and much of the bagasse flowed through at the bottom in a funnelling fashion. At intermediate speeds there was sufficient cascading and cross-flow of bagasse and heated air, promoting better drying and improving the hold-up in the drum. At the higher drum speed the bagasse was held at the walls of the drum due to centrifugal force and poor contact between the solid material and heated air resulted in less efficient drying.

Table 2. Results of experimental drying tests using the perforated drum apparatus

Run no.	Temp. (°C)	Air velocity ($m \cdot s^{-1}$)	Drum speed (rpm)	Feed rate ($g \cdot s^{-1}$)	Drum angle (°)	Estimated residence time (s)	Air demand ($cm^3 \cdot g^{-1}$)*	Exit mass of bagasse (g)	Exit moisture content (%)	Exit moisture ratio
1	80	2	44	0.106	13	7.4	15	37.9	11.79	0.27
2	80	2	51	0.106	13	6.5	15	37.1	15.16	0.36
3	80	2	56	0.106	13	5.9	15	37.7	20.21	0.50
4	80	2	60	0.106	13	5.6	15	30.5	17.80	0.43
5	80	2	67	0.106	13	5.0	15	21.6	14.32	0.34
6	80	2	79	0.106	13	4.4	15	25.8	17.08	0.41
7	80	2	33	0.106	13	9.6	15	37.8	15.44	0.37
8	80	1.5	44	0.106	13	7.4	11	43.5	14.12	0.33
9	80	1	44	0.106	13	7.4	7	46.4	16.29	0.39
10	80	2	44	0.208	13	7.4	8	36.4	13.22	0.30
11	80	2	44	0.368	13	7.4	4	36.7	14.73	0.35
12	80	2	44	0.735	13	7.4	2	38.3	16.51	0.40
13	80	2	44	0.106	15	6.4	15	42.5	10.75	0.24
14	80	2	44	0.106	17	5.6	15	30.2	17.79	0.43
15	90	2	44	0.106	13	7.4	15	42.3	11.86	0.28
16	100	2	44	0.106	13	7.4	15	40.5	11.82	0.29
17	110	2	44	0.106	13	7.4	15	40.0	11.90	0.30

* Volume of air used per gram of bagasse dried

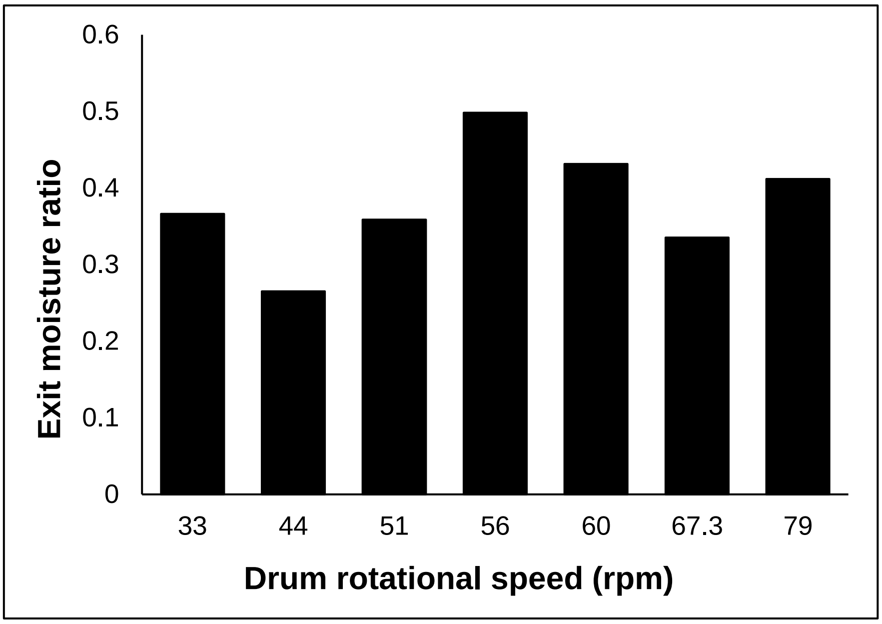

Figure 1. Effect of drum rotational speed on the exit moisture ratio

Figure 2 shows the effect of air velocity on the exit moisture ratio, with all other operating variables held constant. By increasing the air velocity, the drag on the bagasse particles moving down the drum was increased. This resulted in a protracted residence time for the solid particles, better contact between the heated air and bagasse and hence a lower exit moisture ratio.

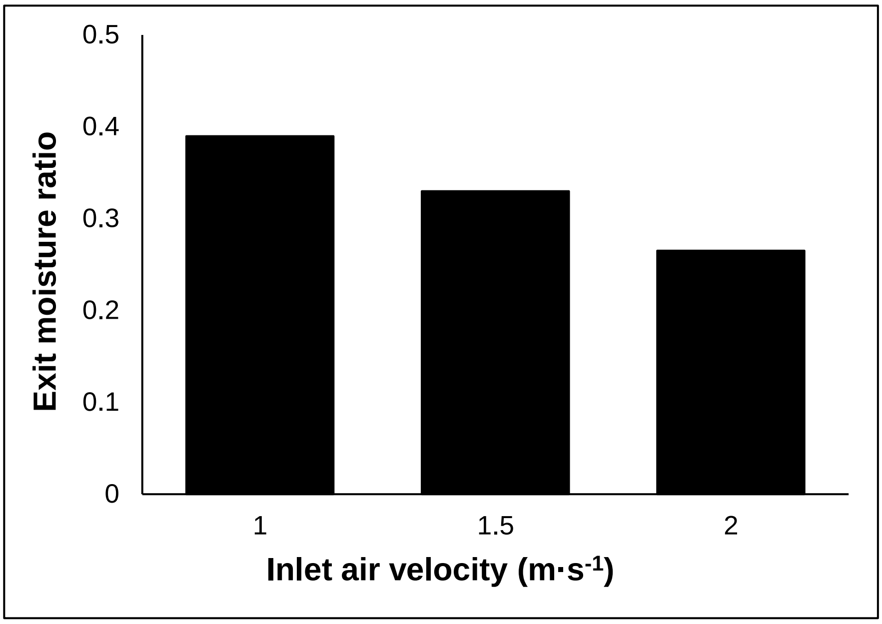

Figure 2. Effect of inlet air velocity on the exit moisture ratio

Figure 3 shows the effect of solids feed rate on the exit moisture ratio, with all other operating variables held constant. The solids feed rate has a direct influence on the residence time for solid particles in the drum. At a higher solids feed rate the residence time is lower and hence a lower degree of drying is achieved. The exit moisture content increased by approximately 40 % when the solids feed rate was increased seven-fold.

Figure 4 shows the effect of drum angle on the exit moisture ratio, with all other operating variables held constant. There was an observable change in the nature of the flow of solid material through the drum when the angle of inclination was changed. Generally, increasing the drum angle improved the cascading movement of the bagasse and promoted contact between the bagasse and heated air, but it also decreased the residence time of the solid material in the drum. This trade-off is seen in Figure 4, where the intermediate angle provided the best drying performance.

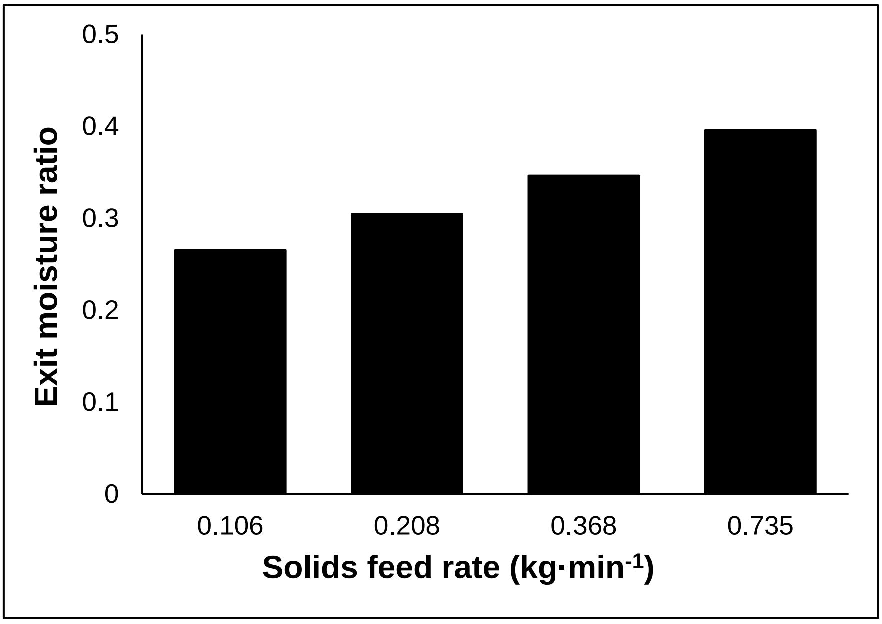

Figure 3. Effect of solids feed rate on exit moisture ratio

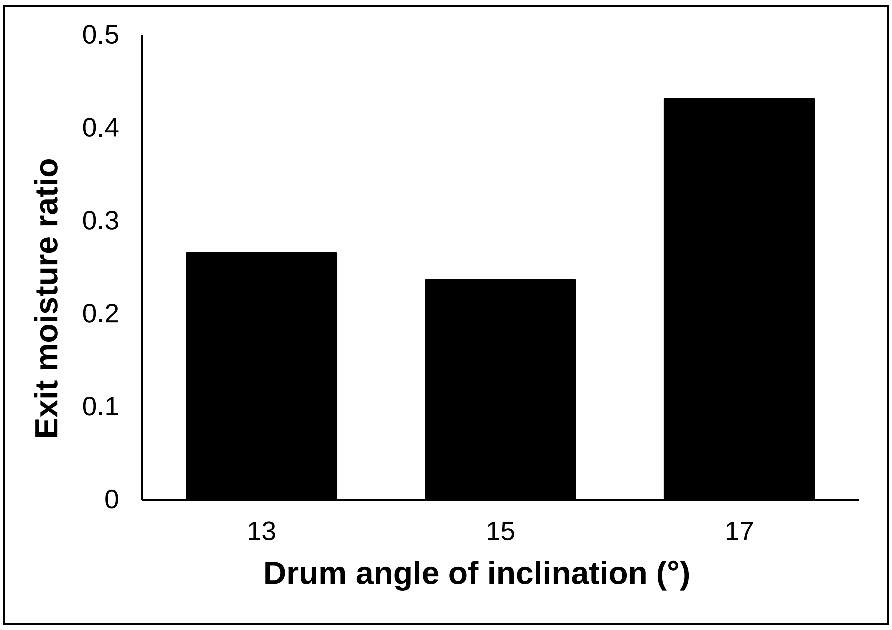

Figure 4. Effect of drum angle on exit moisture ratio

Figure 5 shows the effect of air temperature on the exit moisture ratio, with all other operating variables held constant. In the narrow temperature range considered there was no significant change in the drying behaviour.

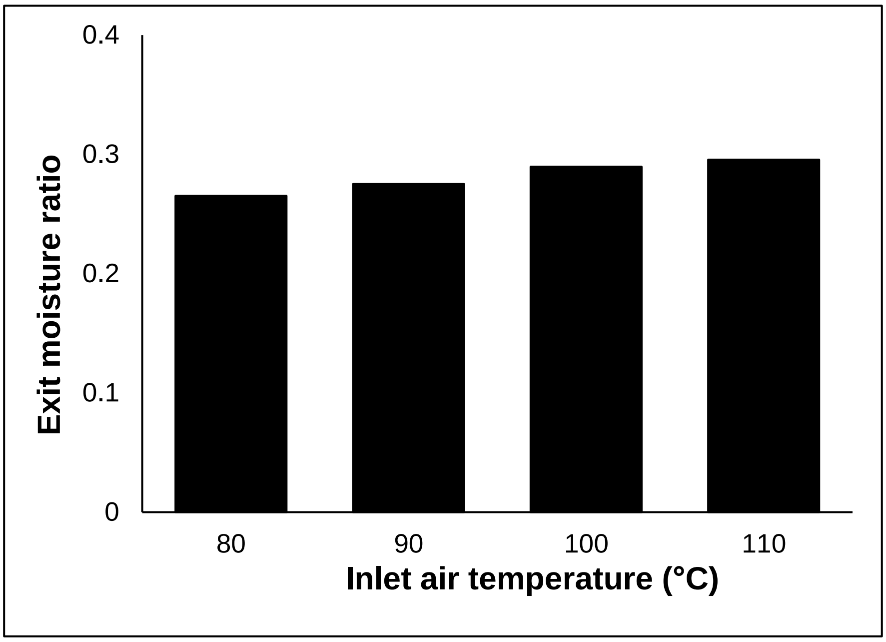

Figure 5. Effect of inlet air temperature on exit moisture ratio

In almost all experimental runs the exit moisture content was reduced from 38.35 % to below 20 %, which is a satisfactory value from the point of view of drying performance. The gross calorific value (GCV) of the dried bagasse samples was estimated using Equation 2 (Don et al., 1977):

$$\text{GCV} = 19605 - \left[196.05 \times (\%\ \text{moisture})\right] - \left[196.05 \times (\%\ \text{ash})\right] - \left[31.14 \times (\%\ \text{brix})\right] \quad (2)$$

Using average values of ash and brix content for bagasse from South African sugar mills as reported by Smith *et al*. (2011), the gross calorific value for the bagasse samples were calculated. The net calorific value (NCV) was calculated by subtracting the latent heat of vaporisation of the imbibed water. These values are reported in Table 2 as percentage increases over the feed. On average, there was a 40 % relative increase in the gross calorific value of the bagasse and a 50 % increase in the net calorific value upon drying.

Mass balances were performed to determine the recovery of solid material on a dry basis. The mass balance for water was given by Equation 3:

$$M_{in} \times w_{in} = M_w + M_p \times w_p + M_b \times w_b \tag{3}$$

where

$M_{in} =$ total mass in

$M_w =$ mass of water removed by drying

$M_p =$ mass of pith fraction removed

$M_b =$ mass of bagasse recovered at exit of drum

$w_i =$ mass fraction of water in stream *i*

The overall material balance is given by Equation 4:

$$M_{in} = M_w + M_p + M_b \tag{4}$$

It was assumed that the same degree of drying had been achieved for both the pith fraction and recovered bagasse. Equations 3 and 4 were solved simultaneously to determine the mass of the pith fraction removed. The mass of the pith on a dry basis was thereafter calculated. The results presented in Table 3 show that the pith content on a dry basis was on average 49 %. This was higher than the experimentally determined pith content of 38.63 % and it was possible that a portion of the straw-like bagasse fibres was also removed through the perforations in the drum. The overall recovery of solid material on a dry basis was dependent on the operating conditions employed but was on average greater than 50 %.

Table 3. Results of energy content and material balance calculations for experimental runs

Run no.	% Change in GCV	% Change in NCV	Mass of pith fraction (g)	Pith content (% dry basis)	Recovery of solids (% dry basis)
1	45.7	55.2	32.0	45.8	54.2
2	39.9	48.2	35.6	48.9	51.1
3	31.2	37.7	39.6	51.2	48.8
4	35.4	42.7	44.6	59.4	40.6
5	41.4	49.9	50.4	70.1	29.9
6	36.6	44.2	48.5	65.2	34.8
7	39.4	47.6	35.1	48.2	51.8
8	41.7	50.3	28.3	39.4	60.6
9	38.0	45.8	27.3	37.0	63.0
10	43.3	52.2	34.6	48.7	51.3
11	40.7	49.1	35.6	49.2	50.8
12	37.6	45.4	35.6	48.2	51.8
13	47.5	57.3	26.6	38.4	61.6
14	35.4	42.7	44.8	59.7	40.3
15	45.6	55.0	27.6	39.5	60.5
16	45.7	55.1	29.4	42.1	57.9
17	45.5	55.0	30.0	42.9	57.1

The performance of the rotary drum dryer was modelled using a simple plug flow approach and considering the degree of segregation of the solid particles. In general, the drying kinetics for agricultural residues can be represented by an exponential model. The simplest model is the Lewis model, written in Equation 5 for the moisture ratio:

$$MR = \exp(-kt) \tag{5}$$

where

$k =$ drying rate constant (min^{-1})

$t =$ drying time (min)

Expressed in terms of the dimensionless time $\theta = \frac{t}{\tau}$ where τ is the mean residence time:

$$MR = \exp(-k\theta) \tag{6}$$

Assuming that the solid particles move in plug flow fashion through the drum, the exit age distribution is given by:

$$E(\theta) = \delta(\theta - \tau) \tag{7}$$

The average exit moisture ratio is then given by:

$$\overline{MR} = \int_0^\infty MR(\theta)E(\theta)d\theta \tag{8}$$

$$\overline{MR} = \int_0^\infty \exp(-k\theta) \times \delta(\theta - \tau)d\theta \tag{9}$$

$$\overline{MR} = \exp(-k\tau) \tag{10}$$

The mean residence time was estimated based on the empirical correlation of Friedman and Marshall (1949) according to Equation 11. Calculated values are listed in Table 1.

$$\tau = \frac{L \times 0.3344}{\alpha N_R^{0.9} D} + \frac{0.6085G}{W \times d_p^{0.5}} \tag{11}$$

where

$L =$ drum length (m)

$D =$ drum diameter (m)

$\alpha =$ drum inclination angle (rad)

$N_R =$ rotational speed of drum (rpm)

$G =$ volumetric flowrate of air ($\text{m}^3 \cdot \text{min}^{-1}$)

$W =$ mass flowrate of solids ($\text{kg} \cdot \text{min}^{-1}$)

The drying rate constant is usually expressed as a function of operating variables such as air temperature, air velocity and particle size (McGaw and Pilgrim, 1991). In this study these dependencies were ignored and a single constant was identified by fitting the experimental data. The identified constant was 9.43 min^{-1} which is an order of magnitude greater than the static drying constant for bagasse reported by Scheufele *et al.* (2015). A parity plot of the observed and calculated exit moisture ratios is presented in Figure 6. The basic model could be improved by considering the aforementioned dependency of the drying rate constant on operating conditions, however, a much larger data set would be required for such an exercise. Experiments are underway to extend the current dataset.

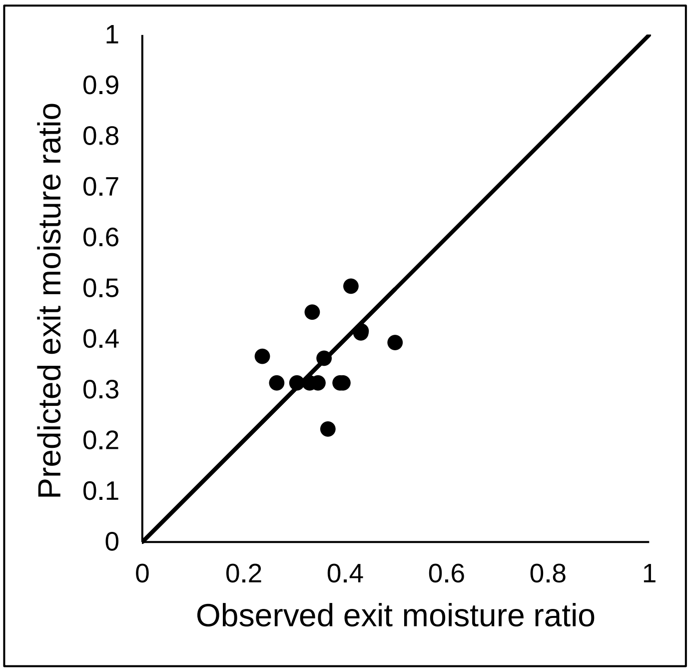

Figure 6. Parity plot of observed and predicted exit moisture ratio

Conclusions

Storage of bagasse for use during the off-crop period poses a problem due to the level of moisture in the bagasse and the propensity for decay. The high moisture content of mill run bagasse also reduces the gross calorific value of the fuel for boiler service. The presence of sand/soil also results in lower boiler efficiency and reduces the lifetime of mechanical components, especially the pelleting dies used for forming bagasse pellets for energy storage. This project aimed to alleviate both problems by developing an intensified solution based on rotary drum dryer technology.

A perforated rotary drum dryer was constructed and tested for the drying of bagasse over a range of operating conditions. The moisture content of the bagasse was reduced from 38.35 % to less than 20 % on average, with a relative increase in gross calorific value of 40 % and net calorific value of 50 %. The drying performance was found to be dependent on the drum rotational speed, drum angle of inclination, inlet air velocity and solids flowrate. The level of moisture removal for air temperatures between 80 and 110 °C was practically unchanged. A simple model of the dryer performance in terms of exit moisture ratio was developed based on the plug flow assumption. The model provided adequate representation of the dryer performance.

The improvement in calorific value of the bagasse due to reduction in moisture content should be carefully weighed against the operational challenges associated with the use of a low moisture fuel for the boiler. Magasiner (1987) showed that the use of low moisture bagasse as a fuel results in an increase in furnace exit temperature of up to 100 °C. This in turn can increase the risk of slagging. Below about 40 % moisture an economiser can be used to minimise the possibility of grate level slagging. For high moisture fuels it is typical to have a refractory band in the ignition zone of the boiler to promote combustion stability. This is omitted in the case of low moisture fuels due to the higher combustion stability offered as well as the increased propensity for slagging (Magasiner, 1987).

Occasionally, explosive mixtures can build up within a biomass boiler's combustion chamber and flue, which are subsequently ignited and an explosion of some form can occur. This is of particular concern in the case of loss of combustion with low moisture fuels. Flame scanners should be incorporated into the boiler's control system. Their primary function is to identify potentially dangerous "flame out" conditions where ignition has ceased and continued addition of fuel could cause an explosion, and implement some preventative action.

With regard to the storage and handling of the dry bagasse, adequate measures should be taken to ensure that the possibility of spontaneous combustion was minimised. For example, frequent pile turn-over, the use of a multiple pile system and the inclusion of dust extraction systems for conveying and transferring the dry fuel may be necessary.

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