ABSTRACT

Maximizing excess bagasse production can create savings by reducing alternate fuel needs as well as additional revenue by conversion to viable downstream end-uses. Such an impact would be essential to the success of the sugar industry. Bagasse drying using flue gas and incorporated into factory operations can be a major contributor to these achievements. This paper examines the drying behaviour of bagasse, postulates a mechanism of moisture movement during drying and emphasizes their implications. Drying rates were a strong function of the operation conditions particularly the gas velocity and the gas humidity. Short drying times occurred justifying the popularity and potential of pneumatic systems. The mechanism of moisture movement postulated was by a combination of capillarity and diffusion. Equations established to be valid and developed from experimental results predicted drying curves accurately enough for computer modeling of bagasse driers for design and operation purposes.

Key words: Bagasse drying, drying equations, moisture movement mechanism.

INTRODUCTION

The interest in drying bagasse using flue gas as the drying medium resurfaced after the fuel crisis of the early 1970s. The need for more efficient bagasse combustion which could be realised with drier bagasse became necessary to reduce the increasing amounts of alternate petro-fuels being used and so minimise the cost of sugar production. The utilisation of the resulting bagasse savings for co-generation or other viable end uses such as animal feed, pulp and paper manufacture also became paramount to creating additional sources of revenue for the beleaguered sugar industry in most parts of the world.

Attempts to dry bagasse have been made since the early part of this century. The specific benefits of bagasse drying have long been recognised and have been documented by many authors. These benefits are listed as follows:

- Increase calorific values of bagasse.
- Reduce bagasse consumption; Increase bagasse savings.
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Reduce consumption of alternate fuels.
Improve bagasse combustion; increase boiler efficiencies.
Reduce pollution.

Bagasse dried to a moisture content of 40% w.b. results in 15% increase in steam production or an additional 17-20 kWh per ton cane of power generation with the available technology of condensing steam turbines. Alternatively, an increase of 4 tonnes of excess bagasse per 100 tonnes cane per hour could also be obtained and used as a raw material for down-stream end-products.

This paper briefly reviews the developments and experiences in bagasse drying in the sugar industry. It also presents the experimental work pursued to determine the drying characteristics of bagasse and the moisture movement mechanism during drying and discusses the results and their implications.

LITERATURE REVIEW

The first reported attempts to dry bagasse occurred in the early part of this century, among them were reports on sun drying. Kerr[1] in 1911 was the first to report experiences with a mechanical drier. In his tower like structure, bagasse fell downwards over inclined vibrating shelves while flue gases flowed upwards through the cascading bagasse. Moistures of 44.5% were obtained. Since then a number of other different mechanical designs were tried. Results reported by Freeland[2] Holgate[3] and Chen[4] indicate that significant moisture reductions were achieved.

From the early 1970s, particularly after the fuel crisis, the number of references reporting on industrial applications of and experiences with bagasse driers increased. The majority of these efforts used co-current rotary driers. Initially the operations of this type of drier were hindered by a plethora of operating and maintenance problems (Furines[5], Martinez[6]) but eventually became the most widely and successful bagasse drier type used (Kroeker[7], English[8]) in the sugar industry. Moistures obtained with bagasse dried for use directly in factory boilers were of the order of 35-38% w.b.

Increasing interest was focused on pneumatic and fluidised bagasse drying systems from the latter part of the 1970s and the emphasis continued throughout the 1980s. Maranhao[9], Edwards[10], Neto[11] and other researchers reported on their designs and developments in which moistures as low as 33% w.b. or lower were achieved sometimes with short retention times of less than five seconds. By the end of the decade, these types of installations were being employed successfully in many sugar producing countries (Maranhao[9], Sharma and Kochhar[12], Arrascada and Friedman[13], Chen and Tso[14]).
In work done in Trinidad at the University of the West Indies, Pilgrim selected the packed bed type drier with a cross-flow configuration as the most appropriate for retrofitting into Caribbean sugar factories where there is usually limited floor space available and little capital for investment. The important criteria in this analysis were the simplicity of the design and construction thus facilitating the fabrication by local factory personnel. Simulation studies with this type of system showed bagasse moisture contents of 33% were practical.

Despite the amount of published information relating to the drying of bagasse, there is little published data on its fundamental drying characteristics and the mechanism of moisture movement during the drying process. Hence most design methods are empirical. The work presented in this paper aims to correct this deficiency by an in-depth study of the results of an experimental programme of single layer drying of bagasse.

**MATERIALS AND METHODS**

The drying characteristics of bagasse was determined from a programme of single layer drying experiments with equipment, a flow sheet of which is depicted in Figure 1. A single layer or thin bed of each of the separated size fractions of freshly milled bagasse was placed in a mesh container and suspended into the drying chamber from the bottom load connection of a balance. Drying air, humidified close to the value of typical flue gas, flowed upwards through the layer of bagasse.

A programme of experiments were carried out over the following ranges of operating variables, chosen to simulate typical plant conditions as closely as possible:

- Gas Temperature: 127 – 212°C
- Gas Velocity: 0.15 – 0.57 ms⁻¹
- Gas Humidity: 0.016 – 0.14 kg Water kg Dry Air³
- Bagasse particle size: 1.2 – 4.2 mm (cross section dimension)

**RESULTS**

Typical results plotted on a semi-log basis of free fractional moisture (moisture content – dry basis/original moisture content + dry basis) against time gave straight lines thus showing that the standard drying equation applies. This equation follows:
FIGURE 1. Flow diagram of drying system.
Free Fractional Moisture = \( a \exp(-kO) \)  \hspace{1cm} (1)

where \( a \) = coefficient,
\( k \) = drying constant,
\( O \) = Time, s.

Figures 2 & 3 show 'a' equal to unity and \( k \) (slopes) to be a function of the system variables. A multiple regression analysis gave the following correlation between \( k \) and the variables:

\[
\begin{align*}
 k &= 0.0019 \exp(0.0073T) + 0.0292 \exp(-0.89S) + 0.00078V \\
 &+ 0.00057 H^{0.87} - 0.00088V \exp(-0.895) - 0.0314 \\
 T &= \text{Gas Temperature, } ^\circ\text{C} \\
 S &= \text{Particle size (cross section dimension), m} \\
 V &= \text{Gas Velocity, m/s} \\
 H &= \text{Gas Humidity, kg water kg dry air} 
\end{align*}
\]

The correlation coefficient was 0.973, the \( R^2 \) value was 0.947 with a statistical significance at the 0.05 level.

The surface temperature of the bagasse particles during drying was measured and typical results are shown as a function of gas velocity in Figure 4. However on a few occasions, a small inflection in the surface temperature profile occurred at about the wet bulb temperature. An example of this is shown in Figure 5.

\section*{DISCUSSION}

\subsection*{General}

The drying rate was a function of the four variables investigated. Increased rates resulted with increasing gas temperature and gas velocity and also with decreasing gas humidity and particle size.

The validity of the relationship for \( k \) was tested by using equations (1) and (2) to generate drying curves and compare with experimental ones. Figure 6 demonstrates close agreement between the predicted and experimental curves down to a moisture ratio of about 0.15.

\subsection*{Mechanism of Moisture Movements}

In considering the mechanism of moisture movement during drying, the nature of the bagasse particle must be considered as well as its moisture
FIGURE 2. Semilog drying curves as a function of air humidities (air temperature - 170°C; air velocity, 0.527 m/s; particle size - 0.00415 m).

FIGURE 3. Semilog drying curves as a function of air velocities (air temperature, 170°C; air humidity, 0.016 kg kg⁻¹; particle size, 0.00415 m).
FIGURE 4. Bagasse surface temperature-time profile as a function of air velocity (air temperature, 174°C; air humidity -0.016 kg kg⁻¹; particle size, 0.00415 m).

FIGURE 5. Bagasse surface temperature-time profile (air temperature, 184°C; Air velocity, 0.573 m s⁻¹; air humidity 0.016 kg kg⁻¹; particle size, 0.00415 m).
A typical bagasse particle consists of bundles of fibres bound along their length and may be attached to a piece of rind forming one outer surface. This structure is impregnated to some extent with fine pith particles (Figures 7&8). The particle size varies from irregularly shaped clumps 75mm long and 25 m in cross section to a fine dust.

**FIGURE 6.** Drying curve (air temperature, 175°C; air velocity, 0.527 m s\(^{-1}\); air humidity, 0.016 kg kg\(^{-1}\); particle size, 0.03 m).
The moisture of bagasse varies from about 48 to 55% of w.b. It was experimentally determined that about three quarters of this moisture is held between the fibres while one quarter within the fibres. The shapes of the drying curves, the surface temperature profiles and the effects of the system variables on these must also be included in the analysis to determine the moisture movement mechanism.

FIGURE 7. Elevations of bagasse particles.

Reference to the drying curves shown typically in Figure 2 and the surface temperature profiles shown in Figures 4 & 5 show that a constant rate drying period does not normally occur, and if it does, only for a few seconds. However, the strong effects of gas humidity and gas velocity indicate external control on the drying process. A lower gas humidity increases the humidity driving force while a higher gas velocity causes increases in the mass transfer coefficient.
FIGURE 8. Cross section of bagasse particle. A - Surface moisture transfer to gas, B - Movement of moisture along passages between fibers by capillarity/vapor diffusion, C - Diffusion of moisture through fiber to surface of fiber, D - Barrier formed by rind.

From the considerations of the results the following model of moisture movement is proposed. Initially drying occurs by the evaporation of surface moisture in contact with the drying gas. If the surface approaches saturation then a short constant rate period may be evident as is the case with a few experiments. Apart from these, no constant rate drying is apparent and the drying at this stage is predominately from evaporation of the diminishing surface moisture.

As drying continues the evaporation plane recedes within the particle. Moisture between the fibres must be transferred to this area to contact the drying gas. Capillarity and gravity are the likely mechanisms for this transfer.

Moisture held within the fibres is transferred to the surface of the fibers by diffusion and subsequently to the area in contact with the drying gas possibly by capillarity and/or vapor diffusion. Figure 7 shows this mechanism schematically.

Implications

Typical and desirable bagasse moistures after drying are 35-40% since lower values contribute to refractory and metallurgical problems. Reference to Figure 2 and 3 show that these moistures would result with drying times of about 1-2 minutes for the larger particles and of the order of seconds for the
smaller particles. Thus the potential for using pneumatic driers is evident particularly in sugar factories with a high degree of cane preparation.

Figure 6 show close agreement between the predicted and the actual drying curves. These predicted curves generated from Equations 1 and 2 could be used along with heat and mass transfer equations in computer simulation modelling of bagasse driers. These can be used for designing driers and for trouble shooting and problem-solving purposes in operating situations.

A model developed for a cross flow configuration of a packed bed bagasse drier, suitable for retrofitting in sugar factories with limited floor space, gave output moistures of 39% w.b. with residence times of two minutes. Current and future work includes adapting and developing the model to other types of driers in particular the pneumatic bagasse drier.

**CONCLUSIONS**

1. Bagasse drying is a strong function of the system variables. Drying times can be very short depending on the operation conditions and the degree of cane preparation.
2. Drying rates can be predicted accurately using Equations 1 and 2 with the coefficient $a = 1$.
3. The mechanism of moisture movement occurs by a combination of capillarity and gravity from between fibres and diffusion from within the fibres.
4. Simulation models can be applied to the designing and operating aspects of bagasse driers.

**REFERENCES**


LE SECHAGE DE LA BAGASSE AVEC LES GAZ DE CHEMINEE

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RESUME

L'emploi optimale de la bagasse reduit la necessite de bruler d'autres combustibles et permet le developpement de suos-produits. Cela est essentiel pour le succes de l'industrie sucriere. Le sechage de la bagasse avec les gaz de cheminee peut contribuer vers ce succes. Ce papier discute le comportement de la bagasse envers le sechage, propose un mechanisme pour decrir le mouvement de l'humidite pendant le sechage et souligne les applications de ce procede. La vitesse des gaz et leurs humidite ont un effet tres marque sur la vitesse du sechage. Les temps de sechage peuvent etre courts, ce qui justifie l'emploi de systemes pneumatiques. Le mechanisme du mouvement de l'humidite prevoit une combinaison entre la capillarite et la diffusion. Des equations valides et basees sur des resultats d'expériences servent pour predire des courbes de sechages. Les resultats sont suffisaments bons pur permettre l'utilisation d'un model, sur ordinateur, pour l'étude et l'operation des secheurs.
SECADO DEL BAGAZO CON GASES DE CHIMINEA

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RESUMEN

Aumentar el exceso de la producción de bagazo puede crear ahorros si se reducen las necesidades del combustible, así como una ganancia adicional si se usa el bagazo como material para diversos y variados usos. Tal impacto sería esencial para la supervivencia de la industria azucarera. El secado del bagazo usando los gases de la chimenea e incorporándolo a las demás operaciones de la fábrica sería una mayor contribución a estos logros. Este escrito examina el comportamiento del secado del bagazo, señala un mecanismo del movimiento de la humedad durante el secado y realiza sus implicaciones. Los valores del secado fueron una fuerte función de las condiciones de operación. Particularmente la velocidad del gas y la humedad del mismo. El secado a corto tiempo, demuestra la popularidad y el potencial del sistema neumático. El mecanismo del sistema del movimiento de humedad señalado, fue una combinación de capilaridad y difusión. Las ecuaciones establecidas son válidas y fueron desarrolladas de resultados experimentales que pronostican curvas para el secado, con suficiente exactitud para su uso en la computarización del diseño y operación de, los secadores de bagazo.