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# CHARACTERISATION OF SPOUTED FLUIDISATION OF RAW SUGAR

By

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## Abstract

An experimental apparatus capable of fluidising sugar under both spouted and standard fluidising regimes was designed and commissioned. The apparatus was operated under spouting conditions using dry raw sugar and dry sand. The general characteristics of the apparatus and the design procedure for sizing this unit have been outlined in the paper. Minimum spouting velocities over a range of dry sugar bed heights (80–220 mm) were determined for dry raw sugar and qualitative examination of the effect of sugar moisture content on fluidisation was undertaken. The advantages of fluidised bed drying have been presented and the potential application of this drying technology has been discussed.

## Introduction

The dryer is a key unit operation across a broad range of industries and is the last unit operation in raw sugar manufacturing. Many different drying technologies have been developed to dry and cool solids. For convenience, these may be considered to fall under two broad categories characterising the movement of the solid material along the dryer length: non-active hydrodynamics (rotary, spray and tray dryers) and active hydrodynamics (cyclone, fluidised bed and pneumatic dryers).

In the raw sugar industry, the most common drying technology in use is the flighted rotary sugar dryer. The main purpose of the rotary sugar dryer is to cool and to dry the final product before transport and storage. Stringent final product quality constraints (i.e. the premium sugar scheme) are placed on the Australian industry in order to drive continuous improvements in technological development. Sugar temperature and sugar moisture are both included as quality parameters within this scheme.

Unfortunately, for industries trying to make premium sugar, significant demands are placed on the performance of the dryer. Late season humid ambient air conditions make drying difficult because the contacting air phase is near saturation and disturbances in the dryer inlet sugar flowrate, temperature and moisture make dryer control very challenging.

While some of these issues are not insurmountable, for example, air conditioning in humid conditions can be used to reduce the relative humidity of the inlet air, others are more costly to solve. Control of rotary sugar dryers under process disturbances is a complicated task made difficult by the non-ideal transport of sugar along the length of the dryer and the coupling between the inlet sugar moisture and temperature. Furthermore, there are capacity limitations in rotary dryers that make increasing throughput in these units difficult.

In the face of such difficulties, the industry needs to consider the options that are available to improve product quality and to increase throughput. Some factories use two rotary dryers in series to achieve drying and cooling in separate stages. Although running costs are low, a new rotary dryer involves a significant and high capital cost to the industry and may lead to the additional problems of crystal breakage and dust formation that are predominant in these unit operations.

An alternative technology considered in this paper is the use of the fluidised bed dryer under the spouted regime. Fluidised drying involves smaller capital costs and greatly intensified drying as a result of the intimate air contact between the phases when fluidised. The most significant advantage, however, is the ability to better control the drying process through improved solids transport (narrow residence time distributions are possible) and uniform temperature distribution within the fluidised bed. These advantages lead to opportunities to increase throughput without compromising quality. They may also be used in series with an existing rotary dryer to supply more uniform feed properties.

Although there has been some examination of these issues in the past (Hanrahan, 1960; Weiland *et al*., 1974), the literature was found to be lacking in the data required to adequately design these units and to assess the potential of this technology for raw sugar drying.

Fluidised bed dryers (FBD) involve a bed of sugar through which a stream of air is passed. The air fluidises the sugar and the bed expands. Intimate air contact is made between the sugar and air at gas velocities greater than 1 m/s compared to rotary dryer air velocities of less than 0.9 m/s, leading to increased heat and mass transfer. Baffles and staged distributor plates may be used to achieve desired solids circulation patterns ranging from CSTR to plug flow behaviour.

Water is evaporated from the sugar to the air and heat is transferred between the two phases (air and sugar). Greater detail on drying mechanisms and fluidisation can be found in Kunii and Levenspiel (1991) and Strumillo and Kudra (1986). Fluidised beds have a uniform bed area throughout their vertical height and spouted beds have a tapered base (typically at $30^o$ to $50^o$). The circulation pattern of solids in spouted beds is illustrated in Figure 1(a) and a picture of the batch spouted bed dryer used in this work is shown in Figure 1(b). Spouted bed dryers (SBD) are often used for drying sticky material where the forces of cohesion between particles are strong, such as sugar. This is because the air velocities used in SBD are higher than those of FBD, working to break inter-particle forces. Bed agitation and baffles can also be used to improve fluidisation of sticky materials.

In order to design a fluidised bed dryer or a spouted bed dryer, a number of parameters characterising fluidisation are necessary. These are the minimum fluidisation ($U_{mf}$) and minimum spouting velocity ($U_{ms}$), the bed pressure drop ($\Delta P_{bed}$) and the bed voidage at fluidisation ($\varepsilon_{mf}$). These parameters may be determined from correlations in the literature (Kunii and Levenspiel, 1991; Strumillo and Kudra, 1986) but, owing to the lack of data in the literature on sugar fluidisation, they are best determined directly by experiment. Additionally, many of the available correlations are based on the dimensionless Reynolds and Archimedes groups and are unable to account for the inter-particle cohesive forces present in raw sugar. A collection of values for $U_{mf}$ *and* $U_{ms}$ from the literature is presented in Table 1.

Although these values are useful, parameters characterising the drying kinetics are also necessary. In particular, the use of fluidisation models for design calculations require both fluidisation properties and single particle drying kinetics (Burgschweiger and Trotsas, 2002; Burgschweiger *et al*., 1999). Furthermore, operational difficulties may be encountered during fluidisation drying of sticky materials because when drying is very fast (such as during the initial drying period), air channeling or crystal agglomeration may occur. Considerable testing and fluidised bed design assessment must also be undertaken to fully achieve the benefits of this technology. Fluidised bed drying is likely to be best used as an additional unit in series with a rotary dryer to improve dryer station control.

**Table 1**—Literature values for minimum spouting (*ms*) and fluidisation (*mf*) velocities.

| Material (source) | $U_{mf}$ (m/s) | $U_{ms}$ (m/s) |
|---|---|---|
| Raw sugar (Chang and Chou, 2000) | ~ | 1–1.4 |
| Raw sugar (Hanrahan , 1960) | 0.47 | ~ |
| Refined sugar (Meadows, 2000) | ~ | 1.1–1.3 |
| Refined sugar (Krell and Schmitt, 1997) | 0.5 | ~ |

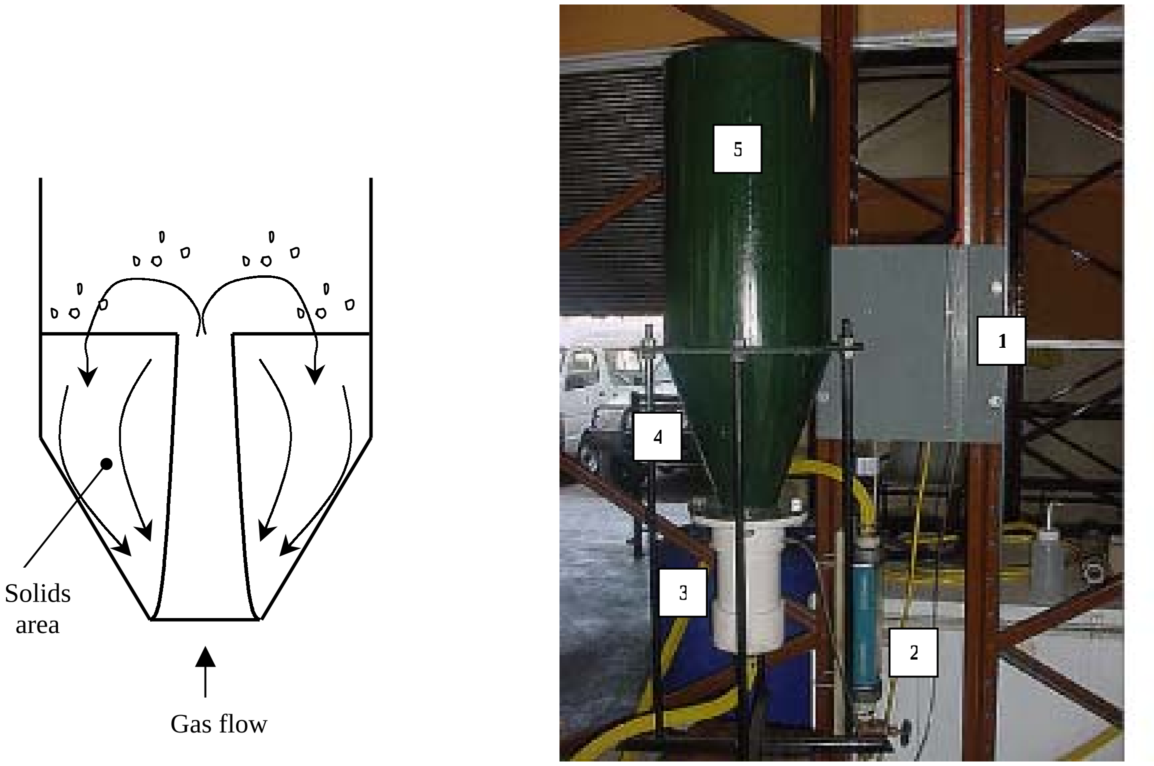
## Fluidised bed design

An experimental laboratory scale (spouted) fluidised bed was designed and commissioned at the School of Engineering at James Cook University. The spouted bed apparatus is illustrated in Figure 1(b). The conical and vertical sections of the bed were made of galvanised mild steel and the distributor and piping were made of high-pressure grade PVC. This apparatus has a modular design and is able to be converted from spouted fluidisation to standard fluidisation regimes by inserting a distributor plate either below (spouted) or above (standard) the conical section.

Furthermore, the modular sections make the apparatus easy to pull apart and clean which is important under some fast drying/wet sugar conditions when the sugar bed may harden into a solid lump. A compressor is used to ensure a consistent supply of air to the base of the bed via a rotameter and gate valve. A pressure tapping was made below the distributor plate and the top of the bed is open to the atmosphere.

The dimensions of the bed and apparatus were sized to enable future drying experiments to be undertaken with minimum experimental error in the determination of drying rates (based on a 5 kg sample size). In the future, the existing spouted bed will be enclosed in a fixed volume containment vessel and humidity, temperature, and flow measurements will be recorded on inlet and outlet streams.

This will ultimately lead to the development of fluidised bed drying curves and the development of heat and mass transfer correlations for spouted and fluidised bed drying. In particular, a maximum 5 kg raw sugar sample was chosen as a basis to ensure that the humidity measurements on inlet (bone dry air) and outlet (maximum 83% RH) air-flows, taken at periodic intervals over the drying period, will be statistically significant given the time delay in humidity measurement devices (typical response times of 15 seconds in still air). The minimum spouting velocity of 1 m/s was used in the design calculations. The raw sugar drying kinetics and resorption limits from the experimental data of Ristikian *et al*. (1999) were also used in these calculations.



**a)** **b)**

Fig. 1—**a)** Diagram of the solids circulation patterns in spouted fluidised beds. The spout runs through the centre of the bed. Gas flows through the centre and percolates through the bed on either side of the spout. **b)** Layout of the spouted bed showing the following components: water manometer (1); Krohne rotameter (2); PVC distributor casing (3); conical section (4), straight section (5) and supporting frame. The distributor mesh can be placed underneath or above the conical section.

The most critical elements of the experimental apparatus were the design and selection of the distributor, cone angle and the height and diameter of the cylinder and cone. A stainless steel wire mesh with a 500 μm aperture was used as the distributor plate and ½″ glass marbles were inserted underneath the mesh to evenly distribute the inlet air across the mesh. The pressure drop across the distributor was negligible (within experimental error).

Unfortunately, the optimum values given by Strumillo and Kudra (1986) for pressure drop across the distributor ($\Delta P_d \cong 0.1\Delta P_b$) were not obtained and further modifications will be undertaken to better achieve these ratios and ensure even distribution of air across the distributor. The cone angle was selected using the method of Johanson (2002) for hopper angle selection. The angle of slide of raw sugar (ASC) was determined for dry, fine-dry and wet raw sugar by compressing material at 4700 Pa onto a steel surface and tilting the surface until the material slid. The values of ASC were $41^o$, $48^o$ and $58^o$ respectively.

The cone angle from the vertical was calculated to be $20^o$, ensuring free flowing material within the bed under the worst-case scenario of wet sugar. The ratio of cone base diameter to cone top diameter was taken as 3 and the ratio of the free height above the cone to the cone base diameter was taken as 5.

## Experimental

Sugar properties were determined experimentally prior to fluidisation experiments. These properties are listed in Table 2. The properties of sand are also listed in this table to allow comparison of spouted bed fluidisation curves for these materials (see also later Figure 3).

**Table 2**—Selected properties of fluidising materials. Sand was sieved prior to fluidisation, ensuring narrow particle size distribution.

| Material | Raw sugar | Sand |
|---|---|---|
| Particle density | 1585 kg/m$^3$ | 2650 kg/m$^3$ |
| Bulk density | 880 kg/m$^3$ | 1335 kg/m$^3$ |
| Sphericity | 0.80 | 0.80 |
| Mean particle diameter | 800 $\mu$m | 800 $\mu$m |

Dry raw sugar was wetted prior to experimental runs using an atomised spray and sub-samples were removed for immediate determination of moisture content. Dry raw sugar was used at ambient conditions (30 ± 3°C).

Moisture content of raw sugar was determined using 10 g samples dried over a 10 minute period using IR heating in the Sartorius MA45 moisture balance. The Sartorius MA100 moisture balance was also used to replicate the results. The moisture content of the dry raw sugar determined using these methods was 0.06%.

Spouted bed fluidisation trials were undertaken for a range of dry sugar bed heights. All trials were repeated to assess the reproducibility of the results. Initial bed heights were determined from the measured total mass of sugar and sugar bulk density using simple geometric functions relating the cone and bed dimensions to the volume occupied by the sugar. Bed pressure drops were determined using a water manometer.

During each trial, the air flowrate was increased gradually and bed pressure drop readings were recorded. The humidity of the air feed was not measured, as drying experiments were not undertaken in this work.

A rotameter (Krohne VA 20K air flow meter) was used on the inlet compressed air line and volumetric flow rates were converted to mass flow rates using manufacturer-supplied correlations. Figure 2 shows an example of the gas velocity versus bed pressure drop for dry sugar with an initial bed height of 130 mm. The spouted fluidisation curves for sand and sugar are overlayed for comparison in Figure 3.

All curves were reproducible and showed the expected form. Figure 4 illustrates the linear relationship between the minimum spouting velocity and the initial bed height. A zero intercept (within experimental error) in this graph was expected.

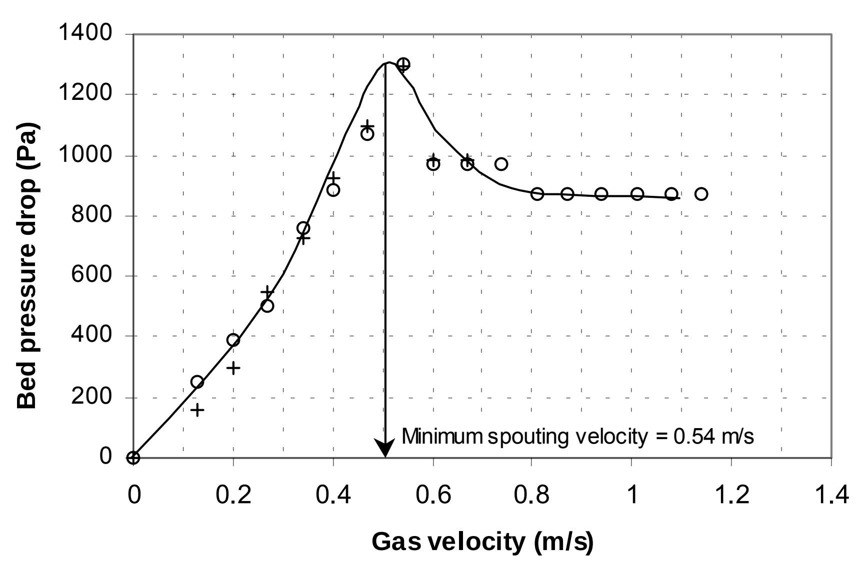


Fig. 2—Bed pressure drop versus superficial gas velocity through the bed, for dry raw sugar with an initial bed height of 130 mm. Replicate runs are shown as + and o symbols.

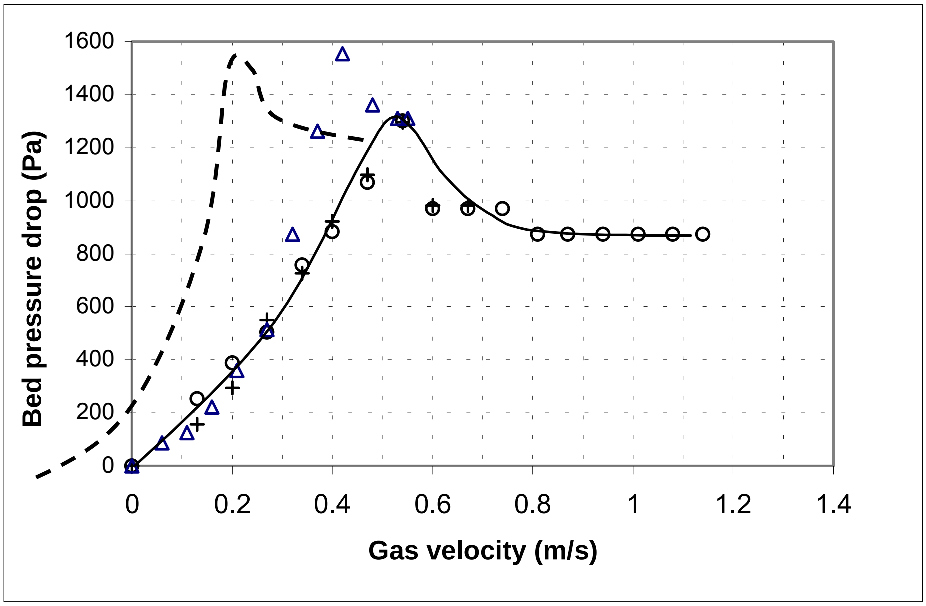


Fig. 3—Minimum spouting velocity curves for dry raw sugar (+, o) and sand (Δ) at initial bed height of 130 mm.

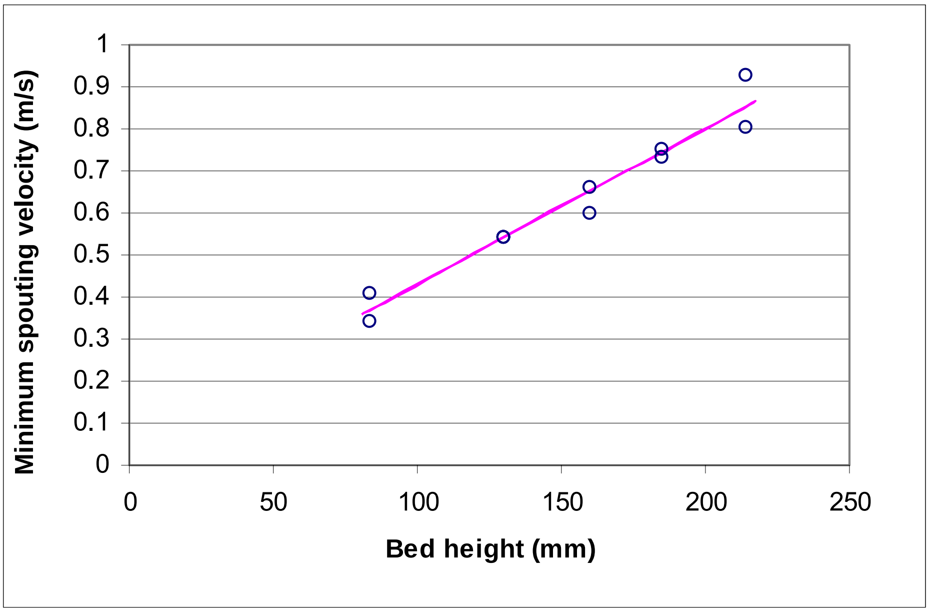


Fig. 4—Minimum spouting velocity verus initial dry raw sugar bed height ($r^2$ = 0.96).

Qualitative observations were made to examine the impact of increasing moisture content on the ability to fluidise raw sugar. These observations and the observations of Hanrahan (1960) for fluidisation are presented in Table 3. Our observations are only slightly lower than those of Weiland *et al*. (1974) who found an upper spouting limit of 1.5% moisture. As a result of the discrepancies in these results, a quantitative examination of these issues is recommended for future studies. The impact of temperature was not examined. However, Kunii and Levenspiel (1991) suggest that the impact of temperature on course particle fluidisation properties is minimal.

**Table 3**—Qualitative observations of the potential to fluidise wet raw sugar.

| Moisture content | Fluidisation possible | Spouting possible |
|---|---|---|
| <1% | | Yes |
| <1.2% | Yes (Hanrahan,1960) | |

## Conclusions

Fluidisation of raw sugar should lead to enhanced drying and cooling of raw sugar, due to improved air-to-sugar contact. Very little data exist describing fluidisation under Australian conditions. As a result, a fluidised bed was designed and constructed in order to fluidise raw sugar under both fluidising and spouting conditions. Experiments carried out under spouting conditions indicated a linear relationship between spouting superficial gas velocity and raw sugar bed depth.

As the spouting velocity through a bed of fixed height increases, the pressure drop across the bed decreases leading to a reduction in power consumption compared to a standard fluidised bed. Qualitative evaluations were made in order to determine the effect of moisture content on raw sugar bed spouting. The feasible operational range of sugar moisture that can be treated using a spouted bed dryer is greater than for a standard fluidised bed dryer. A critical moisture level of approximately 1.2% was observed, above which fluidisation stalls.

Given the ability to spout moist raw sugar, drying experiments will be undertaken and described in future work by the authors. An enclosed system will be constructed, and humidity and temperature measurements under controlled air-flow conditions will be used to determine drying kinetics and heat and mass transfer correlations. These will ultimately lead to a better understanding of the potential to integrate fluidised drying into the Australian raw sugar industry.

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## REFERENCES

**Burgschweiger, J., Groenewold, H. and Hirschmann, C.** (1999). From hygroscopic single particle to batch fluidised bed drying kinetics. The Canadian Journal of Chem. Engg., 77: 333–341.

.

**Burgschweiger, J. and Trotsas, E.** (2002). Experimental investigation and modelling of continuous fluidised bed drying under steady state and dynamic conditions. Chem Engg Science, 57: 5021–5038.

**Chang, H.S. and Chou, C.C.** (2000). Raw sugar storage and handling. In: Chou, C.C. ed. Handbook of Sugar Refining: A Manual for the Design and Operation of Sugar Refining Facilities. John Wiley and Sons, Brisbane.

**Hanrahan, P.J.** (1960). The Fluidised Drying of Raw Sugar. University of Queensland, BE thesis.

**Johanson, J.R.** (2002). Trouble shooting bins, hoppers and feeders. Chem. Engg Process magazine, April, 24–36.

**Krell, L. and Schmitt, W.** (1997). Sugar drying and cooling in a fluidised bed drier. Zuckerind, 8: 585–603.

**Kunii, D. and Levenspiel, O.** (1991). Fluidisation Engineering. Butterworth-Heinemann, Melbourne.

**Meadows, D.** (2000). Refined sugar drying. In: Chou, C. C. ed. Handbook of Sugar Refining: A Manual for the Design and Operation of Sugar Refining Facilities. John Wiley and Sons, Brisbane.

**Rastikian, K., Capart, R. and Benchimol, J.** (1999). Modelling of sugar drying in a counter current cascading rotary dryer from stationary profiles of temperature and moisture. Journal of Food Engg., 41: 193–201.

**Strumillo, C. and Kudra, T.** (1986). Drying: Principles, Application and Design. Gordon and Breach Science Publishers, New York.

**Weiland, R.H., Low, G. and Leung, L.S.** (1974). The drying of raw sugar in fluidised and spouted beds. Proc. Int. Soc. Sugar Cane Technol., 15: 1561–1567.