Improved energy performance of small-scale pneumatic dryers used for cassava processing

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This document describes an adjustment made to the feeding rate of a pneumatic dryer used to produce cassava flour in Ghana. The adjustment resulted in a significant improvement on the dryer's energy performance. The work was funded by the CGIAR Research Program on Roots, Tubers and Bananas (RTB) and executed by the Natural Resources Institute (NRI) of the University of Greenwich, UK, in partnership with the Food Research Institute (FRI) of the Council for Scientific and Industrial Research (CSIR), Ghana.

Background

Cassava (*Manihot esculenta*) is a perennial root crop originally from the central region of South America but nowadays cultivated throughout the humid tropics. Cassava roots are rich in carbohydrates, and for this reason is the main source of calories for many people in the tropical regions, particularly for those living in Africa. Cassava has a short shelf-life and needs to be processed into flour or other dried products within two days after harvested. The most suitable equipment to dry cassava is a pneumatic dryer.

The pneumatic dryer at Tropical Starch

In 2018, as part of RTB activity, equipment manufacturers in Ghana learned how to dimension and build pneumatic dryers for cassava processing. During the training, a pneumatic dryer was built and installed at a cassava processing centre named Tropical Starch. Two innovations were developed during the design of this dryer. One was a segmented drying duct (Figure 1) that allows easy installation inside an existing building. The other was a feeder with a hopper with vertical walls and a venturi as a feeding mechanism (Figure 2).

Figure 1 Pneumatic dryer installed at Tropical Starch processing centre featuring a segmented drying duct.

Figure 2 Innovative feeder featuring a hopper with vertical walls and a venturi feeding mechanism.

Feeder for cassava grits

In pneumatic dryers, the feeder has the function to introduce the material into the drying duct. The material should be introduced in a controlled, specified rate and should be well dispersed with the airstream. A feeder has two main components, a hopper and a feeding mechanism. The hopper has the function to hold the material and dispense it to the feeding mechanism. The feeding mechanism has the function to control the rate that the material is discharged. For pneumatic dryers, most feeders use hoppers of conical or trapezoidal shape, where the walls are in an angle. However, because of the wet cassava grits flow properties, this kind of hoppers cause bridging (Figure 3a) and ratholing (Figure 3b).

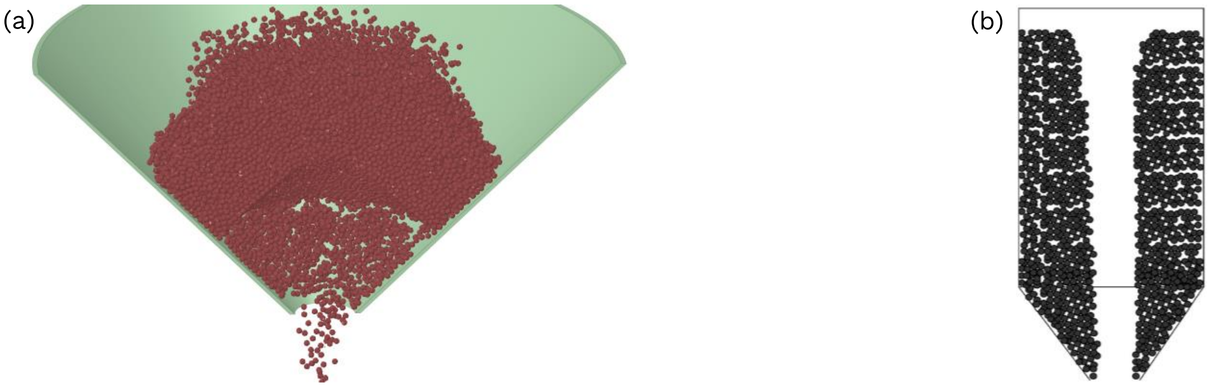

Figure 3 Hoppers of conical or trapezoidal shape are not suitable for wet cassava grits due to bridging and ratholing.

Regarding the feeding mechanism, most of the pneumatic dryer uses a screw system (Figure 4). However, this kind of mechanism promotes material agglomeration. This is particularly problematic for wet cassava grits, that are highly cohesive, and easily agglomerate into lumps. Therefore, when screw feeders are employed it requires an additional pulveriser, to break the lump and assure good dispersion to the airstream.

Figure 4 Screw mechanism promotes caking and product agglomeration when used with wet cassava grits.

For cassava, a better choice of feeding mechanism is a rotary valve (Figure 5). However, this mechanism still promotes a certain degree of lumps and agglomeration. In addition, this kind of feeding mechanism is more expensive to build and requires more frequent maintenance.

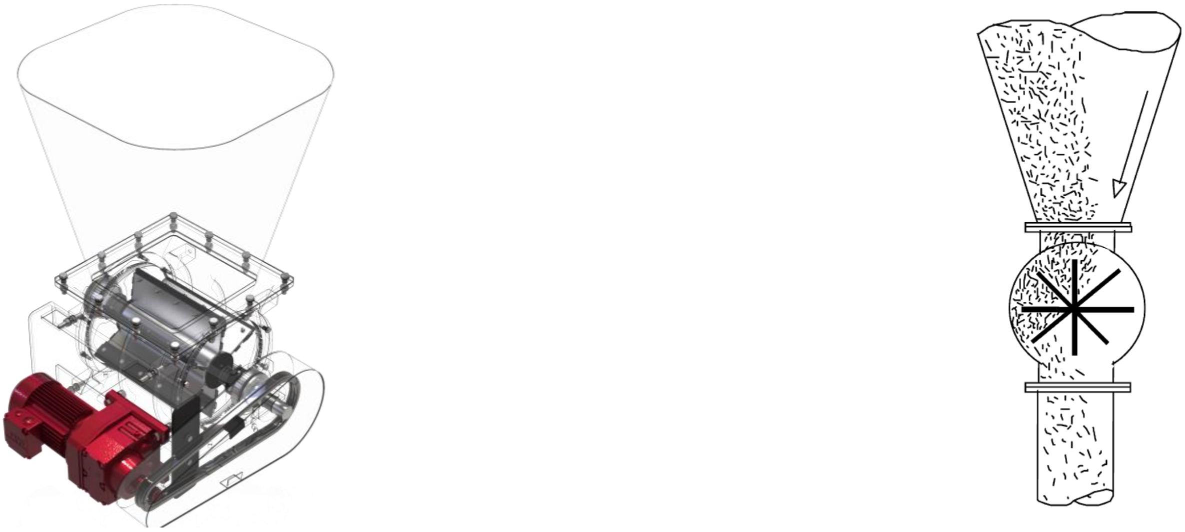

Figure 5 Rotary valve feeding mechanism commonly installed on pneumatic dryers used for cassava processing.

To address those issues, the innovative feeder had a hopper with vertical walls. It had a shape of a drum with an orifice at the bottom. The drum was placed tilted, by an angle of 15°, and inside it, there was a slow-moving blade. The feeding mechanism was a venturi duct that creates negative pressure. The feeding rate was controlled by the size of the orifice at the bottom of the drum, not by the speed of the blade rotation (Figure 6).

Figure 6 Concept of the innovative feeder with a hopper of vertical walls and a venturi as a feeding mechanism.

The objective of this work was to adjust the material feeding rate in order to maximize dryer energy performance. First, the energy performance of the dryer was evaluated and the optimum feeding rate calculated. After that, the orifice of the bottom of the feeding rate was enlarged to bring the feeding rate close to the optimum value, and finally, the energy performance of the dryer was one more time evaluated, to assess the impact of the modification. Experiments were performed in quintuplicates.

Calculation of optimum feeding rate

To determine the optimum feeding rate ($\dot{m}^*_{\mathrm{dm}}$) the lowest allowable air temperature and the highest allowable relative humidity at the dryer outlet were calculated (T^*_{out} and φ^*_{out}, respectively). Based on that, the highest possible absolute humidity at the dryer outlet (Y^*_{out}) was determined and used to calculate $\dot{m}^*_{\mathrm{dm}}$ as shown in Equation 1:

$$\dot{m}^*_{\mathrm{dm}} = \frac{\dot{m}_{\mathrm{air}}\left(Y^*_{\mathrm{out}} - Y_{\mathrm{amb}}\right)}{X_{\mathrm{ws}} - X_{\mathrm{ds}}} \tag{1}$$

Where: $\dot{m}_{\mathrm{air}}$ is the air mass flow rate, Y_{amb} is the absolute humidity of the ambient air, X_{ws} is the wet solid moisture content on a dry basis, and X_{ds} is the dried solid moisture content, also on a dry basis.

The calculations of T^*_{out} and φ^*_{out} took into consideration the air enthalpy at the dryer outlet (h_{out}), and the equilibrium moisture content of the dried solid (MC^*_{dp}), as determined by the cassava sorption isotherms. The value of h_{out} was calculated from the air temperature and relative humidity of dryer outlet (T_{out} and φ_{out}, respectively). T_{out} was measured with a thermometer at the dryer outlet, but φ_{out} was calculated from the measured temperature and relative humidity of the air leaving the cyclone exhaust. Entering a value of 12%$_{\mathrm{wb}}$ for MC^*_{dp} and constraining the enthalpy of the air to remain the same ($h_{\mathrm{out}} = h^*_{\mathrm{out}}$) the values for T^*_{out} and φ^*_{out} were determined.

Before the modification to the dryer, T_{out} was 69.4 ± 2.6 °C and φ_{out} was 33.2 ± 4.9%, resulting on a h_{out} 249.2 ± 12.8 kJ/kg. Keeping this h_{out} constant, outlet air relative humidity could be raised to 77.7% and temperature lowered to 52.7 °C. At those levels of φ^*_{out} and T^*_{out}, product equilibrium moisture content, predicted by sorption isotherm, would be 12%$_{\mathrm{wb}}$. Figure 7 shows the combination of temperature and relative humidity that results on a specific enthalpy of 249.2 kJ/kg. It also shows the combination of temperature and relative humidity where solid equilibrium moisture content is 12%$_{\mathrm{wb}}$. The intersection between the curves defines T^*_{out} and φ^*_{out}.

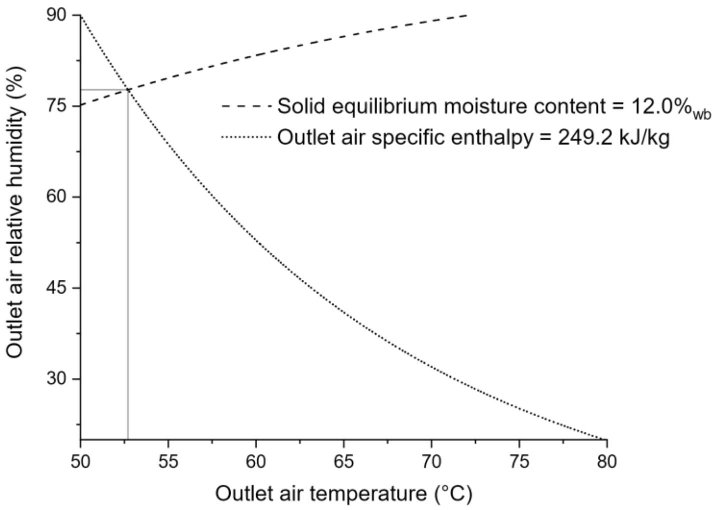

Figure 7 Determination of highest possible relative humidity of the air at the outlet keeping the same enthalpy.

To decrease outlet temperature and increase relative humidity at the dryer outlet, the feeding rate on a dry basis could be increased from 37.5 kg/h to 46.5 kg/h, the value obtained for $\dot{m}^*_{\mathrm{dm}}$ On a wet basis, this would translate into an increase from 68.8 kg/h to 85.3 kg/h. Based on that, the orifice at the feeder was enlarged and data collected once again.

Energy performance evaluation

To evaluate the energy performance of the dryer, specific energy consumption, specific heat utilisation, energy efficiency and solid loading ratio were calculated. Specific energy consumption (q_{s}) was defined as the ratio between the heat supplied to the dryer ($\dot{Q}_{\mathrm{in}}$) and the water evaporation rate ($\dot{m}_{\mathrm{w}}$), as shown in Equation 2:

$$q_{\mathrm{s}} = \frac{\dot{Q}_{\mathrm{in}}}{\dot{m}_{\mathrm{w}}} = \frac{\dot{m}_{\mathrm{air}}\left(h_1 - h_{\mathrm{amb}}\right)}{\dot{m}_{\mathrm{w}}} \tag{2}$$

Where: h_1 is the enthalpy of the air at the dryer inlet and h_{amb} is the enthalpy of the ambient air.

Energy efficiency (η) was defined as the ratio between the heat used for moisture evaporation ($\dot{Q}_{\mathrm{w}}$) and $\dot{Q}_{\mathrm{in}}$, as shown in Equation 3:

$$\eta = \frac{\dot{Q}_{\mathrm{w}}}{\dot{Q}_{\mathrm{in}}} = \frac{\dot{m}_{\mathrm{w}} \cdot Q_{\mathrm{st}}}{\dot{Q}_{\mathrm{in}}} \tag{3}$$

Where: Q_{st} is the cassava heat of sorption, used instead of the latent heat of vaporisation, to account for the energy required to overcome capillary forces.

Specific heat utilisation (q_{U}) was defined as the ratio between the heat supplied to the dryer and the dried solid output rate ($\dot{m}_{\mathrm{dp}}$), as shown in Equation 4:

$$q_{\mathrm{U}} = \frac{\dot{Q}_{\mathrm{in}}}{\dot{m}_{\mathrm{dp}}} \tag{4}$$

Solid loading ratio (S_{lr}) was defined as the ratio between the product mass flow rate on a dry basis ($\dot{m}_{\mathrm{dm}}$) and the air mass flow rate on a dry basis ($\dot{m}_{\mathrm{air}}$) as shown on Equation 5:

$$S_{\mathrm{lr}} = \frac{\dot{m}_{\mathrm{dm}}}{\dot{m}_{air}} \tag{5}$$

Table 1 shows the dryer operation conditions before and after the modification to the feeder. Feeding rate ended up above the calculated $\dot{m}^*_{\mathrm{dm}}$ and on a wet basis was 109.4 ± 5 kg/h. Nevertheless, the target moisture content was reached, but to achieve it, drying air temperature was higher – without product overheating. The temperature of the air at the outlet was higher than T^*_{out} and relative humidity was lower than φ^*_{out} . However, the increment on feeding rate result at a lower T_{out} and a higher φ_{out}.

Table 1 *Operating conditions of the dryer before and after increasing the solid feeding rate.*

	$\dot{m}_{\mathrm{dm}}$ Solid feeding rate on dry basis (kg/h)	MC_{ws} Wet solid moisture content ($\%_{\mathrm{wb}}$)	MC_{ds} Dried solid moisture content ($\%_{\mathrm{wb}}$)	T_1 Dryer inlet temperature (°C)	T_{ds} Dried solid temperature (°C)	T_{out} Dryer outlet temperature (°C)	φ_{out} Dryer outlet relative humidity (%)
Before	37.5^{a}	45.5^{a}	10.7^{a}	232.3^{a}	57.5^{a}	69.4^{a}	33.2^{a}
After	61.0^{b}	44.1^{b}	12.0^{a}	270.8^{b}	55.9^{a}	61.5^{b}	57.9^{b}

Means followed by a common letter are not significantly different by Fisher's Least Significant Difference (LSD) test at 5% level of significance.

Table 2 shows energy performances indices before and after increasing the solid feeding rate of the dryer. Because of the increase in drying air temperature, heat supplied to the dryer also increased and, on its turn, the specific enthalpy of the air at the dryer's outlet. However, the increment on water evaporation rate was much higher and consequently, both specific heat consumption and energy efficiency improved significantly. The energy needed to produce 1 kg of dried solid also reduced significantly. Regarding the ratio between solid and air, the modification increased it, but the conveying mode remained in the dilute phase and transport was not jeopardised. The ratio between solid and air, both on a dry basis was 8.6 ± 1.1 kg/kg before the modification and decreased significantly, by a Least Significant Difference test at 5% level, to 5.4 ± 0.3 kg/kg.

Table 2 *Energy performance indices of the dryer before and after the increment of the solid feeding rate.*

	Q_{in} Heat supplied rate (kW)	h_{out} Outlet air enthalpy (KJ/kg)	$\dot{m}_{\text{w}}$ Water evaporation rate (kg/h)	q_{s} Specific heat consumption (kJ/kg)	η Energy efficiency (%)	q_{U} Specific heat utilization (kJ/kg)	S_{lr} Solid loading ratio (g/kg)
Before	33.6^{a}	249.2^{a}	26.7^{a}	4574.7^{a}	54.9^{a}	2914.8^{a}	64.0^{a}
After	41.5^{b}	287.8^{b}	40.0^{b}	3753.6^{b}	66.2^{b}	2154.6^{b}	103.1^{b}

Means followed by a common letter are not significantly different by Fisher's Least Significant Difference (LSD) test at 5% level of significance.

Regarding the sorption isotherm equation and its accuracy in predicting product equilibrium moisture content, using the T_{out} and the φ_{out} figures, before increasing the feeding rate, a value of 4.3%$_{\text{wb}}$ for MC^{*}_{dp} is obtained. When entering the figures from after the increment on the feeding rate, a value of 7.1%$_{\text{wb}}$ is obtained. The disparity between those predicted values and the actual moisture content of the dried products could be a limitation of the sorption isotherm model but most likely can be attributed by the fact that at the end of the drying duct the material hasn't reached equilibrium moisture content.

Outcome and recommendations

The results indicate that the dryer has been properly dimensioned and has high energy efficiency, even before the adjustment to the solid feeding rate. When compared to the energy performance of other small-scale pneumatic dryers, with shorter drying duct, it corroborates with previous research, indicating that the length of the drying duct has a high influence on the energy performance of the equipment.

The work shows that sorption isotherm can be used to calculate optimum feeding rate and that can also be used to determine the optimum air temperature at the dryer outlet. Based on that, a recommended place to install the temperature sensor that controls the on-and-off function of the diesel burner could the cyclone outlet.

For cassava pneumatic drying, the value of 180 °C is usually used as general guideline for maximum temperature of the drying air. However, it was observed that higher temperatures can be used without overheating the product nor promoting starch gelatinization. Also, for cassava pneumatic drying, a value of 8:1 is often recommended for the ratio between air-and-solid. However, this ratio was much inferior, both before and after the feeding rate adjustment, but neither drying nor transport was compromised. Therefore, it is suggested that a better figure to be used as a rule-of-thumb is the ratio between heat supplied and water evaporation.