Dramatic efficiency gains through improved heat exchangers: the case of cassava flash drying in Nigeria

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Flash dryers form a significant component of the cassava processing industry in Nigeria, with approximately 150 units installed; however, many are no longer operational because of the poor margins, in part due to the relatively high cost of oil and low efficiency levels. Fuel typically comprises 30 per cent of the total production cost. This paper outlines the results of performance testing at processors, and the resultant data for specific energy consumption is given, ranging from a worst of 14.2 MJ/kg to an improved 2.9 MJ/kg. Cashew nut shells (CNS) and palm kernel shells (PKS) are a common waste product in Nigeria, and therefore an ideal alternative fuel. Local fuels were analysed for the net calorific value (NCV), since there is a significant variation in this for PKS due to method of processing. NCV (dry basis) of PKS ranged from 10.7 to 17.6 MJ/kg, and for CNS 19.9–23.9 MJ/kg. A retrofit heat exchanger was developed and results from trials and subsequent installations at SMEs over a 15-month period are reviewed. An economic and carbon emission assessment of the heat exchanger is given, with fuel cost reductions of 90 per cent.

Keywords: cassava, flash dryer, palm kernel shell, cashew shell

NIGERIA IS BOTH A MAJOR producer of cassava and a major importer of wheat, and high quality cassava flour (HQCF) can be used as a partial substitute for wheat flour thus reducing imports as well as supporting rural livelihoods. There is also scope for industrial use in board making and the beverage industry. Starch production from cassava in Nigeria has been limited, but this also requires drying, typically with a flash dryer. The Federal Government has targeted the sector for support over the years, including the most recent initiative of 2014.

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Background to the process

The processing and drying of cassava roots at a non-smallholder scale is well documented; for example Udoro et al. (2008) in terms of traditional systems and Sanni et al. (2007) for more advanced and larger scale SMEs (small to medium-sized enterprises). In summary there are four major post-harvest operations: peeling, grating, mechanical dewatering, and drying.

Background to the economics of cassava processing

The economic viability of cassava production is affected strongly by three of these stages. The efficiency of peeling is important in terms of removal of non-peel, since these losses affect the total marketable yield. Mechanical dewatering typically reduces the moisture content (m.c.) from 70 per cent to 40–45 per cent, and is an almost cost-free component of drying (see for example Kolawale et al., 2011). It is axiomatic that if this is 20 per cent less efficient then that component of water removal must be made good by the thermal drying process. At present the final moisture content that can be achieved by mechanical dewatering, due to bound water limitations, is unclear (Aguerre and Suarez, 2004). The drying itself will be the most expensive, both for capital and also operational expenditure, utilizing an external fuel source to provide heat, generally fossil fuel-derived.

As with any agricultural produce the costs of inputs and outputs varies; however Figure 1 shows an indicative breakdown of these in Nigeria based on 2014 data, using fossil fuel as the energy source for the drying heat.

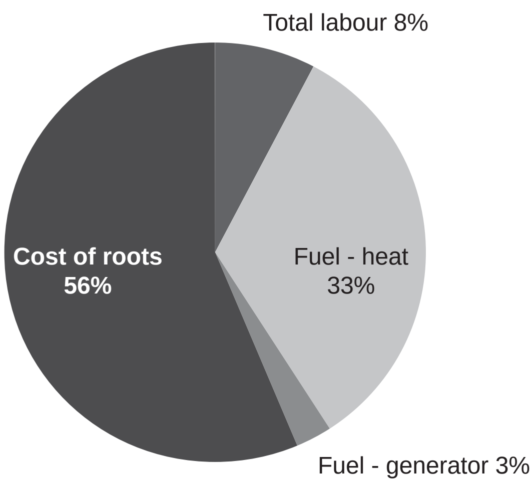

Figure 1 Principal costs of cassava processing: fossil fuel
Note: Based on a cost of roots of N10,000/t (approximately US$63) and conversion ratio of 4:1 (i.e. 1 tonne of flour requires 4 tonnes of roots). Roots are normally in the range N6,000–15,000/t ($30–95/t)

Table 1 Flash dryers in Nigeria

Geopolitical zones	*Number of states*	*Number of SMEs with flash dryers*
North–Central	7	18
North–East	6	1
South–West	6	82
South–East	5	17
South–South	6	35
Total	30	153

As can be seen in Figure 1, the fuel for drying is a major component of the overall operational cost; thus any reduction makes a significant improvement to the viability of the business.

The predominant drying technology in Nigeria is the flash dryer, although there are sites employing other technology types, including rotary, tray, bin and tunnel. The principle of flash dryers is well documented (for example Green, 1984). Flash dryers offer several advantages, summarized below.

- They operate continuously (continuous flow rather than as a batch process).
- Compared to other continuous flow systems they have a relatively low capital cost.
- Fabrication is possible within country, thus aiding the local engineering base and ensuring ease of maintenance.
- There is minimal impact on the quality of the product.
- Control is very simple.

Flash dryers in Nigeria for cassava processing are all of the column type, with no toroidal ones.

There is a mature Nigerian industry for the fabrication of processing equipment, including flash dryers. Historically these are similar to those in other machines, but included a locally designed burner system for waste oil (referred to in country as 'black' oil). This was a gravity-fed, atmospheric unit working on partial vaporization by the Venturi effect and subsequent combustion of the oil as a jet, with vaporization occurring as the oil burned along the length of the flame. There were obvious limitations in terms of throughput and efficiency, and this was affecting the viability of the SMEs.

The recent study for the Federal Government (Sanni, 2012) indicated approximately 180 SMEs involved in cassava production, of which there are 153 flash dryer installations as shown in Table 1.

Development programme

The preliminary phase was data collection, establishing the operational parameters and measuring throughput and efficiency. This then progressed to collaborating with Nigerian fabricators to improve both of these. These stages are summarized below.

- *Preliminary*. Assessment of the current state of the industry.

- *Phase 1*. Improvements to individual components – fans, controls, feeder, motor sizing, cyclones, heat exchanger.
- *Phase 2*. Design of retrofit components to facilitate use of alternative fuel.

Although the primary objective was to improve the financial viability of the SMEs a very important secondary one was to collaborate closely with the local fabricators to assist in capacity building and ensure that developments were maintained and supported.

Testing and benchmarking method

Testing of flash dryers at SME level *in situ* in Nigeria requires a flexible and robust approach, due to the difficulties of transport to site, lack of repair and maintenance to equipment, and the complexity of organizing what are usually sporadic operations to coincide with the test programme. The latter includes the need to organize both labour and root supply, and to ensure that all equipment is operational and has fuel to run. Testing also has to be sufficiently non-invasive in order to permit the SME to undertake its primary task of producing HQCF. The key information required is throughput, requiring both mass in and mass out, initial and final moisture content, and energy consumption, based on mass and calorific value. Other parameters were also measured: airflow and pressures, temperature profiles, and exhaust humidity. For most sites the whole operation was monitored, including measuring the weights of roots in, after peeling, and then after dewatering prior to drying.

In order to have an objective benchmark for comparison purposes, it was decided to express the efficiency of the dryers as a percentage of the theoretical energy requirement for a reduction in moisture content from 40 per cent to 10 per cent. This is a reasonable level that can be expected after dewatering and is the target m.c. required by millers, less a safety margin of 2 per cent. For benchmarking throughput a standardized day of 8 hours and a reduction from 40 per cent to 10 per cent m.c. was employed.

The theoretical energy requirement for this benchmarking figure is 1.609 MJ/kg flour, based on the heat of vaporization for the moisture content, and allowing for 85 per cent thermal conversion. Although this is an over-simplification, as a measure for benchmarking it is satisfactory. It ignores both lesser thermodynamic principles, for example the sensible heat, and chemical ones that have less influence (since water at low m.c. requires a greater energy input to free it from the chemical and physical binding; i.e. Landfield et al., 2008).

Fuel use for drying does not include the start-up period when the dryer is reaching temperature, since the impact of this is dependent upon the subsequent drying period, and tends towards zero on long runs. Clearly for an operation that employs frequent short drying runs this is an important factor; however this is bad practice and reduces the economic viability dramatically. Since the impact of the start-up is dependent upon both the subsequent drying run and the interval to the next run it is also impossible to quantify in a meaningful manner.

Since all actual systems have losses it is clear that it will not be possible to achieve the theoretical 100 per cent value under any circumstances, and typically values of 50 per cent and above would be considered good.

Phase 1 Development and results

The approach adopted was to alter and re-design individual components rather than the whole, thus allowing manufacturers the ability to assess improvements. The key stages and a summary of results (Table 3) are shown below. The Stage 1 improvements applied to the burner, main fan, electrical energy, and wet meal feed; and Stage 2 improvements to the multiple cyclones and heat exchangers.

Burner. Conventional pressure jet burner units operating on diesel oil were substituted for the original burner, and have generally been accompanied by a new heat exchanger.

Main fan. Early models had an induced draught (ID) fan with a smaller fan to assist with feeding of wet meal. Nobex Ltd introduced the change to a single positive pressure fan with cage mill, which overcame issues of poor quality preparation (large particles that dropped out of the airstream) and achieved far greater consistency of final material. Fan design (blade) and manufacturing (accuracy and tolerances) were improved.

Electrical energy. Table 2 shows the results of measurements on electric motors for the main fans (typically accounting for 75–90 per cent of the total load) installed in the existing machines, showing significant over-sizing, with the worst case operating at only 20 per cent of rated capacity, and the best at only 51 per cent.

As a result of correct motor sizing now employed on new installations there has been a cost saving and also an efficiency gain to the operator. A further serious economic effect of this over-sizing is that generators for site supply have been grossly over-capacity, thereby increasing installation and operational costs (see also section on generator mismatching, below).

Wet meal feed. The early systems were manual, and it was observed that on many sites the issue of feed rate is a significant cause of variation of throughput. The use of hydraulically coupled gearbox drives with variable speed connected to a locally fabricated rotary valve has assisted with reducing this issue, although operator skill still remains a source of variability (see, further, section on sustainability, below).

Multiple cyclones. Rather than going down the route of larger single cyclones, the approach adopted has been a modular one; thus the same cyclone can be used for

Table 2 Electric motor summary

	Rated motor size (kW)	*Measured load (kW)*		
Site 1 Double cyclone flash dryer	4.0	0.81	20%	Burner fan
	5.5	2.49	45%	Feeder fan
	5.5	1.44	26%	Main fan
Site 2 Double cyclone flash dryer	15.0	7.60	51%	Main fan
Site 2 Single cyclone flash dryer	5.4	1.55	29%	Main fan
	6.3	2.26	36%	Secondary fan

Table 3 Summary of key results

	Mean throughput (kg per 8 h)	*Mean energy consumption MJ/kg flour*	*Mean efficiency %*	*Number of sites*	*Energy cost of flour N/t*	*$/t*
Original dryer	823	14.3	11	1	55,960	350
Stage 1a[1]	939	5.2	32	5	16,700	104
Stage 1	1,198	4.6	38	3	14,920	93
Stage 2	2,002	3.2	50	2	12,670	79

Note: Based on an oil price of N150/l ($0.94/l)

[1] With pressure jet burner only

different capacity models multiplied up. At present dryers have been manufactured with up to six cyclones.

Heat exchanger. The existing dryers were made of concentric tubes, thus giving at best a single pass heat exchanger design, which, combined with insufficient furnace length, gave a very low efficiency. On some sites it was possible to see flame well beyond the heat exchanger in the flue. An improved design three-pass, counter-flow heat exchanger was developed and coupled with a standard low-cost pressure jet burner rated at 150 kW. The heat exchanger design uses tube bundles within a shell with smoke boxes at either end and the furnace underneath, in a conventional manner.

Controls. For the flash dryers employed at an SME level these are a difficult problem to resolve. Systems that have included electronic controls have not proved durable, in terms of both equipment reliability but also operator understanding, thereby leading to them being discarded. This can even be seen on standard pressure jet burner controls, which are almost invariably wired out and discarded and a manual ignition sequence employed, with no flame detector or other safety controls. It was therefore decided to retain the current practice of manual operation and control using dial type thermometers.

Results. The throughput of the dryers was increased from a mean of 919 kg flour to 1,905 kg per standardized day. The increase in throughput is predominantly associated with the increase in the number of cyclones, from one to six.

The energy to dry 1 kg of flour decreased from 6.7 to 2.9 MJ, associated with the change of burner and improved heat exchanger efficiency.

Phase 2 improvements: waste fuel heat exchangers

Justification. Current fuel costs in Nigeria are shown in Table 4, based on a delivered price (local, for nut shells). In some locations the nut shells are available for significantly less than this, since most of the cost is delivery. Prices as low as N1,000/t have been obtained.

Table 4 Fuel costs in Nigeria

	Unit cost	*Cost raw energy*	*Cost at normal efficiency*[1]
Diesel	N150/l	N3.9 MJ	N4.0 MJ
Kerosene (subsidized as a cooking fuel)	N60/l	N1.6 MJ	N1.6 MJ
Palm nut shells	N7,000/t	N0.44 MJ	N0.88 MJ
Cashew nut shells	N7,000/t	N0.33 MJ	N0.66 MJ

Note: US$1 = N165 (exchange rate, March 2015)

[1] Allowing for losses in processing the fuel (in the case of waste fuels, for example, removing fines out) and incomplete combustion losses

Sustainability, availability, and fuel quality. For palm nuts approximately 6–7 per cent of the harvested weight is kernel shell (Husain et al., 2002). As an indication, if a cassava flash dryer producing 1 tonne of flour per day for 220 days per year operated on shells, and assuming the current average energy input of 6.3 MJ/kg, then the required quantity would be around 90 tonnes/year. Thus if 50 dryers were converted it would require around 4,500 tonnes of shells annually.

2013 data for Nigeria (FAO, 2015) indicates an area of 2.0 million ha under palm oil cultivation, thus assuming a yield of 4 t oil per ha (CIRAD, 2015) around 2.4 million tonnes of shells. This would suggest that within producer areas there should be little difficulty in sourcing materials. FAO lists cashew production as 366,000 ha in 2012. Cashew nut shells are generally disposed of by incineration, whereas some palm kernel shells are used in the winter for heating and some other small applications (blacksmithing for example). The majority of both are clearly a waste product.

The analysis of fuels is shown in Table 5, also demonstrating the difference that processing systems can have on fuel.

Existing situation. There were three flash dryers identified as already operating on waste fuel, one of which had been designed as such and two which had been modified from original black oil burner units. Of these units two were burning palm kernel shells and one cashew nut shells. All use wood to start the furnace prior to shells being loaded. The purpose-designed dryer had an external furnace with thermal oil heat exchanger, the latter then passing through another heat exchanger to provide the drying air. These three units were tested with results as shown in Table 6.

Development of waste fuel heat exchanger. The objective was to develop a unit that could be retrofitted to the older style flash dryers that are currently uneconomic to operate. The initial design was based on a three-pass heat exchanger with under feed stoker and retort for shell combustion, which minimizes fabrication time and cost, optimizes materials use, and is capable of fabrication using the limited machine tools available. Impressively, most fabrication is undertaken with a welder, 9-inch grinder, and drill. Materials employed were sheet steel for the majority and steel tube for the fire-tubes. No refractory lining is included and it was felt that at this stage steel plate can be treated as sacrificial (i.e. that no attempt will be made to protect it, and when it rots through a new sheet will be welded in its place).

Table 5 Fuel analysis

	Unit	Cashew nut shells	Palm kernels shells (processing method 1)	Palm kernel shells (processing method 2)
Total moisture content	%	12.9	11.8	11.1
Gross calorific value GCV	MJ/kg	21.4	18.9	12.1
GCV (dry basis)	MJ/kg	24.6	21.4	13.6
GCV (dry ash free)	MJ/kg	25.2	22.1	14.5
Net calorific value NCV	MJ/kg	19.9	17.5	10.5
NCV (dry basis)	MJ/kg	23.2	20.2	12.4
Ash content (dry basis)	%	2.5	2.8	6.1
Carbon (dry basis)	%	55.7	50.9	47.9
Hydrogen (dry basis)	%	6.38	5.68	5.53
Nitrogen (dry basis)	%	0.58	0.48	0.39
Oxygen by difference (dry basis)	%	34.8	40.1	40.1
Sulphur (dry basis)	%	0.04	0.03	0.03
Chlorine (dry basis)	%	<0.001	<0.001	<0.001

Table 6 Existing waste fuel dryers

Site	*Mean throughput (kg per 8 h)*	*Mean energy consumption MJ/kg flour*	*Mean efficiency %*
Site 1 (PKS)	770	6.5	24
Site 2 (PKS)	192	10.0	16
Site 3 (CNS)	160	23.1	7
Mean	374	13.3	16

Note: Assuming NCV (for a blended mix) of 16 MJ/kg for PKS and 20 MJ/kg for CNS

The combustion component comprises a furnace with under feed stoker auger to a conical retort, as per standard practice for solid fuel systems.

The unit was initially tested using charcoal as fuel, this being more readily available than actual palm kernel shells. Subsequent testing with palm kernel shells showed that various modifications would help, primarily relating to combustion (feed rate speed, increased air slots in the retort, and a larger capacity motor for the feeder). A small number of improvements, mostly relating to simplifying the fabrication process, were then identified for the subsequent units.

Under feed stoker. The design employed is a simple hopper which is manually loaded with fuel, feeding to a horizontal auger to under the centre of the retort, and vertical discharge to this. In order to ease manufacturing the retort is fabricated from 5 mm stainless steel plate, pressed to a 25° angle and seam welded, with air holes cut into it. Individual cast iron tuyeres are not readily available in Nigeria. There is a single under fire fan which positively pressurizes the combustion chamber. This has a manual air control damper valve.

Results

Combustion quality. Combustion characteristics are good, with zoning according to normal practice (drying/volatization/char) as can be seen in Figure 2.

Throughput. The four retrofit units tested had throughputs ranging from 663 to 831 kg of HQCF per standardized day, with a mean of 740 kg/standardized day (mean of best two units was 815 kg/standardized day; see Table 7). This is broadly similar to that prior to the retrofit, and therefore satisfactory to the SME, which obtained the large cost saving with no loss of production. The worst two dryers had easily identifiable installation issues, such as leaking flanges and seals, which, if rectified, would lead to an increase in throughput. Data on temperatures across the components also indicates that there could be improvements obtained by altering fan speeds. The dilemma with retrofit units is how much additional work is viable on the remainder of the older system.

Figure 2 Classic combustion pattern showing drying phase (unburnt) in centre, and then outwards to volatiles and char combustion, and ash lower down (wood is residue from start-up)

Table 7 Summary of results for retrofit unit and comparison to previous

	Throughput (kg HQCF/day)	*Energy consumption (heat) MJ/kg*	*Efficiency %*
Mean of 4 retrofit sites	740	8.9	20
Best 2 of retrofit sites	815	8.2	21
Early oil system type	823	14.0	11

Table 8 Calculated efficiency and losses from retrofit heat exchanger on PKS

Raw energy input (kW)	*Heat to dryer (kW)*	*Drying duct heat (kW)*	*Shell losses (kW)*	*Efficiency %*
257	136.3	8.1	41.3	72

Efficiency. Based on measurements taken on site, the heat exchanger efficiency was calculated as 72 per cent (Table 8). Note that calculations are based on measured airflow and temperatures, ignoring the enthalpy of the water content of air which will be insignificant on these units.

There is approximately 20 per cent greater radiation from solid fuel firing systems (Beer and Howarth, 1969) than from liquid fuelled pressure jet burners, and thus the shell losses (i.e. the waste heat emitted from the external shell) from the heat exchanger are greater. As part of the programme the heat exchanger units will be insulated, which will further increase both throughput and reduce operating costs.

Analysis

Economic

Figure 3 shows the relative significance of the drying costs using waste fuel; thus heating fuel has dropped from 33 per cent of input costs to 8 per cent (c.f. Figure 1).

The costs shown in the figure are based on the mean of four oil-based systems, and four retrofit waste fuel systems, at current prices: oil, N3.95/MJ; waste fuel, N0.59/MJ; labour, N4,500/t peeling fresh roots plus processing of N1,000/t processed roots; and roots, N10,000/t.

Operational

Over-feeding of fuel. One of the main problems is variation in fuel handling characteristics, such that the single speed drive for the fuel feed is likely to be incorrect. In order to provide sufficient fuel this has to be set such that it is likely to be too fast for much of the time. Monitoring of one site showed the air temperatures into the drying tube were often in excess of 300ºC, in contrast to the target of 150–200ºC.

Throughput. The throughput is broadly similar to what was achieved with the oil-fired system previously, and thereby acceptable; however there are clearly

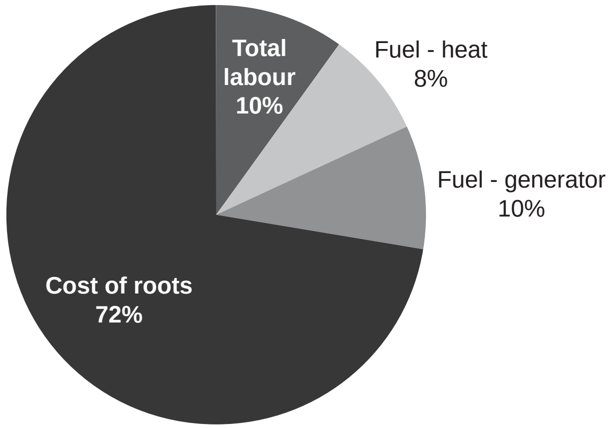

Figure 3 Principal costs of cassava processing: waste biomass fuel

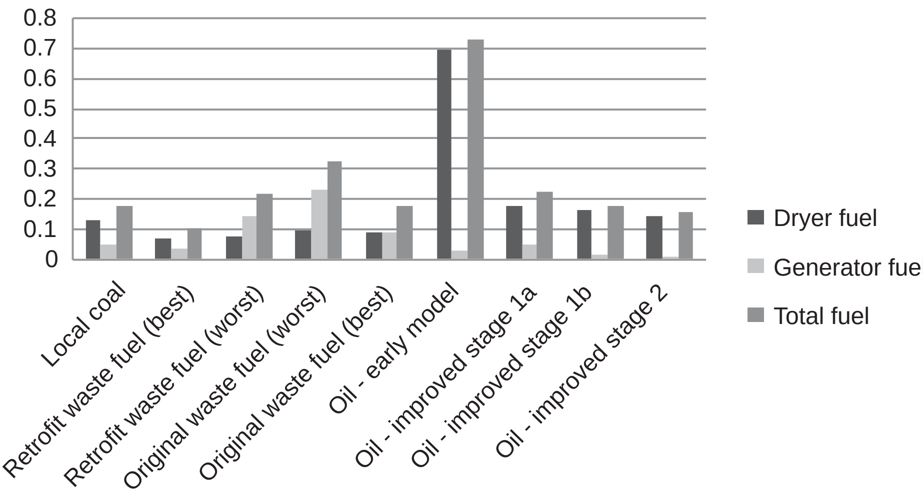

Figure 4 Fuel costs as a percentage of sale price of HQCF
Note: The data for the early oil-fuelled dryer is included in Figure 4 to demonstrate how much of a problem oil costs would be with that system and current oil and flour prices. This is clearly uneconomic to use now, and thus the retrofit waste fuel heat exchangers have extended the usable life of this equipment. It can be seen on this basis that the cost savings on fuel for the dryer are just under 90 per cent.

periods when operational and management issues mean that it is dramatically reduced. As with most solid fuel combustion systems there is a substantial amount of residual heat, and therefore it is important to maintain a continuous throughput over many hours of operation. Many SMEs undertake short production runs of only a couple of hours, sometimes deliberately to fulfil a small order, and other times because of cash flow limitations or equipment breakdowns.

Table 9 CO_2 emissions

	Energy consumption (MJ/t of flour)	*Fuel & quantity*	*CO_2 emissions (t/t)*	*Reduction over base (%)*
Original low efficiency unit (base)	14,100	370 l medium oil	1.11[1]	—
Most developed oil fired unit	2,900	77 l diesel oil	0.20[1]	82
Original unit retrofitted with waste fuel heat exchanger	6,200	357 kg PKS	0.005[1,2]	99

Notes: [1] Emissions data from Ministry of Economic Development, 2009
[2] Based on that for woodchip, comprising mainly transport emissions

Generator matching. The issue of generator mismatch becomes more significant with the lower costs of the primary fuel. The standard retrofit unit on a single cyclone flash dryer has an installed load of around 12 kW, thus even with ancillary equipment (grater and mill) the maximum load will only be around 20 kW. The majority of SMEs have 100 kVA (prime) generators, which are therefore operating at between 13 and 22 per cent at a power factor of 0.9. Most generators in Nigeria are older designs, wherein the reduction in efficiency at low loads will be of the order of 40 per cent (for example Oosterkamp, 2013).

CO_2 emissions

Emissions figures for three stages of the project are given in Table 9, showing the initial low efficiency oil unit, the most developed dryer burning oil, and a basic unit retrofitted for waste fuel.

Discussion of results

Nigerian cassava processing SMEs

The main flash dryer manufacturer in Nigeria has now fabricated around 25 of the improved high efficiency, high throughput oil fired units for SMEs in Nigeria, and exported one unit. There are now 15 SME sites that have been retrofitted with waste fuel heat exchangers. The theoretical maximum daily output from these units is around 200 t/HQCF per day, larger than the current largest industrial scale producer in the country; they thereby have the potential to make a significant economic and social impact.

It is apparent that some of the perceived equipment issues are now limited by management of the SME; thus for example actual operational efficiency is substantially reduced by short production runs and associated warm up times and residual heat after drying.

Nigerian equipment manufacturers

The observable benefits of the capacity building are a production run approach to manufacturing, which was previously bespoke and ad hoc; improved quality of manufacturing, including the greater use of specialist subcontractors such as sheet metal workers with specialist manufacturing capability such as lock-forming; and a modular approach to reduce production costs.

Sustainability

The 99 per cent reduction in CO_2 emissions is dramatic, due both to improved heat exchanger design and also change of fuel. The waste fuel retrofit has extended the life-span of the older black-oil installations, and improved their sustainability both in carbon emissions and financial viability.

Conclusions

The work discussed in this paper has identified a wide fluctuation in efficiency of drying at an SME level. Subsequent to identifying this, the programme of collaboration with the Nigerian manufacturers has led to various improvements and a reduction in specific energy consumption of 80 per cent over the base level. The further work on developing the waste biomass fuel system has reduced costs from 33 per cent of total to 8 per cent. These have made a significant difference to the profitability of such SME processing operations and therefore to the smallholder famers that supply them.

The method of working with the manufacturers of drying equipment in country proved to be effective, and has led to additional gains in manufacturing techniques.

The headline figures for financial savings and CO_2 emissions are impressive, but demonstrate that part of the residual problem is with the daily management of the sites, and further effort is required here.

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