Modeling energy efficiency during dehydration process of cooked yam

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Abstract: Studies on drying have focused on developing mathematical models and kinetics of drying crops, but literature is sparse on energy and exergy analysis of cooked yam used for instant-pounded yam flour production. This work presents the effect of drying temperature and size on energy consumption during cooked yam dehydration, a major unit operation in instant-pounded yam production. Cooked yam with uniform surface area but different thickness (5 mm, 10 mm, 15 mm, 20 mm, 25 mm and 30 mm) were dried in a cabinet dryer at varying temperatures (60°C, 70°C and 80°C) and constant air velocity of 1.5 m s^{-1}. During the drying process, parameters including inside chamber temperature, outside chamber temperature, ambient temperature, drying time and power output of the oven were recorded. These data were used to calculate energy demand, energy input, energy output, exergy, anergy, work lost and energy efficiency according to standard equations. Results showed that the energy supplied for drying increased with increasing yam size from 16,500 to 30,360 kJ, 13,860 to 27,720 kJ and 5,940 to 23,760 kJ at drying temperature of 60°C, 70°C and 80°C respectively. The actual energy utilized for drying (exergy) also increased as the size of the yam slice increased. It increased from 14,963.96 to 27,533.76 kJ, 13,167 to 27,628.51 kJ and 5,768.10 to 23,681.58 kJ at drying temperature of 60°C, 70°C and 80°C respectively. Drying at 5 mm thick cooked yam at 70°C gave highest efficiency of 92.68% whereas least efficiency of 85.84% was recorded when 30 mm thick cooked yam was dried at 80°C. It is not desirable to dry cooked yam whose thickness is less than 10 mm at 60°C because the work lost would be relatively high work. We recommend that the process should be optimized.

Keywords: Drying, Cooked yam, Energy analysis, Exergy efficiency, Instant-pounded yam flour

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1 Introduction

Pounded yam is a special dish in some parts of West Africa. Traditionally, it was processed by using pestle and mortar but gradually replaced in the market by instant-pounded yam flour. Instant pounded yam flour requires short processing time and less energy. The aim of the practice was to preserve yam and reduce human drudgery associated with pounded yam production (Komolafe and Akinoso, 2005). The process includes peeling, washing, slicing/dicing, cooking, drying, milling and packaging. Just as energy is the major determinant of cost in any production sector, about 66% of energy utilized in instant-pounded yam flour production was reported to be used for dehydration of cooked yam (Akinoso and Olatoye, 2013).

Energy and exergy analyses evaluate the available energy at different scenarios in a system and provide useful information required to choose appropriate variables and operating conditions in order to achieve the best performance of a system. The increasing awareness of the fact that energy resources are limited has caused many countries to re-examine their energy policies and take drastic measures in eliminating waste. It has also sparkled interest in the scientific community to take a closer look at the energy conversion devices and to develop new techniques to better utilize the existing limited resources (Cengel and Boles, 2008). Previous works on dehydration have been focused on developing mathematical models and studying drying kinetics, which

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are useful in the design of equipment, and analysis of mass and heat transfer processes. However, little insight is provided for optimization of energy and exergy analyses of the drying process (Dincer and Cengel, 2001). In addition, documented literature is sparse on energy and exergy analyses during dehydration of cooked yam, a major unit operation production in instant-pounded yam flour production. In order to improve energy intensity of dehydration of cooked yam, this work quantified the energy and exergy input during the unit operation.

2 Materials and methods

2.1 Material preparation

Yam (*Dioscorea rotundata*) used for the experiment was sourced from a local market in Ibadan, Nigeria. Washed, peeled yam tuber was sliced into rectangular shape of 50 × 20 mm with varying thickness (5, 10, 15, 20, 25 and 30 mm). The samples were immersed in 0.2% sodium metabisulphite solution for 3 min and cooked in water at 100°C for 12 min (Akinoso and Olatoye, 2013). Cooked samples were cooled in cold water (25°C) for 5 min to remove excess heat.

2.2 Dehydration

The dryer (model OV/200/SS/F/DIG/R38, Genlab Limited, UK) was run for 30 min at desired drying temperature (60°C, 70°C, 80°C) at air velocity of 1.5 m s^{-1} before loading. Cooked yam samples of known size and weight were thinly spread in the dryer and were brought out at 30 min intervals and re-weighed until constant weight was achieved. Cooled samples were then weighed and the difference in weight before and after drying would be the moisture loss. Ratio of moisture loss to weight of wet material in percentage was recorded as moisture content wet basis.

2.3 Energy analysis

During the drying process, parameters including inside chamber temperature, outside chamber temperature, ambient temperature, drying time and power output of the oven were recorded. These data were used to calculate energy demand, energy input, energy output, exergy, anergy, work lost and energy efficiencies using Equation (1), Equation (2), Equation (3), Equation (4) and Equation (5) as applicable (Wang 2009).

$$E_n = Pxt \tag{1}$$

$$E_{xin} = Pxtx\frac{T_o}{T_{low}} \tag{2}$$

$$E_{xout} = Pxtx\frac{T_o}{T_{high}} \tag{3}$$

$$W_{lost} = E_{xin} - E_{xout} = PxtxT_o(1/T_{low} - 1/T_{high}) \tag{4}$$

$$E_{xeff} = \frac{E_{xout}}{E_{xin}} \times 100\% \tag{5}$$

where, E_n - energy used for dehydration, kJ; P - power rating of the cabinet dryer, kW; t - time taken for drying, h; E_{xin} – exergy in, kJ; E_{xout} – exergy out, kJ; T_o - reference temperature, K; T_{low} - outlet temperature, K; T_{high} - inlet temperature, K; W_{lost} - work lost, kJ; E_{xeff} – exergy efficiency, %.

3 Results and Discussion

3.1 Effect of moisture content on energy demand

Figures 1, Figure 2 and Figure 3 showed the relationship between the moisture content and energy supplied at different drying temperatures. As the thickness of yam increased, higher energy was needed to reduce moisture contents. Darvishi (2012) reported similar observation on potato slices. The results also showed that higher energy was needed to dry cooked yam slices at 60°C than at 70°C and 80°C. This is probably because energy supplied is generally proportional to the power rating of the drying equipment and drying time. However, since the power rating of the drying equipment was constant at the three drying temperatures and then drying time becomes a main factor that indicated the amount of energy supplied by the dryer. More time was required to dry cooked yam slices at lower temperatures than at higher temperatures due to lower heat supply from the heating element. This perhaps could have been the reason for the slowest rate of drying at 60°C observed in Figure 1. Therefore, higher amount of energy was supplied by the dryer to dry yam slices of the same size at 60°C than at 70°C and 80°C.

Generally, the size of the yam slices and the drying temperature affect the energy required for drying since 30 mm thick sample will contain much water than 5 mm thick sample. Therefore, more energy was needed to remove moisture from thicker samples. This same trend was observed at each drying temperature. These results indicated that heat transfer rate due to evaporation of the dryer decreased as the surface moisture evaporates until the end of the drying process. This is because surface moisture evaporates very quickly due to high heat energy and mass transfer coefficients in the drying of the yam slices. The drying rate was very high at the initial drying stage due to increase in the energy supplied to the system, but decreased exponentially when all surface moisture evaporates as heat diffuses into the material. Similar findings were reported for drying of potatoes and pumpkin slices in convective type dryer (Akpinar et al., 2005). This is also in agreement with previous studies by Senadeera et al. (2003) on potato. The report attributed moisture movement during dehydration of *Dioscorea alata and D. rotundata* to diffusion.

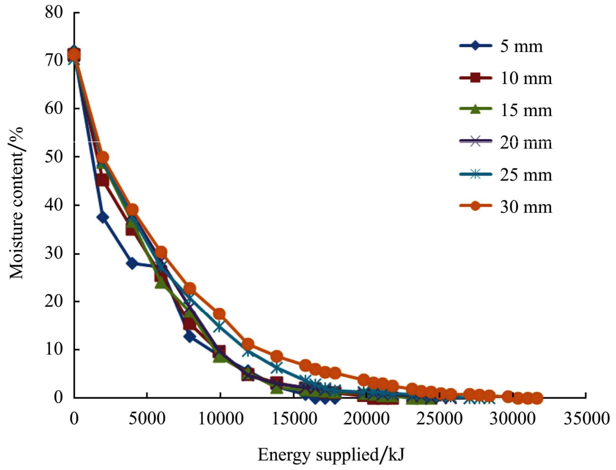

Figure 1 Plot of moisture content against energy input at 60°C drying temperature

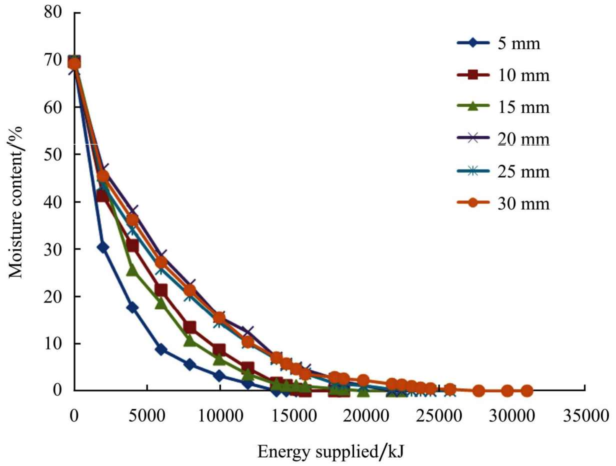

Figure 2 Plot of moisture content against energy input at 70°C drying temperature

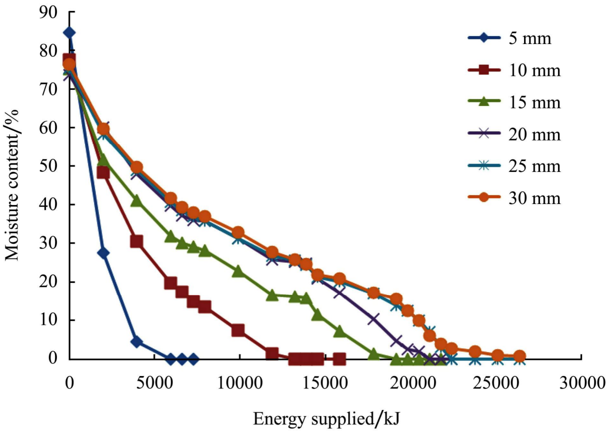

Figure 3 Plot of moisture content against energy input at 80°C drying temperature

3.2 Effects of yam size on exergy

Exergy efficiency measures workability of the system. Figures 4, Figure 5 and Figure 6 represent the relationship between exergy efficiency and the sizes of the yam slice at the drying temperature of 60°C, 70°C and 80°C respectively. At drying temperature of 60°C, exergy efficiency decreased as the yam thickness increased. Exergy efficiency of 5mm thick yam slice at 60°C was 92.49% while exergy efficiency of 90.99% was observed for 30 mm thick sample. Same trend was observed at drying temperatures of 70°C and 80°C. A very high exergy efficiency of 92.68% was obtained when the 5 mm thick yam slice was dried at 70°C. Ten-millimeter sample gave 89.50% exergy efficiency while exergy efficiency of 85.84% was observed for 30 mm thick sample. At drying temperatures of 80°C, exergy efficiencies of 88.10%, 87.54% and 85.84% were observed for slices of 5 mm, 10 mm and 30 mm thickness respectively.

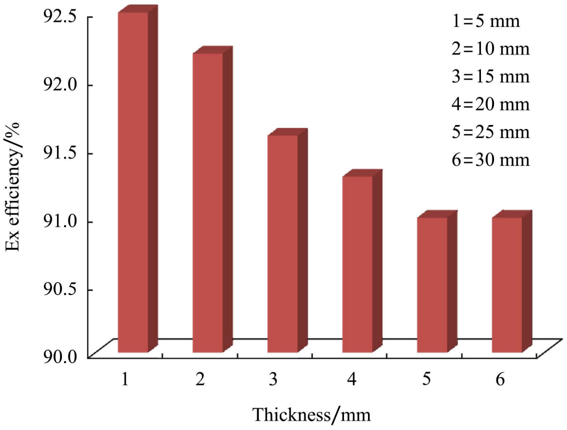

Figure 4 Exergy efficiency of yam samples at 60°C drying temperature

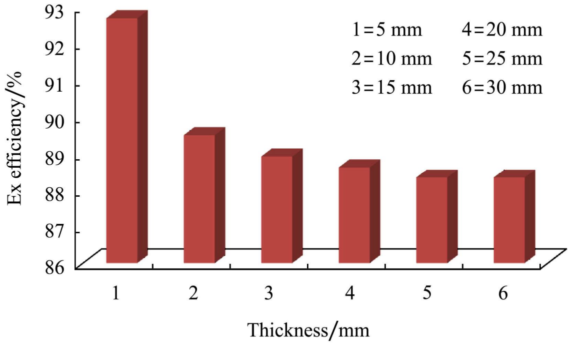

Figure 5 Exergy efficiency of yam samples at 70°C drying temperature

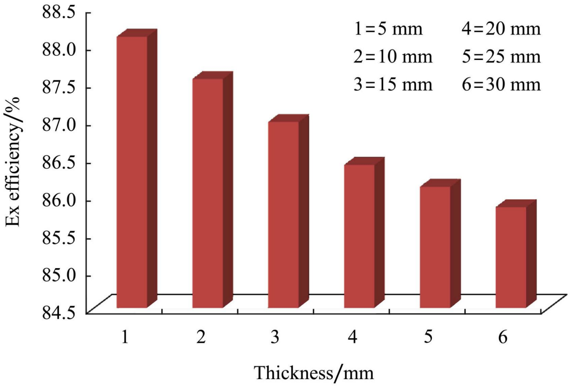

Figure 6 Exergy efficiency of yam samples at 80°C drying temperature

The result indicated that at a particular drying temperature, much of the energy supplied by the dryer for drying cooked yam slices was better utilized in 5 mm thick sample than in 10mm sample, which also utilized the energy more than the yam slice of 30 mm thickness. The implication of this is that more energy was wasted when drying yam samples of thicker sizes than those of thinner sizes at a particular drying temperature. Thus, the amount of energy, or the remaining part of the original heat that was transferred to the environment, increases as the size of the yam slices increases. This has serious implications on power cost and invariable total production cost considering the fact that energy is the major determinant of cost in production industry.

3.3 Effects of drying temperature on exergy

Figures 7, 8, 9, 10, 11 and 12 show the relationship between exergy efficiency of sizes of the yam slice and the drying temperature. Very high exergy efficiencies of 92.68% and 92.49% were recorded for 5 mm thick yam slices at 70°C and 60°C drying temperature respectively, while the least values were obtained at drying temperature of 80°C irrespective of the yam size although the least exergy efficiency value of 85.84% was obtained for yam slice of 30mm thickness. The result showed that the lower the temperature of drying, the higher the exergy efficiency. In essence, the heat energy supplied by the dryer during the drying of yam slices was better utilized at lower temperature of drying than 80°C. This is because drying yam slices at very high temperatures result in rapid surface dryness (crust formation) thereby preventing the penetration of heat into the lower parts of the sample. Since energy supplied for drying cannot be utilized efficiently, heat loses are thereby encountered especially at very high temperatures. The results are similar to that reported by Mborah and Gbadam (2010) who reported exergy destruction at very high temperatures in the combustor and super heater tubes of a power plant. It also indicated that for a real process such as dehydration, the exergy input always exceeds the exergy output causing an imbalance due to irreversibility, or otherwise known as exergy destruction. At each point in time, the exergy-in was always greater than the exergy-out, implying that the available energy for work or utilizable energy that flows into the system was always greater than that, which flows out of the system thus obeying the second law of thermodynamics. The resultant difference therefore, produced significant work lost ($p<0.05$) at each drying temperature and yam size (Table 1).

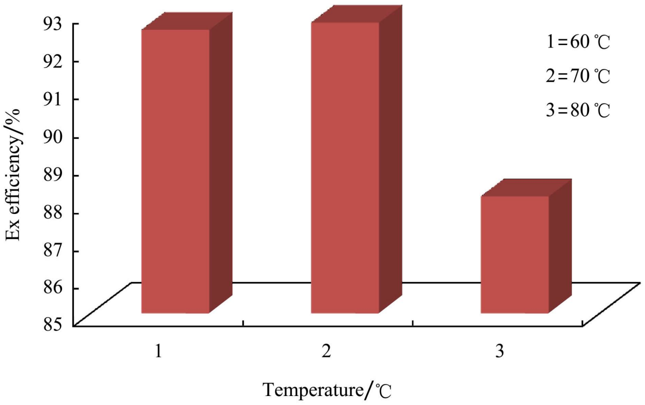

Figure 7 Effect of temperature on exergy efficiency at 5 mm thickness

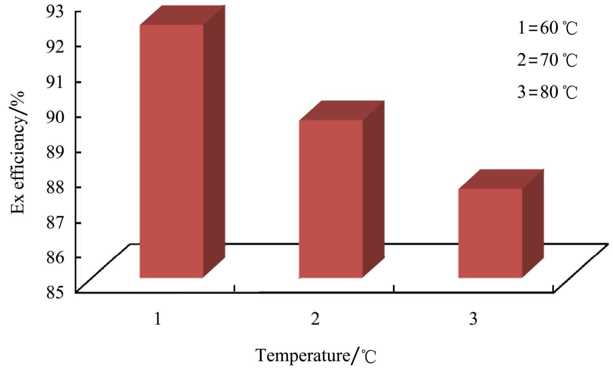

Figure 8 Effect of temperature on exergy efficiency at 10 mm thickness

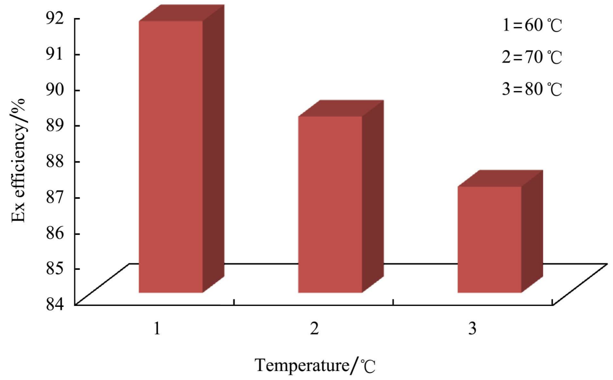

Figure 9 Effect of temperature on exergy efficiency at 15 mm thickness

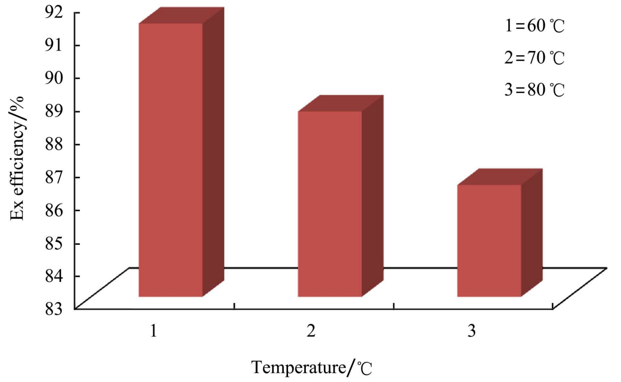

Figure 10 Effect of temperature on exergy efficiency at 20 mm thickness

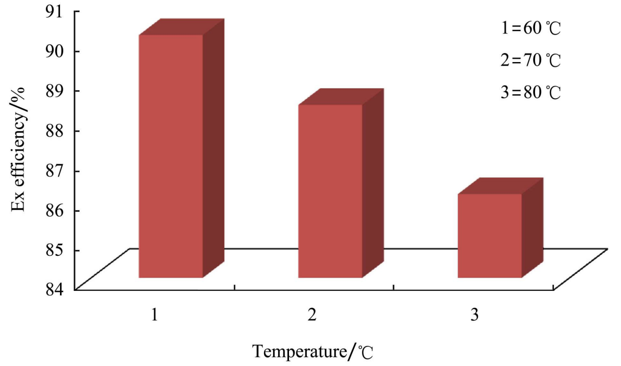

Figure 11 Effect of temperature on exergy efficiency at 25 mm thickness

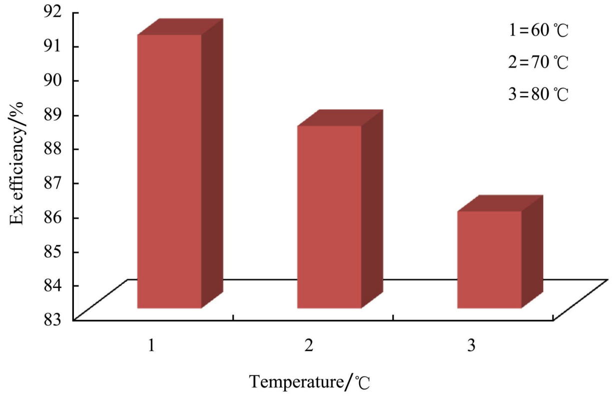

Figure 12 Effect of temperature on exergy efficiency at 30 mm thickness

Table 1 Work loss at varying drying temperature

Thickness /mm	Work lost /kJ		
	60°C	70°C	80°C
5	1214.61^{a}	963.73^{b}	686.29^{c}
10	1571.46^{a}	1101.60^{b}	1608.05^{c}
15	1923.19^{a}	2172.25^{a}	2453.54^{c}
20	2169.72^{a}	2460.41^{b}	2843.59^{c}
25	2429.73^{a}	2685.26^{a}	3003.40^{c}
30	2726.04^{a}	3222.51^{b}	3354.33^{b}

Note: Values on same row with different superscript are significantly different at p>0.05.

4 Conclusions

Energy requirements for dehydration of cooked yam significantly depend on size and drying temperature. Drying at high temperature increase drying rate and reduce energy input, while keeping the efficiency of energy utilization of this process is low. Drying at 5 mm thick cooked yam at 70°C gave highest exergy efficiency of 92.68% whereas least exergy efficiency of 85.84% was recorded when 30 mm thick cooked yam was dried at 80°C. It is not desirable to dry cooked yam of thickness less than 10 mm at 60°C because of relatively high work lost. Generated data are relevant in energy and cost analysis of dehydration of cooked yam for instant-pounded yam flour production. Process optimization was recommended.

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