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Mass and Energy Balance Analysis of Pneumatic Dryers for Cassava and Development of Optimization Models to Increase Competitiveness in Nigeria

S. A. Adegbite[1,2*], A. Adebayo[3], O. J. Olukunle[2], A. P. Olalusi[2], W. B. Asiru[1] and W. Awoyale[3]

[1]*Federal Institute of Industrial Research Oshodi (FIIRO), Lagos, Nigeria.*
[2]*Federal University of Technology Akure (FUTA), Ondo State, Nigeria.*
[3]*International Institute of Tropical Agriculture (IITA), Dar es Salaam, Tanzania.*

Authors' contributions

This work was carried out in collaboration between all authors. Author SAA is the leading investigator who coordinated the research activity. Author AA contributed in the proposal that lead to the award of the grant for the research and also facilitate the provision of tools and equipment for the research. Authors OJO and APO supervised the research activity. Author WBA contributed in the proposal that lead to the award of the grant for the research. Author WA contributed in the proposal that lead to the award of the grant for the research. All authors read and approved the final manuscript.

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ABSTRACT

The use of locally fabricated flash drying system is a major challenge for the production of High Quality Cassava Flour (HQCF). Thus, this study focuses on analysis of pneumatic dryers for cassava processing and its significance relates to its promise to further our understanding of the performance of the existing design models of pneumatic dryers and to identify new way to improve drying performance of the dryers. Four different design models of pneumatic dryer for HQCF drying were evaluated at three cassava processing centers. The dryers were subsequently modified based

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*Corresponding author: E-mail: adegbitesirojdeen@yahoo.com;

on minimum air. The dryer models were assessed based on energy efficiency, specific heat consumption and thermal efficiency. The highest energy efficiency was recorded for the positive, single cyclone system, dryer model 2 (+1C) which increased from 63.27 to 78.55% while its specific heat consumption was reduced from 3.79 to 3.06 MJ/kg after modification. Furthermore, the modification reduces the fuel consumption in all the dryer models by 22%, 14%, 14% and 16% respectively. Thus, it is established that the positive, single cyclone system had the better drying performance of all the dryer models evaluated.

Keywords: High quality cassava flour; energy efficiency; specific heat consumption and thermal efficiency.

1. INTRODUCTION

An increase in cassava processing has been shown to contribute to sustained growth in cassava production in Nigeria [1]. However, the inherent high moisture content of fresh cassava root promotes both microbial deterioration and unfavorable biochemical changes in the commodity [2]. Consequently, cassava roots need to be processed into more shelf stable product like HQCF in order to improve it flavor and reduce post-harvest losses. Current challenges for the cassava industry in Nigeria, is the area of cassava processing in general and drying in particular. This include reducing the drying time, improving throughput and product quality as well as reduction in the production cost per kg of product through appropriate equipment design or modification [3].

Drying is a unit and an essential operation in the production of cassava products such as high quality cassava flour, cassava starch and fufu flour. Mechanical drying ensures improved and consistent product quality. Flash dryers among the different types of dryers (such as rotary dryer, and tunnel dryer) have the shortest residence time. They have several advantages over more complex gas suspension dryers such as fluid bed or rotary types as result of short residence time, hence, most suitable for drying heat-sensitive products like cassava [4]. Pneumatic flash dryers have been fabricated and installed in Nigeria Since 2004, however, all these flash dryers are inefficient in terms of energy consumption and or product quality [5]. Hence, the need for innovative cassava processing technologies is enormous. Consequently, the evaluation of the existing flash dryers is required for better improvement and optimization.

2. MATERIALS AND METHODS

2.1 Studied Processing Centers

The studies were carried out at three cassava processing centers. These processing centers were Niji Foods Limited located at km 5 Komu road, Ilero in Oyo State, Open Door International Limited, located at Akileye village, Iju Ebiye via Ota, Ogun State and Fadett Cassava Processing Center, located at Ofada via Mowe, Ogun State, which is being managed by Dowog Enterprise under lease. All the three cassava processing centers were located in Southwest region of Nigeria. The features of the pneumatic flash dryers evaluated are presented in Table 1 while the dryer models were shown in Appendix 1.

2.2 HQCF Processing Method and Sample Collection

HQCF samples were produced using the method as described by IITA, [6], from the four models of flash dryers. Set of wet and dried product samples were collected per day, after the systems had reached a steady-state condition. Wet samples were collected from the feeder and dried samples collected at the cyclone outlet every 20 minutes.

Table 1. Features of flash dryer models at the processing centers

Features	Model 1 (+6C)	Model 2 (+1C)	Model 3 (-1C)	Model 4 (-1C)
System types	Pressure	Pressure	Vacuum	Vacuum
No. of cyclone	Six	One	One	One
Fuel type	Kerosene	Diesel	Black oil	Diesel
Burner type	Imported	Imported	Locally built	Imported
Drying duct length (m)	7.20	13.50	12.00	12.5
Dry duct diameter (m)	0.76	0.32	0.31	0.31
Outlet diameter (m)	0.25	0.28	0.31	0.27

2.3 Dryers Evaluation and Dryer Modification

First the unmodified dryer was evaluated, during three consecutive days. The minimum air flow rate was then calculated and the dryer was subsequently modified. The minimum velocity was used as a basis for the flash dryer modification by selecting a driver pulley which result into speed equivalent to these velocities for the fan blower. Dryers were modified using the minimum air flow determined from sorption parameters [7]. The modified dryer was, then evaluated for another three consecutive days, following the same procedure used for the unmodified dryer.

2.4 Tools, Measurements and Experimental Procedure

Measurement were performed using tools, sensors and Data Acquisition System during steady state of the dryers which were being logged directly on to computer system at every 10 seconds. These tools were: digital industrial balance, thermocouples sensors, temperature-resistant pressure transducer (PAA35X-V-3; Omega Engineering Inc.), OMB-DAQ-54, humidity–temperature probes (HC2-S; Rotronic, Bassersdorf, Switzerland), HygroLab 2; Rotronic, miniature hot-wire anemometers (TVS-1008; Omega Engineering Inc.) and data logger (HC2-S; Rotronic, Bassersdorf, Switzerland). The sensor were connected to the dryers as shown in Fig. 1.

2.5 Parameters Measured and Calculated

The dryer parameters measured were: temperature & humidity (ambient air, hot air inlet, outlet and exhaust air), pressure (ambient and outlet air), air velocity and weight of feed, product and fuel. The parameters calculated were feed rate and discharge rate, fuel consumption, air density, air enthalpy, minimum air flow rate using standard procedures.

2.6 Dryer Performance Parameters

Dryer performance was determined using methods as described by Precoppe et al. [3]. The performance indices were specific energy consumption, energy efficiency, thermal efficiency, heat rate, heat losses via exhaust air and heat losses to the ambient.

2.7 Statistical Analyses

Analysis of variance (ANOVA) was adopted in analyzing the data. SPSS version 17.0 software package was used to statistically analyze the data obtained for all treatments. The significance of treatment means was tested at $P < 0.05$ probability level using Duncan's New Multiple Range Test (DNMRT) [8].

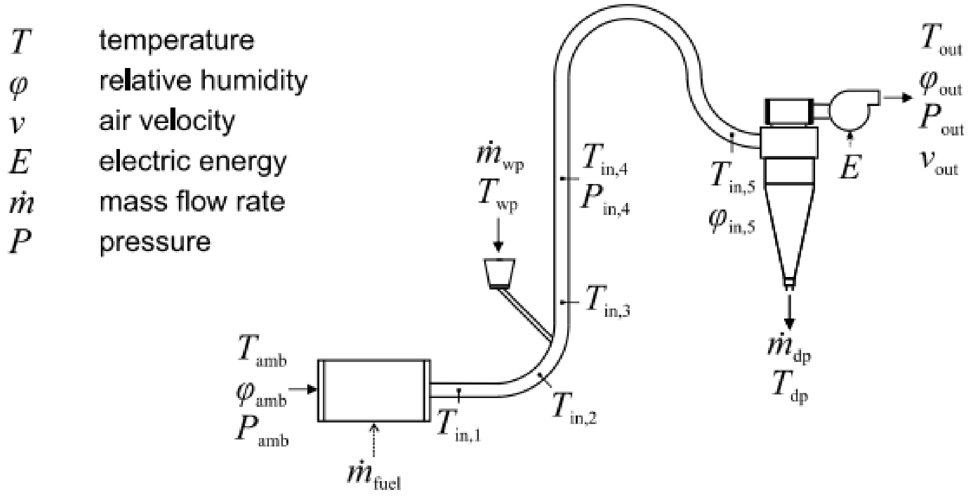


Fig. 1. Flash dryer cross section

2.8 Energy Analysis

Specific energy consumption (q_s) was calculated according to Kudra, [9] based on the heat rate added by the dryer's heating unit to the ambient air ($\Delta \dot{Q}_{in}$) and the water evaporation rate ($\dot{m}_{\omega}$) as shown in Equation 1

$$\textbf{Specific energy consumption } (\mathbf{q_s}) = \frac{\Delta \dot{Q}_{in}}{\dot{m}_{\omega}} = \frac{\dot{m}_{air}(h_{in} - h_{amb})}{\dot{m}_{\omega}} \quad (1)$$

Where $\dot{m}_{air}$ is the air mass flow rate and h_{in} and h_{amb} are the enthalpy of inlet and ambient air, respectively. The value for $\dot{m}_{air}$ was calculated from the air density, air velocity and cross-sectional area of the exhaust air. While the air density was determined based on the air temperature, relative humidity and pressure, using the equation of state called CIPM-2007 formula [10].

Energy efficiency (η_e) was calculated by dividing the heat used for water evaporation by the heat added to the ambient air by the dryer's heating unit (ΔQ) according to Kudra, [9]

$$\textbf{Energy efficiency } (\boldsymbol{\eta}_\mathbf{e}) = \frac{Q_w}{\Delta \dot{Q}_{in}} = \frac{m_w \cdot \lambda}{\Delta \dot{Q}_{in}} \quad (2)$$

Where $\boldsymbol{\lambda}$ is the latent heat of the vaporization of water at the inlet temperature of the product [11]

Thermal efficiency, (η_T), was defined according to Strumiłło et al., [12] based on the inlet air temperature (T_{in}), the outlet air temperature (T_{out}) and the ambient temperature (T_{amb}), as shown in Eq. (3):

$$\text{Thermal efficiency } (\eta_T) = \frac{T_{in} - T_{out}}{T_{in} - T_{amb}} \quad (3)$$

2.9 Determination of Minimum Air Flow Rate

Minimum air flow rate ($\dot{m}^*_{air}$) was determined considering the heat and hydrodynamic demand of the dryer, as suggested by [13]. The highest allowable outlet air relative humidity (ϕ^*_{out}) and the lowest allowable outlet air temperature (T^*_{out}) was determined based on the sorption isotherm of cassava using the modified Halsey model [14] and the parameters for desorption presented by Aviara and Ajibola, [7]. $\dot{m}^*_{air}$ was determined by dividing water evaporation rate ($\dot{m}_w$) by Y^*_{out} and taking into consideration the absolute humidity of the ambient air as shown in Equation (4):

$$\dot{m}^*_{air} = \frac{\dot{m}_{\omega}}{Y^*_{out} - Y_{amb}} = \frac{\dot{m}_{dm}(X_{wp} - X_{dp})}{Y^*_{out} - Y_{amb}} \quad (4)$$

Where $\dot{m}_{dm}$ is the dry basis feed rate and X_{wp} and X_{dp} are the moisture content in dry basis of the wet product and of the dried product, respectively. The hydrodynamic demand took into consideration that the minimum air velocity at the drying duct should be higher than the wet product terminal velocity.

3. RESULTS AND DISCUSSION

3.1 Dryers Performance

The results of the unmodified dryers in the Table 2 indicated that significant variation ($p \geq 0.05$) was found in the performance indices for the all the flash dryer models except for the energy efficiency 1(+6C) & 4 (-1C) and specific energy consumption of the dryer models 1(+6C), 3 (-1C) & 4 (-1C). Flash dryer model 2 (+1C) had the highest energy efficiency (63.4 %) while the lowest value of (47.47 %) was recorded for dryer model 3 (-1C) using the mean values over different feed rates. In addition, the lowest value (3.63 MJ/kg) of specific heat consumption was recorded for dryer model 2 (+1C) while the dryer model 3 (-1C) also had the highest value (5.07MJ/kg) using the mean values. According to Kudra [10], energy efficiency and specific heat consumption are the most frequently exploited to assess the dryer performance of all the indices from the energy view point. The higher the energy efficiency and the lower the specific heat consumption, the better the dryer performance hence, the pneumatic flash dryer model 2 (+1C) had the best performance.

Furthermore, according to Mujumdar [15], the specific energy consumption of a pneumatic dryer ranges from 4.5 to 9.0 MJ/kg water while Tolmac *et. al.,* [16] reported the range of specific consumption of energy to be between 3.50 to 5.04 MJ/kg. Strumiłło et al*.,* [12] reported that the energy efficiency of convective dryers is typically between 20 and 60%. The specific energy consumption and the energy efficiency of the flash dryer models evaluated fall within these range. In addition, the thermal efficiency of pneumatic dryers range from 50 to 75% [17] but the thermal efficiencies obtained for the dryer models 3 (-1C) and 4 (-1C) were within this range however, that of dryer models 1 (+6C) and 2 (+1C) were slightly higher. This might be due to the elevated temperature of the hot air inlet recorded for the two dryer models.

3.2`Performance Comparison between Modified and Unmodified Dryers

There were significant difference between all the performance indices except the specific heat consumption of dryer model 3 (-1C) and thermal efficiency of the dryer model 2 (+1C). There were significant improvements in the performance of modified dryers for all the dryer models, as showing in Table 2 that the energy efficiencies of all the dryers increased while their specific heat consumption reduced with the exception of the dryer model 3 (-1C). Furthermore, the results revealed that 94.1 g/kg, 88.2 g/kg, 89.8 g/kg and 101.2 g/kg for dryer models 1 (+6C), 2 (+1C), 3 (-1C) and 4 (-1C) respectively) of fuel shall be required to dry 1kg of wet product. Whereas in the modified dryers, these values reduced to 73.1g/kg, 75.9g/kg, 77.1g/kg and 85.3 g/kg. This reduction (22%, 14%, 14% & 16%) in fuel consumption is directly proportional to production cost, hence, improvement on investment return.

3.3 Temperature Distribution

Fig. 2 presents the temperature distributions along the drying ducts of the flash dryers models. There was high rate of heat transfer between the drying air and the product, thus enhancing the high rate of moisture evaporation during the constant drying period. The temperatures of the drying air which follow the same trend for all the dryer models reduce progressively along the drying duct.

3.4 Effect of Feed Rate on the Energy Efficiency for the Different Dryer Models

The energy efficiency increases with increase in the feed rate for all the dryer models reaching the maximum at the optimum feed rates in both unmodified and modified dryers as shown in Figs. 3a and 3b. However, significant improvement in energy efficiency was observed in all the dryer models after modification. This was as a result of reduction in the air inlet velocity. However, dryer model 2 had the highest energy efficiency which increases from 72.3% at velocity of 9.45 m/s and feed rate of 171.70 kg/h to 84.4% at velocity of 7.39 m/s and feed rate of 175.59 kg/h. While the lowest values were observed in the dryer model 3 which increases from 56. 0% at velocity of 9.45 m/s and feed rate of 171.70 kg/h to 74.1% at velocity of 7.4 m/s and feed rate of 193.49 kg/h. This was as a result of the low calorific value of spent oil compared to diesel or kerosene. Hence, dryer model 2 of all dryer models is the best in term of drying performance. Precoppe, et al*.,* [15] reported similar result of energy efficiency of a pneumatic flash dryer for HQCF drying which increases from 43.1% to 54.0% after modification by reducing the air velocity from 9.5 m/s to 7.2 m/s.

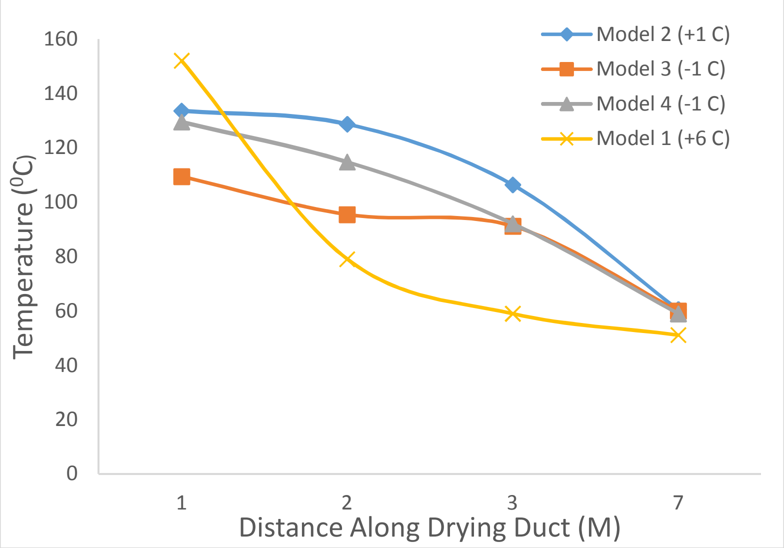
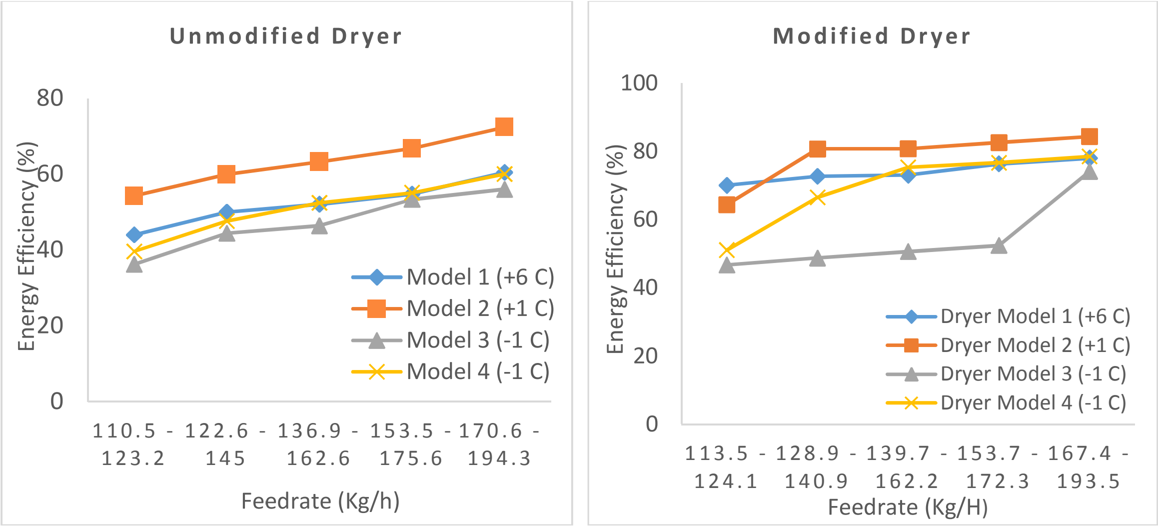


Fig. 2. Temperature Distribution along the Drying Ducts

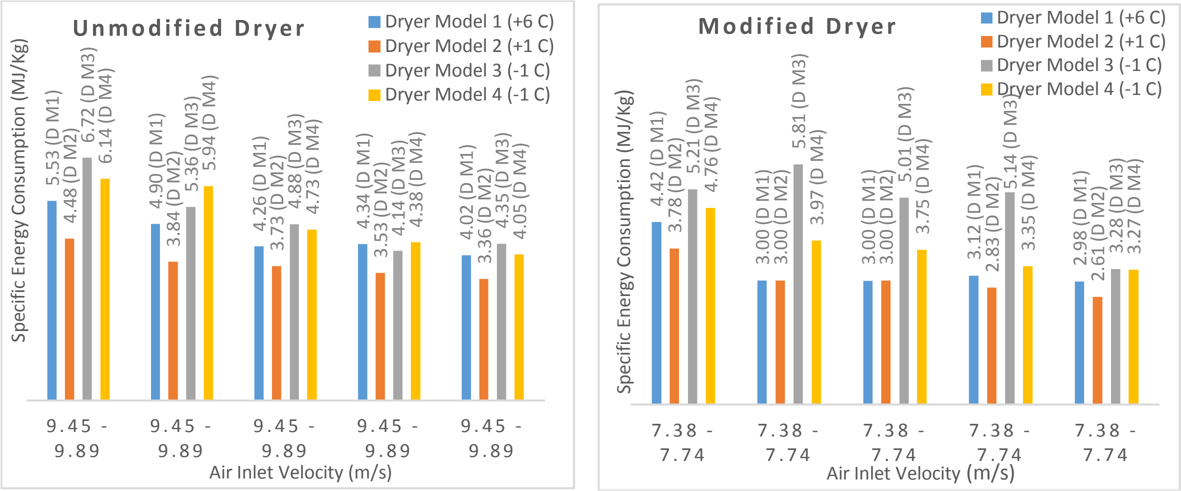
Table 2. Comparison of performance data of unmodified and modified flash dryer models

Dryer model	Dryer type	Fuel consumption (kg/h)	Heat input rate (kW)	Energy efficiency (%)	Specific energy consumption (MJ/kg)	Thermal efficiency (%)
Dryer model 1 (+6C)	Modified	17.41^{b} ±.01	76.18^{b} ±.02	74.01^{a} ±.06	3.24^{b} ±.04	86.06^{b} ±.09
	Unmodified	22.49^{a} ± .10	106.51^{a} ±.44	52.02^{b} ±.02	4.61^{a} ±.06	87.13^{a} ±.08
Dryer model 2 (+1C)	Modified	18.11^{b} ±.01	82.34^{b} ±.02	78.55^{a} ±.01	3.06^{a} ±.04	80.31^{b} ±.05
	Unmodified	21.09^{a} ±.03	100.60^{a} ±.45	63.27^{b} ±.02	3.79^{a} ±.10	80. 49^{b} ±.03
Dryer model 3 (-1C)	Modified	17.71^{b} ±.10	118.72^{b} ±.02	54.51^{a} ±.10	5.09^{a} ±.10	81.75^{a} ±.05
	Unmodified	20.82^{a} ±.02	127.47^{a} ±.51	47.24^{b} ±.04	5.09^{a} ±.06	54. 40^{b} ±.03
Dryer model 4 (-1 C)	Modified	18.37^{b} ±.08	78.63^{b} ±.05	69.81^{a} ±.11	3.82^{b} ±.10	74.15^{a} ±.07
	Unmodified	21.95^{a} ±.12	102.83^{a} ±.19	50.93^{b} ±.32	5.05^{a} ±.52	65.29^{b} ±.71



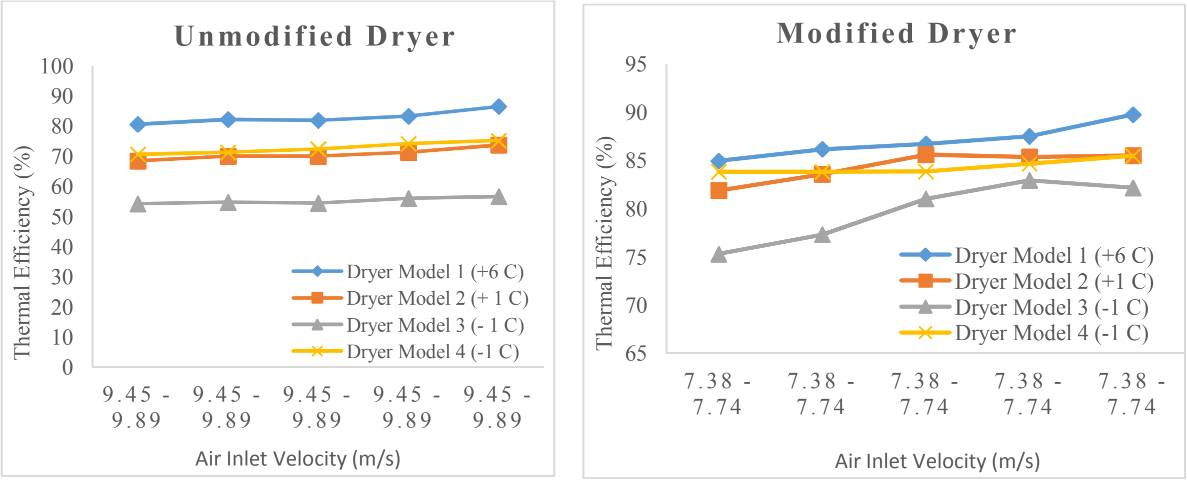
3a **3b**

Figs. 3a and 3b. Effect of feed rate on the energy efficiency (Unmodified and Modified Dryers)



4a **4b**

Figs. 4a and 4b. Effect of inlet air velocity on the specific heat consumption at different feed rates (Unmodified and Modified Dryers)



5a **5b**

Figs. 5a and 5b. Effect of inlet air velocity on the thermal efficiency at different feed rates (Unmodified and Modified Dryers)

3.5 Effect of Inlet Air Velocity on the Specific Energy Consumption for Different Dryer Models

Figs. 4a and 4b show the effect of inlet air velocity on the specific energy consumption of all the dryer models for both unmodified and modified dryers at different feed rates. The highest specific energy consumption of 6.72 MJ/kg was recorded at 9.89 m/s velocity and feed rate of 123.48 kg/h for dryer model 3 while the lowest value of 3.36 MJ/kg was obtained at 9.45 m/s and feed rate of 171.70 kg/h for dryer model 2 for unmodified dryers. Also, the highest specific energy consumption of 5.21 MJ/kg was recorded at 7.4 m/s velocity and feed rate of 193.49 kg/h for dryer model 3 while the lowest value of 2.61 MJ/kg was obtained at 7.39 m/s and feed rate of 175.59 kg/h for dryer model 2 for modified dryers. With the exception of dryer model 3, the specific energy consumption of modified dryers reduces compared to unmodified dryers. This reduction indicates improvement in the performance of modified dryers for all the dryer models. Furthermore, dryer model 2 also gave the best performance for having the lowest value. This is also similar to report of Precoppe, et al. [3] of specific energy consumption of a pneumatic flash dryer for HQCF drying which decreases from 5.75 MJ/kg to 4.60 MJ/kg after modification by reducing the air velocity from 9.5 m/s to 7.2 m/s.

4.2.7 Effect of inlet air velocity on the thermal efficiency for different dryer models

Figs. 5a and 5b show the effect inlet air velocity on the thermal efficiency of the dryer models before and after modification at different feed rates. The thermal efficiency increases with increase in the feed rate for all the dryer models for both unmodified and modified dryer. It was also observed that the thermal efficiency increased in all the dryer models at the same feed rates after modification. This was also as a result of reduction in the air inlet velocity for all the dryer models. The maximum thermal efficiency was recorded for dryer model 1 which increases from 86.5% at velocity of 9.45 m/s and feed rate of 192.15 kg/h to 89.8% at velocity of 7.38 m/s and feed rate of 193.09 kg/h after modification while the lowest values was observed in the dryer model 3 which increases from 56. 6% at velocity of 9.89 m/s and feed rate of 194.32 kg/h to 82.2% at velocity of 7.4 m/s and feed rate of 193.49 kg/h after modification.

4. CONCLUSION

The four models of pneumatic flash dryers were successfully evaluated. It is established that the positive single cyclone system had the best performance in term of energy efficiency and specific heat consumption among the design model of pneumatic flash dryers evaluated. The qualities of the HQCF samples obtained from the model of flash dryers were within the limits set by the relevant Nigerian standards which is an indication that those dryer models are suitable for HQCF production. However, some drawbacks observed in the flash dryers models were absence of insulation on the drying duct which facilitate greater heat loss to the ambient, absence of feeder on some of the flash dryer models, improper design of the multiple cyclone which affect proper separation of product from the exhaust air and absence of heat control system on the burners. These draw backs were militating against the optimum performance of pneumatic dryer models. Hence, the need for new engineering design of a functional and well efficient pneumatic flash dryer for HQCF production because there is a limit to which modification could be carried out on existing flash drying system.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Ugwu BO, Ukpai UJ. Potential of cassava flour processing to sustain increasing cassava production in Nigeria. Outlook on Nigeria Agriculture. 2002;31(2):129-133.
2. Wenham JE. Post-harvest deterioration of cassava. A biotechnology perspective. FAO. Plant Production and Protection Paper. 1995;130:6-35.
3. Precoppe M, Chapuis A, Müller J, Abass A. Tunnel dryer and pneumatic performance evaluation to improve small-scale cassava processing in Tanzania. Journal of Food Process Engineering; 2015.
4. Oveet CB, Sardo MS. Find the optimum flash dryer to remove surface moisture. Chemical Engineering Progress. 2001;54-58.
5. Kuye A, Raji AO, Kwaya EI, Otuu OO, Abdulkareem BI, Alenkhe B. Computer aided fabrication of flash dryer components. Lagos: Raw Materials Research and Development Council; 2010.
6. IITA. Cassava Starch Production. Integrated Cassava Project. Nigeria; 2005.
7. Aviara NA, Ajibola OO. Thermodynamics of moisture sorption in melon seed and cassava. Journal of Food Eng. 2002;55: 107-113.
8. Steel RGD, Torrie JH. Principles and procedures of statistics. New York: McGraw-Hill; 1980.
9. Kudra T. Energy aspect in food dehydration. In Advances in Food Dehydration (C. Ratti, ed). CRC Press, Boca Raton, FL. 2009;423-445.
10. Picard A, Davis RS, Gläser M, Fujii K. Revised formula for the density of moist air (CIPM-2007). Metrologia 45, 2008;149-155.
11. Chapuis A, Precoppe M, Méot JM, Sriroth K, Tran T. Pneumatic drying of cassava starch: Numerical analysis and guidelines for the design of efficient small-scale dryers. Drying Technology. 2017;35(4): 393-408.
12. Strumiłło C, Jones PL, Zyłła R. Energy aspects in drying. In Handbook of Industrial Drying, 4th Ed. (A.S. Mujumdar, ed.) pp. 1077–1100, CRC Press, Boca Raton, FL; 2014.
13. Kudra T. Energy performance of convective dryers. Drying Technol. 2012;30:1190-1198.
14. Iglesias HA, Chirife J. Prediction of the effect of temperature on water sorption isotherms of food material. Int. J. Food Sci. Tech. 1976;11:109–116.
15. Mujumdar AS. Principles, classification, and selection of dryers. In Handbook of Industrial Drying, 4th Ed. (A.S. Mujumdar, ed.), CRC Press, Boca Raton, FL. 2014;3–29.
16. Tolmač D, Prvulović S, Radovanović L. Effects of heat transfer on convection dryer with pneumatic transport of material. FME Transactions. 2008;36(1):45-49.
17. Rotstein E, Crapiste GH. Design and performance evaluation of dryers. In Handbook of Food Engineering Practice (K.J. Valentas, R.P. Singh and E. Rotstein, eds). CRC Press, Boca Raton, FL. 1997;121-162.

APPENDIX 1

Plate 1a. Negative Single Cyclone System

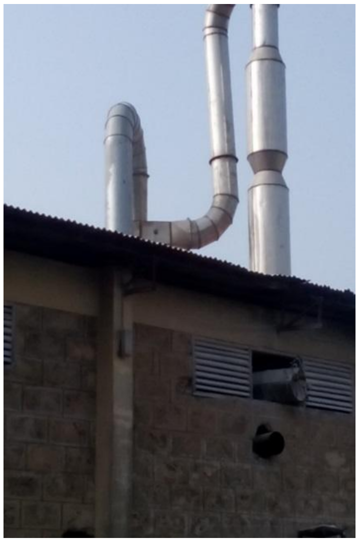

Plate 1b. Positive Single Cyclone System

Plate 1c. Positive Six Cyclone System

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