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Energy and exergy analyses of native cassava starch drying in a tray dryer

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ABSTRACT

Energy and exergy analyses of native cassava starch drying in a tray dryer were carried out to assess the performance of the system in terms of energy utilization, energy utilization ratio, energy efficiency, exergy inflow and outflow, exergy loss and exegetic efficiency. The results indicated that for the starch with ash content of 0.76%, 0.85% crude protein, 0.16% crude fat, negligible amount of fiber, average granule size of 14.1 μm, pH of 5.88, amylose content of 23.45% and degree of crystallinity of 22.34%, energy utilization and energy utilization ratio increased from 1.93 to 5.51 J/s and 0.65 to 0.6 as the drying temperature increased from 40 to 60 °C. Energy efficiency increased from 16.036 to 30.645%, while exergy inflow, outflow and losses increased from 0.399 to 2.686, 0.055 to 0.555 and 0.344 to 2.131 J/s respectively in the above temperature range. Exergetic efficiency increased with increase in both drying air temperature and energy utilization and was lower than energy efficiency. Exergetic improvement potential also increased with increase in drying air temperature. Model equations that could be used to express the energy and exergy parameters as a function of drying temperature were established.

1. Introduction

Nigeria is the World's leading producer of cassava [1–3]. Presently, efforts are geared toward promoting the exportation of the produce and its by-products from Nigeria to other countries. Owing to the poor storability characteristics of the cassava tuber in its fresh or unprocessed state, there is the need to have the product processed into a more storable form in order to minimize deterioration and transportation losses during export. One of the forms in which cassava can easily be stored and transported without deterioration and losses is as dried cassava starch.

Starch is the common name applied to a white, granular or powdery, odorless, and tasteless complex carbohydrate, $(C_6H_{10}O_5)_x$, which is abundantly found in the seeds of cereal plants and in bulbs, roots and tubers. It occurs in commercial quantities in such roots and tubers as cassava, yam and potato and cereal grains such as sorghum, millet and maize. It consists of two types of molecules namely the amylose, which constitutes about 20–30% of ordinary starch, and the amylopectin, which makes up the remaining 70–80%. Starch finds applications as an important raw material in the food, cosmetic, pharmaceutical, chemical and oil industries. It functions as thickening agent in food, water binder, emulsion stabilizer, bulking agent, flow aid, fat substitute and gelling agent. Its other industrial uses include the manufacture of synthetic polymers such as plastics and adhesives. It finds application as molecular sieve and binder, and as surface coating for papers. In drug tablets, starch is used to bind and carry the active components. It acts as viscosity modifier in paints and is used much in the textile industry as stiffener. In the oil industry, it is mixed with pumping water to assist in the cooling of the superheated drilling bits.

Starch is normally extracted from the source material in aqueous medium. It is usually packaged and supplied in granular or powdery form and this makes drying a fundamental unit operation in starch processing.

Drying is a complex process involving heat and mass transfer between the product surface and its surrounding medium [4] which results in the reduction of the product moisture content to a safe storage level or to a level required for the commencement of other processing operations. The role of the dryer is to supply the product with more heat than is available under ambient conditions so as to sufficiently increase the vapor pressure of the moisture held within the product to enhance moisture migration from within the product, provide the latent heat of vaporization of the moisture and

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significantly decrease the relative humidity of the drying air to increase its moisture carrying capability and ensure a sufficiently low equilibrium moisture content [5]. The drying industry utilizes large quantities of energy, making it one of the most energy-intensive industrial operations. High energy inputs in drying operations arise due to the high latent heat of water evaporation and relatively low energy efficiency of industrial dryers [6,7]. Thus, one of the most important challenges of the drying industry is to reduce the energy cost for obtaining good quality dried products [8]. Since energy is a major cost factor, it is essential to perform the energy and exergy analyses of a drying process to provide energy savings and optimum process conditions. According to Singh [9], energy analysis is useful in quantitative evaluation of energy requirements of energy generating and delivery systems and in the detection of mode and evaluation of energy loss. Information obtained from energy analysis can be used for quantifying energy conservation practices.

The first law of thermodynamics which stands for the principle of conservation of energy is commonly used in engineering systems performance analysis. Energy analysis, however, has some deficiencies. Fundamentally, the energy concept is not sensitive to the assumed direction of the process, e.g. energy analysis does not object if heat is considered to be transferred spontaneously in the direction of the increasing temperature [10]. It gives no information about the inability of any thermodynamic process to convert heat into mechanical work with full efficiency [11], nor does it provide any insight into the reason why mixtures cannot spontaneously separate or unmix themselves. It also does not distinguish the quality of the energy, e.g., 1 W of heat equals 1 W of work or electricity. Energy analyses on their own can incorrectly interpret some processes, e.g., environmental air, when isothermally compressed, maintains its energy (enthalpy) equal to zero, whereas the exergy of the compressed air is larger than zero.

Exergy is defined as the amount of work that can be obtained from a stream of matter, heat or work as it comes to equilibrium with a reference environment, and is a measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment [5]. It is the combination of the property of a system and its environment because it depends on the system and its environment. Unlike energy, exergy is not subject to a conservation law; rather it is consumed or destroyed due to irreversibilities in real processes such as drying, with the exergy consumption being proportional to the entropy generation produced by the irreversibilities associated with the process. Exergy analysis is a method that utilizes the conservation of mass and energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems. It is a more useful tool for assessing the efficient use of energy resources [12] as it provides a more realistic view of process, sometimes dramatically different in comparison to standard energy analyses. Dincer [13,14] highlighted the importance of exergy and its essential utilization as follows:

- It is a suitable technique for furthering the goal of more efficient energy resource use for it enables the location, types and true magnitudes of wastes and losses to be determined.
- It is an efficient technique revealing whether or not and by how much it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems.
- It is a primary tool in best addressing the impact of energy resource utilization on environment.
- It is a key component in obtaining sustainable development.

Dincer and Cengel [11], Dincer [5] and Dincer [15] provided excellent treatises on energy and exergy analyses of the drying process.

Several other investigators conducted energy and exergy analyses on the drying of different agricultural and food products using different drying systems. Hepbasli [16] gave out a comprehensive review of the exergy analysis of renewable energy resources and provided two approaches for defining the exergetic efficiency as the brute force and functional approaches. Panwar et al. [17] performed a detailed review of energy and exergy analyses of solar drying systems, Akpinar and Kocyigit [10], Sami et al. [18] and Saidur et al. [19] carried out energy and exergy analysis of different solar drying systems, Prommas et al. [20] conducted energy and exergy analysis of porous media drying using heated air, and Aghbashlo et al. [21] (2013) conducted a thorough review of the exergy analysis of drying processes and systems. Studies on the energy and or exergy analysis of food material drying in different drying systems included solar drying of pistachio [4], pepper, yam slices, water leaf and okra slices in mixed mode solar dryer [22], olive mill waste water [23], mulberry [24], jackfruit leather [25], parsley leaves [26], shelled corn [27], and red sea weed [28]. Others are on fluidized bed drying of wheat [6], potato [29] and eggplant plant [30]drying in cyclone type dryer, drying of red pepper slices [31] and coroba slices [32] in convective type dryer, mint leaves drying in heat pump dryer [33], green olive [34], palsey [35] and olive leaves [36] drying in tray dryer, spray drying of fish oil encapsulation [37], microwave drying of sour pomegranate arils [38]and pasta drying in an industrial dryer [39]. These investigations show that energy efficiency is higher than exergy efficiency. Energy utilization, energy utilization ratio, exergy inflow and outflow, exergy loss, energetic and exergetic efficiencies, all varied with product, drying conditions and type of drying system. Van Gool [40] noted that maximum improvement in the exergy efficiency of a process or system could be achieved when the difference between total exergy output and total exergy input is minimized. Consequently he suggested the concept of exergetic IP (improvement potential) as a useful tool in the analysis of different processes and systems. The rate form as given by Hammond and Stapleton [41] is commonly used in computing improvement potential.

Information on the energy and exergy analyses of starch drying appears to be scanty in the scientific literature. The main objective of this study was to investigate the energetics and exergetics of native cassava starch drying in a tray dryer and establish the variation of the efficiencies with the drying conditions of inlet and out temperatures.

2. Materials and methods

2.1. Starch extraction and characterization

The cassava tubers used for starch extraction were obtained from a farm at the Amina Way in the University of Ibadan, Ibadan, Nigeria. Starch extraction from cassava was carried out at the Industrial Chemistry Laboratory, Department of Chemistry, University of Ibadan, Ibadan.

The cassava tubers were peeled and thoroughly washed in clean water. The peels were discarded and the peeled tubers were crushed in a rasp bar ‘grating’ machine. The resultant pulp was mixed with sufficient amount of water to form slurry. The slurry was sieved with the aid of a muslin cloth and 75 μm mesh size sieve. The fiber was thoroughly washed and discarded. The starch milk obtained was allowed to settle and the supernatant was decanted. The starch was resuspended and washed several times with distilled water to remove the impurities and protein debris. The cassava starch obtained was divided into two portions and utilized as follows:

The first portion was dried in open air and used for proximate composition and pH determination, scanning electron microscopy