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Exergetic analysis of deep-bed drying of rough rice in a convective dryer

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ABSTRACT

This research work was aimed at a detailed exergy analysis of paddy deep-bed drying process in a laboratory-scale convective dryer. The drying experiments were conducted at different inlet drying air temperatures and flow rates, and exergy loss, exergy destruction, exergy efficiency, improvement potential rate and sustainability index were investigated. Normalized exergy destruction of the process ranged from 1.67 to 7.46. Exergy efficiency of the drying process and drying chamber was specified to be in the ranges of 5.10–29.41% and 32.64–67.75%, respectively. The results indicated that applying higher drying air temperatures resulted in higher exergy efficiencies. The obtained improvement potential rates showed that the process is highly capable of ameliorating exergy performance improvement. The sustainability index of drying process ranged from 1.05 to 1.42, augmenting with the increase in the air temperature.

1. Introduction

Generally, safe and long-term storage of fresh agricultural products is particularly difficult since the high water contents affect the physical, chemical, and nutrient quality of the products during the storage period. In this regard, drying process is employed to decrease moisture content of the products to a certain value to improve shelf life, preserve the quality of appearance and nutritional value during postharvest life, and reduce the packing cost [1]. Furthermore, certain agricultural products such as grains must be dried for further postharvest processes [2].

Agricultural and food products are dried using traditional and industrial drying methods. Open sunlight is the main traditional method, still widely used since it is facile and inexpensive. Notwithstanding, sun drying poses some critical problems such as the need for a long drying time and a large space, dust and microbial contamination of the materials, and undesirable effects on the physical and chemical qualities of the dried products [3]. To surmount such obstacles, industrial dryers have been developed and implemented [4]. Even though industrial dryers have a brilliant capacity and offer advantages, there exist some challenges. High latent heat of water evaporation and the relatively low efficiency of the dryers ensuing the consumption of great amounts of energy and raising environmental concerns [5]. Thus, like other energy-intensive industries, the drying industry is searching for energy-saving strategies to achieve the most effective and economic methods [6].

Traditionally, energy analysis via the first law of thermodynamics has been employed to assess and improve the performance of various energy conversion systems. However, energy analysis is not able to provide useful insights on the quality of different energy forms; moreover, the sufficiency of energy concept for sustainable design and/or improvement in the performance of thermal systems has been criticized [7]. Therefore, over the past decades, the exergy concept has been widely applied to provide a more realistic view of a thermal system and overcome the inefficiencies and shortcomings of energy analysis [8,9]. From a thermodynamic point of view, exergy is the maximum work obtainable from a system as it completes the thermodynamic equilibrium with common components and a reference environment through reversible processes [5]. The distinctive capability of exergy to design, optimize and retrofit energy-intensive systems originates from the fact that the approach has unique conceptual features in considering the quantity of energy using both the first and second laws of thermodynamics [10].

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On the other hand, energy consumption has been identified as the most major cause of environmental issues such as water, air and maritime pollution, land use and siting impact, solid waste disposal, acid deposition, stratospheric ozone depletion, and global climate warming. Accordingly, although a myriad studies appeared in the 1970s and 1980s recognizing the link between energy utilization and the environment, exergy and its related issues have been regarded over the past two decades to best address the impact of energy utilization on environment and to result in maximum efficiency in energy use [11]. Since the topics are the serious fundamentals for sustainable growth, exergy further conduces to providing the basis for the development of comprehensive policies for sustainability.

Rosen and Dincer (2001) introduced exergy as the confluence of energy, environment and sustainable development (Fig. 1) [11]. Exergy has also been deemed as the most appropriate link between environmental impact and the second law of thermodynamics [9]. An accurate knowledge of the connection between exergy and environment contributes to observing important patterns and helps better deal with environmental hazards [6]. The relationships between exergy and environmental impact have been categorized into i) order destruction and chaos creation, ii) resource degradation and iii) waste exergy emissions [11]. Moreover, unlike energy, exergy can be destroyed because of internal irreversibilities, hence its analysis can enhance sustainability [12]. The relationship between exergy and sustainability and environmental impact has been illustrated by Rosen and Dincer (2001) (Fig. 2) [11]. As observed, increasing the exergy efficiency of a process reduces the environmental impact while enhancing sustainability.

In the recent years, a growing number of studies have focused on applying exergy concept and its extensions to analyse and optimize different energy systems as far as efficiency and sustainability are concerned (Table 1). In the case of food industry, several works have been conducted to investigate the exergetic performance of dehydration process regarding different agricultural and food products (Table 2).

Despite the new drying methods for agricultural products and foods, convective fixed deep-bed drying is still the most common system practiced in paddy industry. However, hot air dryers ensue certain critical disadvantages such as low energy efficiency and significant losses of thermal energy. Furthermore, based on previous researches, exergy analysis is indubitably a useful tool for improving and optimizing drying processes. As far as we know, there is no articles published on exergy analysis for deep-bed drying of rough rice, hence the main objective of the present study was to perform a complete exergy analysis on deep-bed drying process of paddy at different drying air temperatures and flow rates.

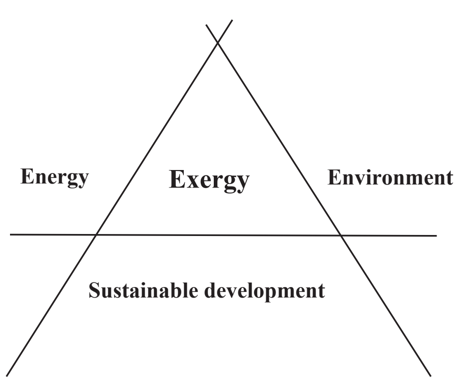

Fig. 1. The interdisciplinary triangle covered by the exergy analysis [11].

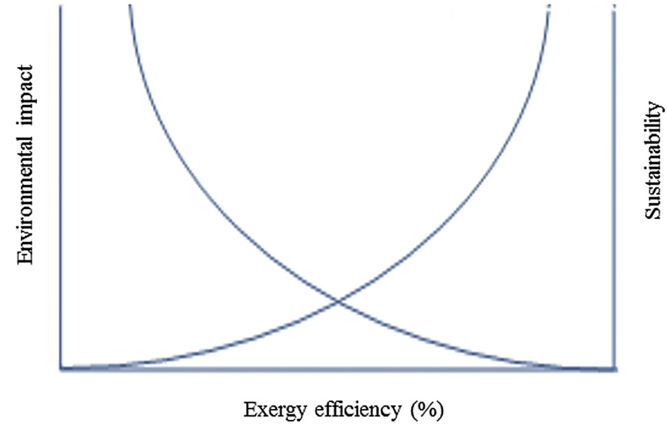

Fig. 2. Qualitative illustration of the relationship between the environmental impact and sustainability of an energy system and its exergy efficiency [11].

2. Material and methods

2.1. Experiments

Fresh rough rice samples were sealed in polyethylene bags to avoid moisture variation due to evaporation, and stored at 4–6 °C until the experiments were conducted. Prior to each drying experiment, the samples were placed in the laboratory for 4 h at room temperature. In order to conduct the experiments, a laboratory-scale dryer capable of controlling and adjusting the drying air temperature, velocity and relative humidity was employed. A schematic view of the dryer set-up is shown in Fig. 3. Drying conditions were selected for different combinations of drying air parameters including temperature (40, 50 and 60 °C) and flow rate (0.5, 0.8 and 1.1 ms^{-1}) at a constant relative humidity level of 40%. In each drying experiment, the dryer was run for at least 40 min to reach a steady state for the set points. The grains was placed in the drying chamber with a uniform height of 20 cm; continuous weighing was further carried out using a digital balance (Sartorius 18100P, Sartorius Co., Germany), and the experiments were continued until the average moisture content of the grains reached about 0.12 $kg_{\text{water}}\ kg^{-1}_{\text{wet matter}}$. A laser sighting infrared thermometer (Testo 860-T3, Germany) was used to measure the surface temperatures of both the outlet sample and the drying chamber. Each set of the experiments replicated three times and the average values were used.

2.2. Experimental uncertainty analysis

During experiments, uncertainties and errors can arise from some factors such as instrument selection, operating condition, data recording, calibration procedure, and reading. In the present study, so as to prove the repeatability and accuracy of the computed parameters, uncertainty analysis was done through the use of the methodology described by Holman [28]:

$$W_F = \left[\left(\frac{\partial F}{\partial y_1} w_1 \right)^2 + \left(\frac{\partial F}{\partial y_2} w_2 \right)^2 + \cdots + \left(\frac{\partial F}{\partial y_n} w_n \right)^2 \right]^{\frac{1}{2}} \quad (1)$$

where, W_F is the uncertainty in the results, $w_1, w_2, \ldots, w_n$ are the uncertainty in the independent variables, $y_1, y_2, \ldots, y_n$ represent the independent variables, and F indicates the function of the independent variables.