Journal of Food Engineering 169 (2016) 238–249

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Thermodynamic analysis of drying process in a diagonal-batch dryer developed for batch uniformity using potato slices

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ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form
3 September 2015
Accepted 6 September 2015
Available online 8 September 2015

Keywords:
Batch dryer
Air distribution
Energy
Exergy
Potato slices

ABSTRACT

Optimized air distribution is important for the energy consumption in a batch drying process. Energy and exergy analyses for an innovative diagonal-batch dryer were performed using potato slices of 5 mm and 8 mm thicknesses at 55 °C and 65 °C. The exergetic efficiency, improvement potential rate (IP) and exergetic factor (f) were taken as performance parameters. The main component for improving the system efficiency was found to be the fan–heater combination, possessing low exergy efficiency, high IP and high f values. The energy utilization, energy utilization ratio, exergy losses and exergy efficiency varied between 1.82 and 12.52 kJ/s, 0.04–0.59, 1.3–4.89 kJ/kg and 0.41–0.94, respectively for potato slices. The specific evaporation energy and specific product energy were found to be in the range of 4.78–6.13 MJ/kg and 16.24–20.63 MJ/kg respectively. The outcomes of the analysis will provide insights into the optimization of a batch dryer for the maximum retention of quality parameters and energy saving.

1. Introduction

Dehydration is an energy intensive unit operation due to high latent heat of water evaporation and the inherent inefficiency of using hot air as drying medium. More than 85% of industrial dryers are of the convective type using hot air or combustion gases as the drying medium (Mujumdar, 2007). Mostly, through-flow or cross-flow type's convective dryers are used for the drying of many fruits and vegetables but a common problem of these food dryers is their high use of energy which is an important parameter in the selection of a drying process (Sagar and Suresh Kumar, 2010).

In context of reducing energy consumption, drying temperature and its uniform distribution is important for the reduction of drying time and maximum retention of product quality in a convective drying process (Krokida et al., 2003; Babalis and Belessiotis, 2004; Araya-Farias and Ratti, 2008). Batch type food dryers are the most extensively applied dryers for the small tonnage products. Temperature distribution is linked with air flow, therefore uniform air distribution over the food trays is required for successful operation both from drying rate and energy consumption points of view. Recently, several studies have been undertaken to overcome the problems of energy consumption and product quality deterioration through the drying uniformity in hot air dryers (Tippayawong et al., 2009; Ehiem et al., 2009; Amanlou and Zomorodian, 2010; Darabi et al., 2013; Roman et al., 2012; Precoppe et al., 2014).

The drying uniformity is always a challenging task and it becomes more difficult for large batch drying systems. Thus, for the industrial batch drying, it is important to reduce the energy consumption along with the quality drying and optimized air distribution plays a vital role for it. In this regard, it is essential to perform an effective thermal analysis of the drying process or system which has designed to provide energy saving and optimum processing conditions (Syahrul et al., 2002). For this purpose, energy analysis, particularly the exergy analysis provide a better understanding of the influence of thermodynamic phenomena on the process, comparison of the importance of different thermodynamic factors, and the determination of the most efficient ways of improving the process under consideration (Sogut et al., 2010).

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http://dx.doi.org/10.1016/j.jfoodeng.2015.09.004
0260-8774/

Nomenclature

T	Temperature (°C)
m	Mass flow rate (kg s^{-1})
ω	Specific humidity (g of water/kg of dry air)
η	Efficiency (%)
ϕ	Relative humidity (%)
h	Enthalpy(kJ kg^{-1})
c_p	Specific heat (kJ kg^{-1} k^{-1})
v	Air velocity (ms^{-1})
W	Energy utilization (kJ s^{-1})
Q	Heat energy (kJ s^{-1})
M	Mass (kg)
E	Electric power supplied (kwh)
SEE	Specific evaporation energy (MJ/kg)
SPE	Specific product energy (MJ/kg)
P	Work rate or power (kJ s^{-1} or Kw)
Ex	Specific exergy (kJ kg^{-1})
Exr	Exergetic rate (kJ s^{-1})
U	Total uncertainty in measurement
f	Exergetic factor (%)
IP	Improvement potential rate (kJ s^{-1})

Subscripts

i	inlet
o	outlet
a	ambient
iw	moisture in inlet air
ew	evaporated moisture
ow	moisture in outflow air
hi, ho	heater inlet and heater outlet
fo	fan outlet
dci	drying chamber inlet
bi, bo	bucket inlet and outlet sides
p	product
t	total
r	rate
k	kth component

Recently, several researchers have reported the thermodynamic analysis of thermal systems but there is a lack of work on the energy and exergy analyses of the drying process in the literature (Akpinar et al., 2005a,b). Some studies were reported conducting energy and exergy analyses to evaluate the tray or batch dryer's performance (Dincer and Sahin, 2004; Midilli and Kucuk, 2003; Akpinar et al., 2006; Colak and Hepbasli, 2007; Corzo et al., 2008). These thermal analyses, especially exergy method provides useful information in the design of the drying system. The outcomes of these analyses mainly vary depending upon the dryer configuration and the product being used. Therefore, dryers with different designs can give different values of energy and exergy analyses for the same product. Thus, the ultimate objective of a modified or new design is to improve the results in the form of less energy consumption and better product quality. Energy and exergy analyses are rarely made for food processes. Detailed literature review has shown that little work has been done on the energetic and exergetic analyses for the hot air batch drying of fruits and vegetables. In case of potatoes, only Akpinar et al. (2005a) worked on the single layer drying process of potatoes via a convective hot-air cyclone type dryer reported by Aghbashlo et al. (2008). So to present more work on the energy and exergy analyses for this product using different drying unit would provide another way to overcome the problems related to energy and exergy throughout the drying process of potato slices.

The above mentioned aspects provide the prima motivation behind performing the thermodynamic analysis of a diagonal-batch dryer developed for spatial drying homogeneity using potatoes as drying material. The objectives of the current study are (1) conducting energy and exergy analyses of single-layer convective drying of potato slices at different drying parameters (drying temperature and sample size) (2) splitting the dryer into components and evaluating the efficiency of the dryer and its components in term of exergetic efficiency, improvement potential rate and exergetic factor (3) comparing the results (energy and exergy analyses) obtained for the system under consideration with that of reported in the literature for hot-air batch drying.

The knowledge gained will provide an understanding of the design performance and help to further reduce the energy consumption by optimization of the drying process.

2. Materials and methods

2.1. Description and operational principle of the dryer

Fig. 1 illustrates the diagonal-batch dryer (11 m × 1.20 m × 1.25 m) that was developed for drying homogeneity. It consisted of three major parts namely: connector, lower half, which also called the heating chamber, and upper half, the drying chamber. The heating chamber was positioned at the bottom of the drying chamber to reduce the space requirement. The heating chamber was comprised on a constant speed axial tube fan (Dia. 0.7 m, 453 m^3/h, 2.2 kW) and an electric water–air heat exchanger. A connector was used to connect the lower half to the upper half of the dryer. In the drying chamber, twenty-five food buckets were arranged diagonally on a railing track (for easy loading and unloading of food buckets). These diagonally arranged buckets gave a shape of diagonal airflow channel at an angle of 1.42° with the wall of the drying chamber in longitudinal direction. That channel acted as inlet for all the food buckets, so the entire food materials get uniform exposure to the drying air. The walls of the dryer were made of polyurethane foam sandwiched into galvanized iron sheets. Two opening doors (0.65 m × 0.36 m) were installed for the loading and unloading of buckets (both sides of the drying chamber). A rectangular passage (0.30 m × 0.15 m) was installed just before the outlet door (0.30 m × 0.15 m) for air recirculation. This passage was opened and closed with the flap of outlet door. The operation of the outlet door (opening/closing time of flap) was controlled based on set temperature. A control panel was used to set temperature and time (three different temperatures can be set for three different intervals of drying time for a drying process).

2.2. Experimental procedure

The experiments were carried out using locally available potatoes (variety: Anuschka). They were washed and sliced of thickness 5 mm and 8 mm using a slicer machine Alexander Solia-M30 SK (1.9 kW). The drying material (150 kg slices/experiment) was loaded in 25 buckets; each had five trays at successive interval of 0.058 m. The area of each tray was 0.206 m^2 and trays were loaded