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Review

Intermittent drying of food products: A critical review

Chandan Kumar, M.A. Karim *, Mohammad U.H. Joardder

School of Chemistry Physics and Mechanical Engineering, Science and Engineering Faculty, Queensland University of Technology, Australia

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ABSTRACT

Drying is very energy intensive process and consumes about 20–25% of the energy used by food processing industry. The energy efficiency of the process and quality of dried product are two key factors in food drying. Global energy crisis and demand for quality dried food further challenge researchers to explore innovative techniques in food drying to address these issues. Intermittent drying is considered one of the promising solutions for improving energy efficiency and product quality without increasing the capital cost of the drier. Intermittent drying has already received much attention. However, a comprehensive review of recent progresses and overall assessment of energy efficiency and product quality in intermittent drying is lacking. The objective of this article is to discuss, analyze and evaluate the recent advances in intermittent drying research with energy efficiency and product quality as standpoint. Current available modelling techniques for intermittent drying are reviewed and their merits and demerits are analyzed. Moreover, intermittent application of ultrasound, infrared (IR) and microwave in combined drying technology have been reviewed and discussed. In this review article the gaps in the current literature are highlighted, some important future scopes for theoretical and experimental studies are identified and the direction of further research is suggested.

Contents

* Corresponding author. Tel.: +61 731386879; fax: +61 731381516.
E-mail addresses: azharul.karim@qut.edu.au, makarim@gmail.com (M.A. Karim).

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1. Introduction

Drying of foodstuffs is an important and the widely used method of food processing (Koyuncu et al., 2007). Due to the lack of proper and timely processing, approximately one third of the global food production is lost annually (Gustavsson et al., 2011). This loss is even more in the developing countries like Bangladesh, where 30–40% of fruits and vegetables are wasted (Karim and Hawlader, 2005a,b). Several techniques have been practiced to reduce food losses and increase shelf life. Among those techniques, drying is one of the oldest, simple and extensively used methods of preserving food.

Drying, however, is probably the most energy intensive process of the major industrial process (Kudra, 2004) and accounts for up to 15% of all industrial energy usage (Chua et al., 2001a). In an energy intensive industry like heating or drying, improving energy efficiency by 1% could result as much as 10% increase in profit (Beedie, 1995). Therefore, any small improvement in energy efficiency in food drying process will lead to a sustainable development to global energy perspective. A considerable amount of research works in improvement of energy efficiency in food drying has been conducted.

Intermittent drying has been considered as one of the most energy efficient drying processes (Chua et al., 2002b, 2003; Kowalski and Pawłowski, 2011a). Intermittent drying is a drying method where drying conditions are changed with time. It can be achieved by varying drying air temperature, humidity, pressure or even mode of heat input. More details about intermittent drying can be found in Section 2. Energy analysis in intermittent drying of yerba mate (Ramallo et al., 2010), squash slice (Pan et al., 1998), grain (Jumah, 1995), kaolin (Kowalski and Pawłowski, 2011b,a) and Ganoderma tsugae (Chin and Law, 2010) demonstrated that intermittent drying is more energy efficient than continuous drying. Various strategies of intermittency in energy input including on–off (Chin and Law, 2010), step-up and step-down (Chua et al., 2002a), square (Chua et al., 2000a; Ho et al., 2002), saw toothed and sinusoidal (Ho et al., 2002) and cosine (Chua et al., 2000a) temperature variation have been applied. These intermittent processes generally showed improvement of energy efficiency when compared with continuous drying.

Quality of dried food is another important issue in food drying. Drying causes changes in the food properties including discoloring, aroma loss, textural changes, nutritive value, and changes in physical appearance and shape (Quirijns, 2006). Condition of drying air has a great effect on quality attributes of dried product. Higher drying temperature reduces the drying time but may result in poor product quality, heat damage to the surface and higher energy consumption (Ho et al., 2002). On the other hand, mild drying conditions with lower temperature may improve the product quality but decrease the drying rate thus drying period is lengthened. Intermittent drying is one of the technical solutions to this because it reduces effective drying time and improve quality of the product (Kowalski and Pawłowski, 2011a). Changes in different quality attributes during intermittent drying of apple (Zhu et al., 2010), yerba mate (Ramallo et al., 2010), Ganoderma tsugae (Chin and Law, 2010), rice (Aquerreta et al., 2007), bananas (Chua et al., 2001a,b; Nishiyama et al., 2006), guava (Chua et al., 2002b; Ho et al., 2002), potato (Chua et al., 2000b), squash slices (Pan et al., 1998) wood and ceramics (Kowalski and Pawłowski, 2011b, 2011, 2011a) have been reported in the literature.

Although studies on intermittent drying processes generally reported improvement in energy efficiency and quality attributes when compared with continuous drying, no critical analysis of these processes and exact comparison of the amount of energy savings and quality improvement have been reported in the literature. A structured critical review is essential for analyzing and evaluating the findings. The objectives of this paper are to discuss, analyze and evaluate the recent advances in intermittent food drying with energy and quality as standpoints. Different types of intermittent drying processes used and energy efficiency and quality improvements reported in the literature are critically reviewed, compared and analyzed. Available models of intermittent drying are also critically reviewed. Finally, a review on intermittent use of alternative energy sources such as microwave and ultrasound is presented and discussed in terms of energy efficiency and product quality. Limitations and research gaps found in the literature are identified and direction of further research on this drying method has been recommended.

2. Intermittent drying

Intermittent drying can be accomplished by controlling the supply of thermal energy, which can be achieved by varying the airflow rate, air temperature, humidity, or operating pressure. One can also vary the mode of energy input (e.g., convection, conduction, radiation, or microwave) to achieve intermittency. The same amount of energy supply throughout the drying process result in quality degradation and heat damage to the surface (Zeki, 2009) and wastage of heat energy. This is because in the later stage of drying, the drying rate decreases as samples do not contain sufficient moisture to be removed. The surface of samples becomes dry towards the later stages of drying and constant use of high temperature air causes quality degradation and damage to the surface. The strategy of using intermittency allows time to transfer the moisture from the center to the surface of the sample during tempering period. Therefore, the quality degradation and heat damage can be minimized by applying intermittent drying.

As mentioned earlier, intermittency can be achieved in many ways. A simplified classification of the types of intermittency based on literature review is outlined in Fig. 1. In this figure, the upper part shows variables that can be changed and lower part shows different modes of applying these variables in achieving different forms of intermittency. The most common form of intermittent drying that studied by previous researchers are the intermittency achieved by changing drying air conditions (Chin and Law, 2010; Chua et al., 2002a, 2000a; Ho et al., 2002). In recent years, intermittency of heat input in combined drying methods e.g., use of microwave, radiofrequency (Ahrné et al., 2007; Botha et al., 2012; Esturk, 2012; Esturk et al., 2011; Soysal et al., 2009b) and ultrasound (Schössler et al., 2012) together with convective heat have been applied.

Different types of intermittency affect product quality and energy efficiency in their own way. Therefore, the intermittency should not be chosen arbitrarily, rather it has to be selected based on the physics involved in the drying method. Otherwise, expected optimum energy efficiency and product quality improvement will remain unattainable. Intermittency should be selected based on heat and mass transfer involved in the particular drying process and material properties of the product to be dried. The recent research on different intermittency and its effect on energy efficiency and quality parameters are discussed in the following sections.

3. Energy aspect in intermittent drying

Intermittent drying decreases the effective drying time and drying air utilization thus it reduces energy consumption (Putranto et al., 2011). Reduction in energy consumption by intermittent drying in different intermittency strategies has been reported in several studies. The most common type of intermittency investigated