Journal of Food Engineering 121 (2014) 48–57

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Review

Intermittent drying of food products: A critical review

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ARTICLE INFO

Article history:
Received 17 December 2012
Received in revised form 18 April 2013
Accepted 6 August 2013
Available online 19 August 2013

Keywords:
Energy
Quality
Modelling
Microwave
Ultrasound

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

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0260-8774/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2013.08.014

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

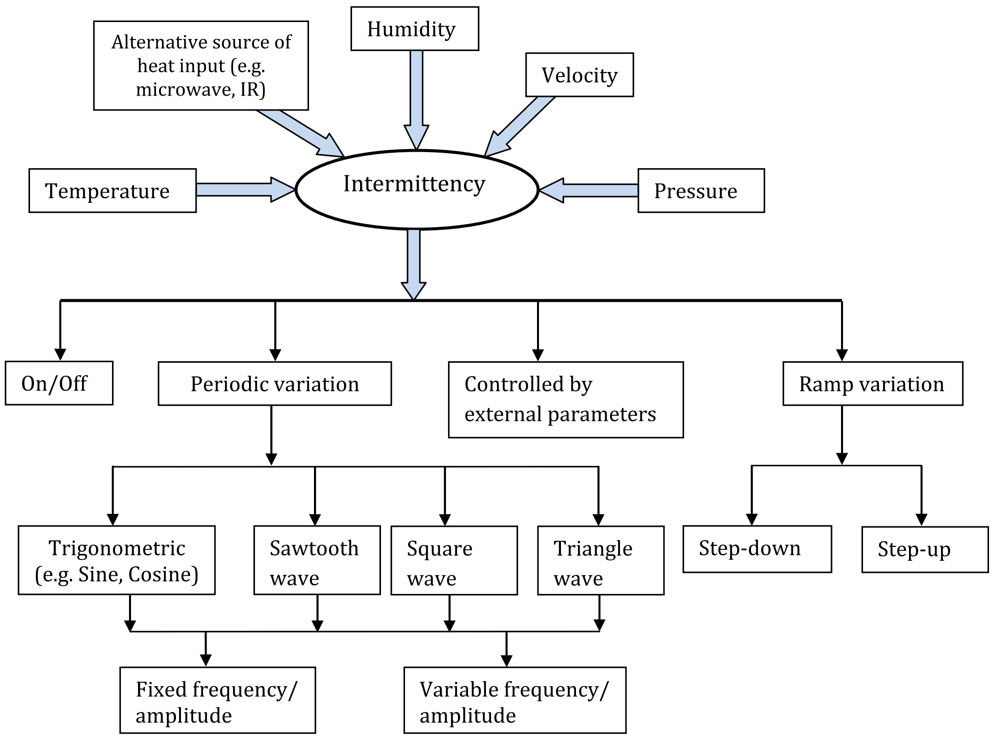

Fig. 1. A general classification scheme for intermittent drying.

Table 1
Energy savings by intermittent drying for different intermittency (α).

Reference	Drying Period τ_{on}, (min)	Intermittency α	Energy saving over continuous drying (%)	Drying air temp and final moisture content	Product
Jumah (1995)	Continuous	0	–	80 °C	Grain
	20	0.33	19	13%db	
	20	0.50	23		
	20	0.67	30		
	20	0.75	37		
Pan et al. (1998)	40	0.88	36	100 °C 14.7%db	Squash slice
Yang et al. (2013)	Continuous	0	–	40 °C	Chinese cabbage
	400	0.50	31	6%db	
	400	0.67	48.1		
	800	0.33	24.4		
Chin and Law (2010)	Continuous	0	–	28.4 °C	Ganoderma tsugae
	60	0.67	40	11.5%db	
	60	0.80	43		
	120	0.33	13		
	Continuous	0	–	40.6 °C	
	60	0.67	52	8%db	
	60	0.80	52		
	120	0.33	21		

so far is on/off strategy, where heat source is periodically turned on and turned off. A comparison of energy savings by on/off intermittency reported by researchers is presented in Table 1. In order to facilitate proper comparison, the authors have transformed the energy savings in a common term. In this paper, intermittency ratio, α is defined as the ratio of tempering time (off time) to total drying time, i.e., $\alpha = \tau_{off}/(\tau_{on} + \tau_{off})$ where τ_{on} and τ_{off} are the on and off period of each cycle, respectively. So, $\alpha = 0$ refers to continuous drying and higher intermittency (α) refers higher tempering period. Jumah (1995) investigated the energy saving applying different intermittency (α) in grain drying in a novel rotating jet spouted bed. This investigation provided a reliable estimation of energy savings as it used same drying conditions and drying period for all intermittencies investigated. The most notable finding of this study was that the higher the intermittency (higher tempering period) the higher energy savings. For example, energy savings were 19%, 23% and 30% for tempering periods 10 min ($\alpha = 0.33$), 20 min ($\alpha = 0.50$) and 40 min ($\alpha = 0.67$) respectively. The maximum energy saving of 37% was attained for 60 min tempering periods ($\alpha = 0.75$) in their study. Increasing intermittency, α, beyond 0.75 would increase the energy savings but total drying time would be significantly longer. Longer total drying time may not be suitable to some products. Longer tempering period may also cause rehydration and quality degradation. Therefore, the value of intermittency should be carefully selected in order to get optimum energy savings. Similar trends of energy saving with intermittency was obtained by Chin and Law (2010) and Yang et al. (2013). Chin and Law (2010) studied the effect of intermittency on quality and drying kinetics of Ganoderma tsugae. Compiled data from Chin and Law's (2010) study, as presented in Table 1, demonstrates the impact of drying air temperature for same intermittency. It was observed that, for the same intermittency (e.g. $\alpha = 0.33$) energy saving was increased from 14% to 21% as drying air temperature was increased from 28.4 °C to 40.6 °C.

Pan et al. (1998) studied continuous and intermittent drying of squash slice at 100 °C in a vibrated fluidized bed dryer. They found that after 95 min of continuous drying moisture content was reduced to 14.75% (wb). On the other hand, if the squash slices were tempered in ambient air after 40 min of drying, it took only 60 min of effective drying time to reach the same moisture content. Thus effective drying time was reduced by 35 min in the intermittent drying. Overall, the results presented in Table 1 demonstrate that significant energy savings and effective drying time reduction can be achieved by applying intermittency. This is because intermittency allows necessary time to accumulate moisture in the surface to be removed, which causes subsequent increase in drying rate.

Another great advantage of intermittent drying is the moisture leveling or moisture uniformity in the samples. Experimental investigation of Olive cake drying has shown that, providing longer tempering period resulted in more moisture leveling, higher initial moisture removal in each active drying period, and the most effective energy utilization as a consequence (Jumah et al., 2007).

Instead of applying intermittency throughout the drying period, only one or two tempering periods have also been investigated. Very recently, Holowaty et al. (2012) determined the reduction in energy consumption during drying of yerba mate branches when one or two tempering periods were applied. Their results showed that drying with one and two tempering periods can save drying time of 15 min and 30 min respectively to achieve same moisture content. They reported an energy savings of 10% with the application of a tempering period of 15 min after 15 min of drying in their experiments. Although applying only one or two tempering period results lower energy savings compared to applying intermittency entire drying period, this strategy significantly decreases the total drying time which may be useful for some products.

Cyclic or ramp variation of drying air temperature, humidity and heat input (microwave, infrared) have been investigated to improve energy efficiency. Cyclic variation of temperature and humidity for drying of kaolin sample was investigated by Kowalski and Pawłowski (2011a,b). According to their study total energy consumption was 1.15kWh for variable temperature compared to 1.5 kW h for the constant temperature drying condition. However in case of variable humidity, energy consumption was 3.30 kW h which was significantly higher as huge amount of energy was consumed by the dehumidifier. There are some theoretical studies in food drying with cyclic variation of temperature (Chua et al., 2002a; Ho et al., 2002). They presented intermittent drying models and quality changes in dried products but have not investigated the energy or drying time savings by applying those intermittencies. Moreover, the drying air temperature was different for various intermittency tests. Therefore, proper comparison of energy savings for those studies was not possible.

Intermittency controlled by other criteria in drying was also investigated in some optimization studies. The optimization of intermittent drying was studied by Váquiro et al. (2009), where enthalpy gain was taken as objective function. They found that in the optimized conditions, effective drying time was reduced by 11% as compared to continuous drying. Intermittency controlled by surface temperature is another option to avoid unwanted quality degradation in products. Gunasekaran and Yang (2007) used intermittent microwave power controlled by the surface temperature of the product in the optimization study of mashed potato drying. Microwave power source was turned off when the product temperature reached a set value. This technique could be helpful for avoiding charring or heat damage to the product.

In the above review, it has been demonstrated that energy savings can be increased by increasing the intermittency in on/off strategy of intermittency. But higher intermittency lengthens the total drying time and therefore intermittency needs to be optimized. Although all the above studies reported higher energy efficiency in intermittent drying, it is difficult to make an exact comparison of energy savings for all these studies as different drying conditions and dryers were used with various intermittencies. For better comparison, the investigations should be done at same drying condition for different intermittencies. Then it would be possible to identify which intermittency is better compared to others. Although the effective drying time in intermittent drying is considerably reduced, the total drying time is, however, prolonged for each process. Higher energy efficiency and product quality improvement generally trade off this extended drying time. Optimization of intermittency is necessary to reduce total drying time, improve energy efficiency and product quality.

4. Quality aspects in intermittent drying

Quality changes in food product is inevitable during the drying process. During the past decade, many advances in drying technologies have been practiced with the goal of minimizing degradation of various quality attributes of dried food products. Intermittent drying is considered one of the effective methods to achieve that objective. Many theoretical and experimental investigations have been done to improve different quality attributes by applying intermittent drying. This section reviews studies that investigated the quality attributes in intermittent drying. Table 2 below lists such studies and presents a summary of quality attributes investigated in the literature for intermittent drying. It is apparent from the table that color is the most frequently investigated parameter in intermittent drying. The following sections provide detail analysis of the quality attributes investigated.

4.1. Nutritional quality

4.1.1. Ascorbic acid and non-enzymatic browning

Ascorbic acid (Vitamin C) is one of the main quality attributes of most fruits. It is generally observed that, if ascorbic acid is well retained, other components are also well retained. Hence, ascorbic acid can be taken as an index of the nutrient quality of foods (Marfil et al., 2008). High retention of ascorbic acid in dried products is highly desired. Recent investigations have examined the effects of intermittent drying on ascorbic acid degradation. Ho et al. (2002) investigated the improvement in ascorbic acid (AA) degradation in potato samples at different time varying drying condition. Table 3 shows the effect of time dependent temperature profile on AA and non-enzymatic browning compared to continuous drying. For continuous drying, air temperature was 35 °C and drying time was 240 min. It is evident from Table 3 that the reduction in AA loss is more prominent in square wave variation with lower mean temperature. Square wave profile with mean temperatures 25 °C and 30 °C reduce the AA loss by 33% and 25% respectively.

Chua et al. (2000a) have experimentally investigated the effect of temperature variation in ascorbic acid of guava and have found that 20% improvement in ascorbic acid retention in guava pieces was obtained with proper selection of intermittent drying compared to those of dried under isothermal conditions. However, it is important to note that the extent of AA retention is highly product dependent. For example, for a product with higher AA content

Table 2
Quality attributes investigated in intermittent drying.

Reference	Quality attributes	Material
Kowalski and Pawłowski (2011b, 2011, 2011a)	Cracking	Wood and ceramics
Zhu et al. (2010)	Non-enzymatic browning	Apple
Ramallo et al. (2010)	Color, sugar and caffeine contents	Yerba mate
Chin and Law (2010)	Color	Ganoderma tsugae
Aquerreta et al. (2007)	Fissuring	Rice
Nishiyama et al. (2006)	Sugar content	Bananas
Ho et al. (2002)	Ascorbic acid and color	Banana and guava
Chua et al. (2002b)	Color	Banana and guava
Chua et al. (2001b)	Color	Banana
Chua et al. (2001a)	Color	Banana
Chua et al. (2000b)	Color	Banana, guava and potato
Chua et al. (2000a)	Ascorbic acid (AA)	Guava
Pan et al. (1998)	Beta-carotene, appearance and rehydration	Squash slices

Table 3
Effect of time dependent temperature profiles on AA content degradation and non-enzymatic browning.

Drying profile	Improvement in AA retention (%)	Reduction in non-enzymatic browning (%)
Saw-tooth at 30 °C	7.5	34.2
Sinusoidal at 30 °C	15.2	51.8
Square wave at 25 °C	33.0	75.6
Square wave at 30 °C	25.7	44.4

may result more improvement in AA retention by applying intermittent drying. Non-enzymatic browning was investigated for the same experimental condition by Ho et al. (2002). Drying profiles also affect non-enzymatic browning similarly as AA. It can be observed from the Table 3 that after 240 min of drying of potato, percentage in ascorbic acid degradation and non-enzymatic browning could be minimized up to 33% and 75.6% respectively by implementing square wave intermittency at 25 °C instead of 35 °C constant drying condition.

4.1.2. Beta carotene

Beta carotene is another important nutrient for fruits, vegetable and grains. It is the main compound of diabetes medicament. Pan et al. (1998) studied the effect of intermittent drying on beta carotene degradation of squash slice. Their study showed that 87.2% of beta carotene in squash is preserved in intermittent drying while it was only 61.5% in conventional continuous drying. So, improvement of beta carotene retention is 41.78% which is much higher compared to ascorbic acid (33%) discussed previously. They developed degradation kinetics and predicted beta carotene loss considering first order reaction kinetics. The predicted data agreed with the experimental data within ±10%. No other studies investigated beta carotene in intermittent drying. Therefore, more studies needs to be conducted to investigate this for other products.

4.1.3. Sugar and caffeine content

Sugar and caffeine content is important properties for many products such as yerba mate, coffee etc. Application of tempering in drying of Yerba mate, a very popular tea, was investigated by Ramallo et al. (2010). They found that, loss of caffeine content was 10% in intermittent drying whereas it was about 30% in continuous drying (Schmalko et al., 2007). Conversely, sugar content was not influenced by tempering. Perhaps this is because caffeine content is more sensitive than sugar content when exposed to higher temperatures or temperature needs to be elevated at a certain level to remove the sugar. Some continuous drying studies also reported no changes in sugar concentration during drying (Borompichaichartkul et al., 2009; Correia et al., 2009). This is an interesting finding. However, further investigation is necessary to explore whether intermittent drying has any impact on sugar content of food items.

4.2. Color

The color of food is one of the key factors behind consumers' decision of buying a particular food. The color changes during intermittent drying was investigated for different food products such as, banana (Chua et al., 2001b), guava (Chua et al., 2002b; Ho et al., 2002), potato (Chua et al., 2000b), and Ganoderma tsugae (Chin and Law, 2010). Effect of drying methods (Chin and Law, 2010) and types of intermittency, for instance, step-up and step-down temperatures (Chua et al., 2001b); cosine and reverse cosine (Chua et al., 2000b) have been investigated. Total color changes (ΔE) can be measured by the following equation:

$$\Delta E = \Delta L^2 + \Delta a^2 + \Delta b^2 \quad (1)$$

where L represents lightness, a represents redness or greenness while b represents blueness or yellowness values and Δ represents changes in each value.

Various drying air conditions affect the color change differently. Chua et al. (2001b) studied stepwise varying drying condition on banana pieces in two stage heat pump drier and observed that time-varying drying air temperature in batch drying of banana slices had a favorable impact on drying kinetics as well as the color of the dried products. They observed that color degradation was reduced by 40% and 23% for step-up and step-down mode of drying respectively in the temperature range between 20 °C and 35 °C. A significant difference in the overall color change of the banana samples dried under step-wise temperature variation when compared with samples under constant temperature drying was reported by (Chua et al., 2002b). Both step-up and step-down temperature variation showed improvement in color changes compared to continuous drying. When a comparison was made between step-up and step-down air temperature profiles, the step-up profile was observed to be more effective in reducing net color degradation for both studies. Whereas step-down profile is more effective than step-up when dryingkinetics is considered.

Effect of various temperature profiles on color parameters for different product was investigated by Chua et al. (2000b). Changes in lightness (ΔL), redness (Δa), yellowness (Δb) and overall color (ΔE) for banana, guava and potato were observed. From their observation, it is clear that the changes of color components for various products do not follow a particular pattern. For instance, lightness (ΔL) changes significantly during drying of potato and guava. Whereas yellowness (Δb) was the major contributors in color change during drying of banana. However, they have shown that applying variable temperature drying condition reduced the color change of potato, guava and banana by 87%, 75% and 67%, respectively. Potato sample was less susceptible to color change because of their low sugar and high moisture content relative to the banana and guava sample samples. Because of their reduced sugar content and high water content, the Maillard reaction was reduced as this reaction requires dehydration of sugar molecules. Their results are consistent with earlier research by Labuza et al. (1972) and Wolfrom et al. (1974) about color inhibition by increasing the water content.

Table 4
Color parameters of intermittent heat pump–dried Ganoderma tsugae for different intermittencies.

Drying period	Intermittency, α	Color components			(ΔE)	Drying temp. (°C)
		L	*a*	*b*		
Continuous	0	17.07 ± 1.41	4.51 ± 0.10	36.80 ± 0.9	15.54 ± 3.10	28.4
60	0.67	18.12 ± 0.28	6.03 ± 0.67	34.19 ± 5.91	9.30 ± 4.80	
60	0.80	14.02 ± 0.96	8.19 ± 1.19	51.77 ± 1.65	10.88 ± 1.96	
120	0.33	19.75 ± 0.66	5.54 ± 0.74	25.83 ± 0.47	12.72 ± 0.49	
Continuous	0	16.56 ± 1.03	4.53 ± 0.83	27.80 ± 1.63	27.32 ± 1.78	40.6
60	0.67	15.97 ± 1.64	3.97 ± 1.01	29.73 ± 5.13	24.18 ± 5.83	
60	0.80	13.16 ± 0.29	8.30 ± 2.07	50.29 ± 0.50	12.52 ± 0.87	
120	0.33	17.09 ± 1.24	3.96 ± 0.94	21.57 ± 1.54	25.18 ± 5.02	

Color component and overall color change with different intermittency was reported by Chin and Law (2010). Table 4 represents color parameters and overall color of intermittent heat pump-dried Ganoderma tsugae for different intermittency strategies. Their experimental results showed that, intermittent heat pump drying of Ganoderma tsugae at 28.4 °C reduces the overall color change up to 40% for $\alpha = 0.67$ when compared to continuous heat pump dried products. The reduction of total color change is more prominent for intermittent heat pump–dried product at a drying temperature of 40.6 °C, which is up to 54.17% at $\alpha = 0.8$.

All the intermittent drying presented in Table 4 show improvement in color change. However, an appropriate intermittency and drying conditions should be chosen based on energy efficiency of the process and expected quality of the dried product. So there is an opportunity to introduce an optimization scheme between reduction in color change versus achieving higher drying rate.

4.3. Physical changes

Effect of intermittent drying on other physical changes like cracking (Kowalski and Pawłowski, 2011b; 2011, 2011a) and rehydration characteristics (Pan et al., 1998) have been investigated experimentally. Cracking is an important issue for wood and clay drying. Apart from visual inspection, the acoustic emission method was applied by Kowalski and Pawłowski (2011) to monitor the micro and macro cracks developed during drying of clay and wood samples. They concluded that changing drying condition at the right moment can avoid fracture and therefore good quality of product can be obtained. They compared the crack intensity under constant temperature, variable temperature and variable humidity conditions. They found that the best quality samples were obtained with variable humidity and lowest energy consumption was obtained with variable air temperature drying condition. However, humidity variation strategy consumes more energy because of the energy consumption by the dehumidifier. Therefore, energy consumption must be considered carefully in choosing variable humidity drying condition. Although the variable humidity drying condition gave better quality kaolin samples, this process has not been tested for food product yet. Probably this will give better structural attributes for food but may increase the energy consumption of the process.

Other physical characteristics, for example, rehydration ability of squash (Pan et al., 1998) and fissuring of rice kernel (Aquerreta et al., 2007) have found to be improved by incorporating intermittent drying. The Rehydration ability of the product gained by intermittent drying is higher when compared to continues drying (Pan et al., 1998). Aquerreta et al. (2007) showed that percentage of fissured kernels was drastically reduced when drying was performed in two or three steps compared to drying in one step. Thus the physical properties of a product can be improved by intermittent drying. However, the authors of these studies did not properly explain the mechanism of how physical properties were improved in intermittent drying. These improvements, possibly can be attributed to the temperature and moisture redistribution during tempering period. Because tempering helps to reduce temperature and moisture gradient and thus the internal stresses. There is enormous opportunity to investigate the effect of intermittency to other important physical properties such as, texture, structure for different food product.

5. Modelling of intermittent drying

Modelling is necessary for evaluating the effect of process parameters and optimizing drying process (Kumar et al., 2012a). The dehydration of foodstuffs is a very complex process because of its complexity in internal structure and behavior during drying. Complexity further increases if any form of intermittency is introduced. Therefore, it is very difficult to represent the exact conditions mathematically during drying. Some assumptions are obvious to develop mathematical models. Developing a reasonably good drying model for agricultural products is a challenging task. Although modelling with time varying drying air condition is challenging (Putranto et al., 2011), several drying models have been proposed to describe the intermittent drying (Baini and Langrish, 2007; Chou et al., 2000; Chua et al., 2003; Ho et al., 2002; Jumah and Mujumdar, 2005; Jurnah et al., 1996; Nishiyama et al., 2006). These models can be categories as empirical and fundamental models.

5.1. Empirical models

Empirical models are simpler to apply and often used to describe the drying curve. These models are generally derived from Newton's law of cooling and Fick's law of diffusions (Erbay and Icier, 2010). List of the empirical models used to describe drying kinetics can be found in Sutar and Thorat, 2011 and Baini and Langarish (2007). The page model (Page, 1949) is most commonly used in drying and described by Eq. (2) shown below:

$$MR = \exp(-kt^n) \tag{2}$$

where MR is the moisture ratio defined as $MR = \frac{M_t - M_e}{M_o - M_e}$, and M_t is the moisture content at time t, M_e is equilibrium moisture content and M_0 is initial moisture content and n is model constants (dimensionless) and k is the drying constants (s^{-1}). Page model was employed by Holowaty et al. (2012), Ramallo et al. (2010) and Zhu et al. (2010) to predict moisture variation during intermittent drying. Holowaty et al. (2012) and Ramallo et al. (2010) observed that, the process conditions did not affect the values of 'n' whereas values of 'k' increase with drying temperature. Zhu et al. (2010) regressed the empirical coefficients (k and n) of page model with processing variables (slice thickness and surface temperature). Their model demonstrated good predictability with a strong correlation between predicted and experimental values.

Intermittent drying is highly nonlinear, strongly interactive, multivariable and time varying process (Jumah and Mujumdar, 2005). Hence the traditional empirical models cannot accurately predict the moisture content during the tempering period (Baini and Langrish, 2007). In that case, artificial neural network (ANN) based model can be used to simulate intermittent drying. Artificial neural network and Fuzzy Interface System (FIS) are proved to be more efficient to model complex and ill-defined process like drying (Jumah and Mujumdar, 2005). Jumah and Mujumdar (2005) developed hybrid neuro-fuzzy system called adaptive-network-based fuzzy inference system (ANFIS) for intermittent drying. The results of their study suggest that an adaptive neuro-fuzzy approach is perfectly suitable for intermittent drying operations. Moreover, ANN model can learn from the successive experiments and in this way user can improve the model (Chen et al., 2001). However, all the empirical models are only applicable in the range of experimental parameters. In addition they are not able to capture the physics during drying. In contrast to empirical model, the fundamental models can capture the physics during drying well (Chou et al., 2000; Chua et al., 2003; Ho et al., 2002).

5.2. Fundamental models

Fundamental mathematical modelling is acceptable for a wide range of application and optimization (Kumar et al., 2012b). Developing a fundamental intermittent drying model is difficult because the parameters needed to model are different from that of continuous drying. Despite this difficulty, many researchers developed intermittent drying model based on some assumptions. For clearer understanding, discussions on fundamental mathematical models for intermittent drying are divided into two parts (1) single phase (moisture) model and (2) double phase (moisture and vapor) model.

5.2.1. Single phase model

Nishiyama et al. (2006) developed moisture transfer model for intermittent drying. They considered mass transfer coefficient and drying constant for tempering period as equivalent to the value that obtained from continuous drying at corresponding temperature. They also assumed that there was no mass transfer at the surrounding during tempering period. But in reality there would be some mass transfer to the air during tempering period. Kowalski and Pawłowski (2010) incorporated intermittency in their model while calculating the partial pressure. In their model, partial pressure is considered as a function of drying air temperature and tempering temperature for continuous and intermittent drying respectively. Change in relative humidity due to change in drying air temperature was also taken into account in their model. Time varying drying air temperature or humidity can also be incorporated during calculation of equilibrium activation energy calculation (Putranto et al., 2011). Putranto et al. (2011) implemented Reaction Engineering Approach (REA) to model intermittent drying under time-varying drying air temperature and humidity. The REA is an application of chemical reaction engineering principles to model drying kinetics (Chen, 2008). They validated their model by comparing drying kinetics investigated by Kowalski and Pawłowski (2010) as shown in Figs. 2 and 3. Both models showed good agreement with experimental results. Recently COMSOL Multiphysics, an engineering modelling and simulation software, is being used to model real world problems. Váquiro et al. (2009) modelled intermittent drying of mango and optimized taking enthalpy as objective function using Comsol Multiphysics.

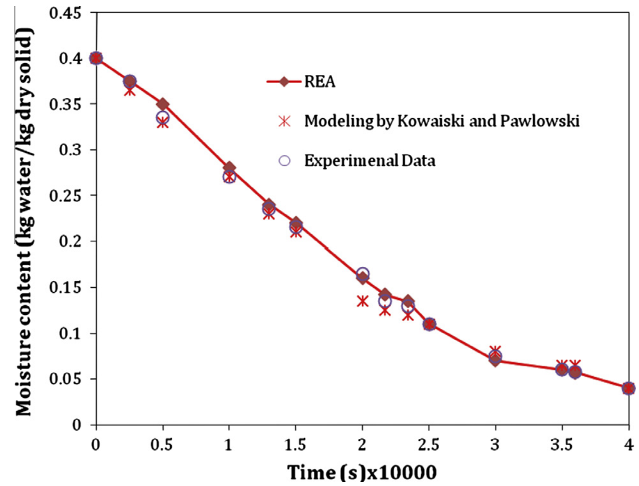

Fig. 2. Moisture content profile of intermittent drying for periodically changed drying air temperature between 65 and 43 °C (Kowalski and Pawłowski, 2010).

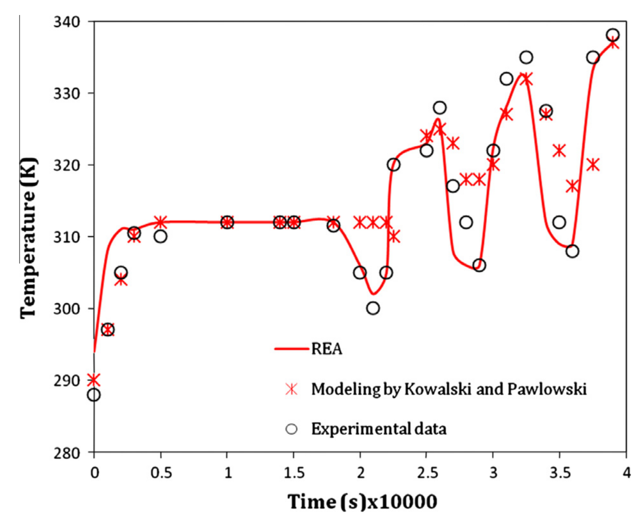

Fig. 3. Temperature profile of intermittent drying for periodically changed drying air temperature between 65 and 43 °C (Kowalski and Pawłowski, 2010).

5.2.2. Double phase model

Both liquid and vapor phases were considered in several models developed by Ho et al. (2002), Chua et al. (2002, 2002a) and Chou et al.(2000) for intermittent drying. Liquid and vapor flux was modelled considering Darcy's law and Fick's law respectively. The intermittency was incorporated considering temperature dependent properties in their model.

However, shrinkage has not been considered in those models discussed above. Ratti and Mujumdar (1993) developed mathematical model of shrinking hygroscopic porous material drying for time varying drying condition. The detail equation and expression can be found at (Ratti, 1991). The important assumptions in that model included one dimensional heat and mass transfer and shrinking food material. The shrinkage parameter (area/volume) was obtained through some empirical correlation as described by Ratti (1991).

However, most of the available mathematical models for intermittent drying may not represent the actual phenomena as mass transfer during tempering period is neglected in these studies. Moreover, the temperature and moisture redistribution during tempering period have been overlooked. Therefore, more rigorous and coupled heat and mass transfer model has to be developed for intermittent drying. Since it is difficult to measure the moisture and temperature distribution inside the food experimentally, the models should be able to predict the temperature and moisture distribution inside the material. Temperature and moisture redistribution take place during intermittent drying, which contribute to improvement in energy efficiency and product quality. The highest level of energy efficiency and product quality could be achieved if the model could recommend an appropriate intermittency based on temperature and moisture redistribution. The model should be simple, accurate and robust and should be able to capture the physics and require shorter computational time. That will help to improve the understanding of the underlying mechanism and develop better strategies for the control of intermittent drying process.

6. Intermittent application of different energy sources

In recent years new technologies in drying have been introduced. Combination of convective drying with intermittent application of ultrasound, infrared, and microwave have been investigated by some researchers.

6.1. Intermittent application of ultrasound and infrared heating

Schössler et al. (2012) studied the effect of ultrasound on the mass transfer and the moisture removal from red bell pepper and apple cubes and evaluated the potential of reducing the energy consumption in ultrasound assisted convective drying. They showed that ultrasound treatment resulted in improved drying characteristics of both products. A comparison between continuous and intermittent ultrasound application showed that intermittent application of ultrasound reduces the net sonication time by 50% in apple drying. The successful application of intermittent ultrasound is an important development for minimizing the energy consumption in drying. Their study can be considered as the basis for a successful integration of ultrasound-assisted processes for industrial drying of food products. Further investigation should be conducted to minimize energy consumption and improve product quality of the ultrasonic system. Zhu et al. (2010) investigated dehydration characteristics of apple slice exposed to simultaneous infrared dry-blanching and dehydration (SIRDBD) with intermittent heating. The technology utilizes catalytic infrared (CIR) energy and can be operated in both continuous and intermittent heating modes. They observe that intermittent heating mode can reduce color degradation whereas continuous heating cause severe color degradation (Zhu and Pan, 2009).

6.2. Intermittent microwave assisted convective drying (IMWC)

Intermittent application of microwave with other drying methods can significantly improve the diffusion rate by creating internal heat generation inside the food material. Microwave penetrates the material until moisture is located and heats up the material volumetrically by dipolar rotation of water molecule and thus facilitates the higher diffusion rate and pressure gradient to drive off the moisture from inside the material (Turner and Jolly, 1991). Thus application of microwave can significantly reduce the drying time supplying sufficient moisture to the surface and reduce the tempering time thus reducing energy consumption. The advantages of intermittent microwave convective drying in terms of energy efficiency and dried product quality have been reported in few studies. For instance, Soysal et al. (2009a) reported that intermittent microwave-convective drying of red pepper produced better sensory attributes, appearance, color, texture and overall liking, than continuous microwave-convective drying and commercial drying.

Soysal et al. (2009b) investigated intermittent microwave-convective air drying (IMWC) and the results were compared to continuous microwave-convective air drying (CMWC) and continuous convective air drying for oregano. They observed that IMWC is 4.7–11.2 times more energy efficient compared to convective drying. The drying time of the convective air drying was about 4.7–17.3 and 12.7–14.0 times longer when compared with the IMWC and CMWC respectively. They concluded that IMWC at 25 °C room temperature with the pulse ratio of 5.0 (15 s on 60 s off) was judged as the most suitable drying method for oregano in terms of essential oil content and quality. Ahrné et al. (2007) compared microwave drying under constant and variable microwave power for banana as a heat sensitive food product and reported drying at variable microwave power as more suitable drying process. They also mentioned that variable microwave can reduce charring of the product. Variable power programs for microwave assisted air drying of osmotically treated pineapple were studied by Botha et al. (2012). They reported that the use of variable microwave power combined with low air temperatures can result in a fast drying process without significant charring of pineapple pieces. Table 5 presents recent research studies on intermittent application of microwave drying for different food materials and investigated quality attributes.

Although all these studies demonstrate quality improvement in intermittent microwave application, there is still lack of theoretical studies. Appropriate theoretical model to describe temperature and moisture distribution and the heat and mass transfer process during intermittent microwave convective drying has to be developed for better strategy for applying this intermittency.

7. Discussion

Energy efficiency of the process and quality of the product are two major concerns in food drying. Both of them are positively influenced by intermittent drying. Appropriate drying scheme would lead to improved quality of the product and energy efficiency of the process. A particular intermittent drying scheme could be more appropriate for a specific product in order to minimize the effective drying time depending on the heat and transfer characteristics of the product Combination of different intermittency strategies, for example, square wave in the first half of drying and step down in the later half, have not been investigated yet. This type of study could further increase in energy efficiency and product quality in intermittent drying. Modelling and simulation study can help to choose better intermittency scheme for intermittent drying. Heat and mass transfer characteristics can only be investigated by appropriate theoretical models. However, there is a lack of rigorous mathematical model for intermittent drying.

Table 5
Recent studies on intermittent microwave convective drying of food materials.

Reference	Material	Quality attributes investigated
Esturk (2012) and Esturk et al. (2011)	Sage (*Salvia officinalis*)	Color and oil content
Botha et al. (2012)	Pineapple	Charring
Esturk and Soysal (2010)	Dill (*Anethum graveolens* L.)	Color and sensory quality
Soysal et al. (2009b)	Oregano	Color, oil contents
Soysal et al. (2009a)	Red pepper	Color and texture
Ahrné et al. (2007)	Bananas (*Cavendish variety*)	Charring
Orsat et al. (2007)	Carrots, mushrooms	Rehydration ratio
Gunasekaran and Yang (2007)	Mashed potato	N/A

Various quality attributes are investigated in intermittent drying and it is found that, negligible degradation of quality attributes could be achieved by strategic application of intermittency. Intermittent microwave convective drying is an attractive option of intermittent drying as both total drying time and effective drying time can be reduced in this drying method. This drying method achieves better energy efficiency and quality improvement. However, much uncertainty still exists about the relations among different power level, power ratio, and initiation time of microwave heating on food quality and energy efficiency.

8. Conclusion

In this paper a review on energy efficiency, quality improvement and modelling aspect of intermittent drying is presented. An analysis on up to date research on intermittent ultrasound, IR and microwave assisted convective drying is also presented. Improvement in energy efficiency and product quality for different intermittency are compared and discussed. The main difficulty in making an accurate comparison is that the drying conditions of these studies are quite different. Therefore, it is essential that investigations should be done at same drying conditions to make a general comparison of energy efficiency and product quality for all intermittency strategies. Since, previous studies were done at different drying conditions for different intermittency, a general comparison was not possible in this review. This review paper conclusively demonstrates that, intermittent drying is an effective method for improving the drying kinetics, enhancing product quality and reducing energy consumption per unit mass of moisture removed. However because of the complexity of food material and conjugate heat and mass transfer involvement during drying and tempering period, present understanding about intermittent drying process may not be sufficient. There is still lacking of in-depth understanding of moisture and temperature evolution during the whole period of intermittent drying. Suitable modelling and intensive research is required for better understanding of the process. Intermittent application of microwave is an attractive alternative approach, which can significantly reduce total drying time and improve product quality. But investigation of this drying method is not being exhausted yet. More experimental and theoretical study on intermittent convective drying and intermittent microwave assisted drying is necessary to establish a better strategy of applying those methods for better energy efficiency and quality.

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