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Review

Applications of superheated steam for the drying of food products

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Abstract. Drying is an ancient process used to preserve foods. Conventional drying (hot air) offers dehydrated products that can have an extended life of a year. Unfortunately, the quality of a conventionally dried product is drastically reduced from that of the original foodstuff. Superheated steam drying has been known for over 100 years, but its acceptance in industry has been slow. Before industry accepts a new technology like processing in superheated steam drying, it must be proven to provide these benefits in the area of processing where drying of a product is not the primary concern.

The comparison of both preservation processes, hot air and superheated steam drying, was done taking into account several important characteristics such as shrinkage, temperature, process-quality interaction, drying kinetics, costs and new improvements. An updated bibliographic research served to investigate and compare the effects of drying in terms of quality such as shrinkage, colour and microstructure for food products. Theoretical results, from several years of research on the subject, are presented and compiled in order to support the conclusions.

Keywords: drying, superheated steam, colour, shrinkage, microstructure

INTRODUCTION

The reduction of moisture is one of the oldest techniques for food preservation. Mechanical and thermal methods are two basic methods to remove the moisture in a solid material. In order to evaporate the liquid inside the material, thermal drying uses heat whereas mechanical drying is based on the application of pressure or centrifugal forces to the material, which acts on the moisture weakly attached to the material (Sun, 2005).

The mechanisms of drying involve vaporization of surface water and water movement under capillary forces, diffusion of liquid, and water vapour (Changrue, 2006). Figure 1 shows a typical drying curve.

In the conventional drying the first stage is when only free moisture at the surface is removed. In that stage the drying rate is constant (constant rate period). Dry spots appear on the surface of the material at the end of the constant rate period where the drying rate decreases (falling rate period). When the surface is completely dried, in other words when moisture is transported from inside of the product to the surface by capillary action, drying is placed on the third period (the second falling rate) where the drying rate is lower than in the previous step (Mujumdar and Menon, 1995).

A number of techniques are presented by researchers to improve the performance of the drying process. Figure 2 shows a general classification scheme of hybrid drying technologies (Sun, 2005). Under the umbrella of hybrid drying are drying techniques that employ multiple modes of heat transfer as well as those that use two or more stages of drying to achieve the desired dryness, product quality, drying time and manufacturing throughout.

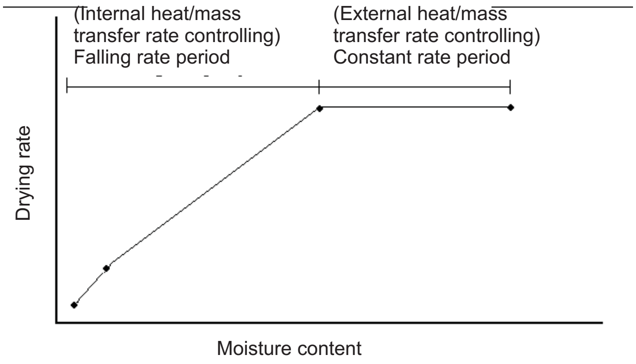

Fig. 1. Typical drying rate curve under constant-drying conditions (Adapted from Mujumdar and Sirikalaya, 2000).

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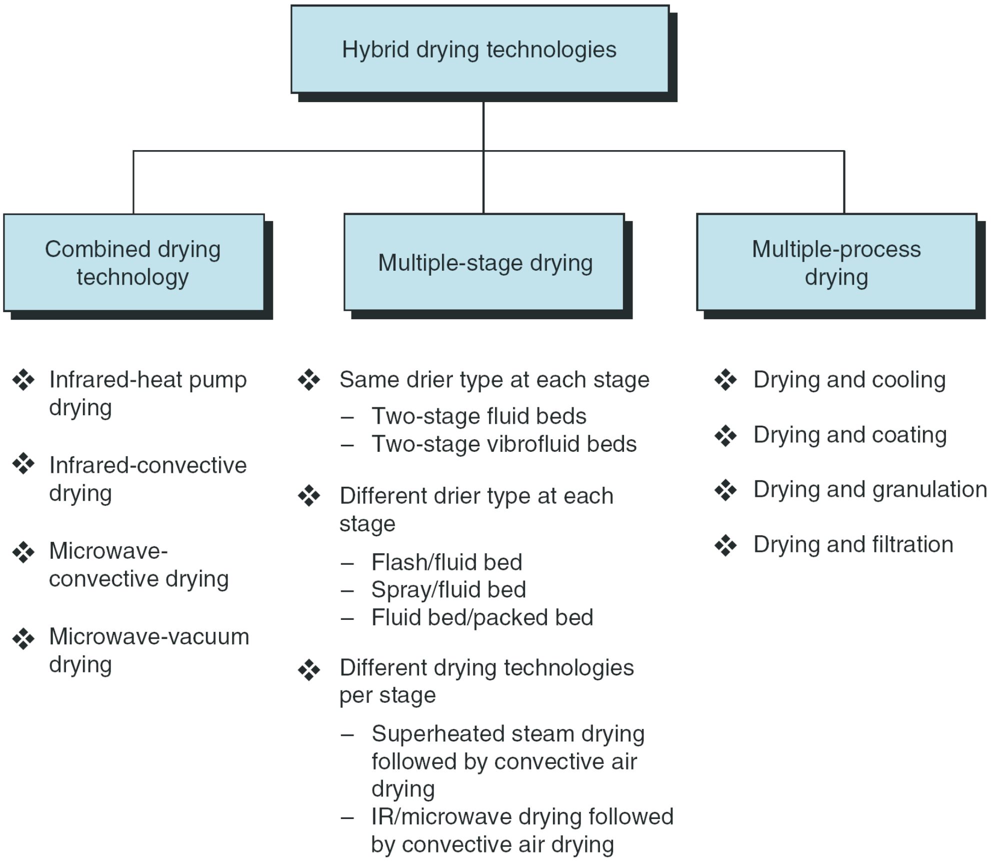


Fig. 2. General classification scheme of hybrid drying technologies (Sun, 2005).

Superheated Steam Drying (SSD) has been known for over 100 years, but has only made small gains in acceptance within certain industrial applications (Pronyk *et al*., 2005). The benefits of superheated steam over hot air are many. It has been shown that energy consumption is often lower, smaller equipment may be used, risks of fires and explosions are reduced, and harmful emissions may be eliminated (Lane and Stern., 1956; Shibata and Mujumdar, 1994; van Deventer and Heijmans, 2001). Overall acceptance of superheated steam as a unit process operation is slow due to a lack of suitable equipment and insufficient knowledge of the process and its effect on product quality (van Deventer and Heijmans, 2001; Kudra and Mujumdar, 2002). Recently the system has been investigated to dry products such as spent grain (Tang and Cenkowski, 2001), potatoes (Iyota *et al*., 2001; Tang and Cenkowski, 2001), sugar beet pulp (Tang *et al*., 2000), wood (Kudra and Mujumdar, 2002), Asian noodles (Markowski *et al*., 2003), shrimp (Prachayawarakorn *et al*., 2002), lumber (Woods *et al*., 1994), wood pulp and paper (Douglas, 1994), coal (Potter and Beeby, 1994) and sludge (Francis and Di Bella, 1996).

The next step in the utilization of superheated steam may be in the field of the processing medium, as superheated steam may change the properties of a product in ways that would not be possible with the use of hot air or other media (Tang, 2002).

The present study investigates three fields concerning superheated steam drying: in the first, characteristics and principles of superheated steam drying are reviewed, in the second section, industrial applications of superheated steam drying are presented to determine the capacity of this technology in the contemporary industry, and the final, the third objective of this study is to review the research and development about the effect of superheated steam drying on quality factors of food and agricultural products such as shrinkage, colour and microstructure in comparison to air drying. It is hoped that this review may be useful for future development work.

CHARACTERISTICS OF SUPERHEATED STEAM DRYING

Hausbrand (1924) introduced the idea of SSD at the beginning of the 20th century, however, it was not until the 1950's that researchers examined the process more closely (Chu *et al*., 1953; Lane and Stern, 1956; Wenzel and White, 1951).

Only after the 'oil crisis' in 1970's many papers were published on fundamental studies and applications of SSD. Conventional HAD is a very energy-intensive operation which accounts for about 15% of the industrial energy consumption in France (Topin and Tadrist, 1997) and 25% in Canada (Drouet, 1984; cited by Woods *et al.*, 1994). The feature of energy saving in SSD makes the technique a desirable alternative, and strict laws regarding environmental pollution offer another incentive to SSD (Beeby and Potter, 1985). Although a broad industrial acceptance has not been reached so far because of a lack of suitable equipment, it seems safe to predict a growing importance of this technique in the future due to its merits (Wimmerstedt, 1995). Currently, commercial application of SSD has been limited to drying industrial products such as paper products and sludge (Devahastin and Suvarnakuta, 2004; Kudra and Mujumdar, 2002).

Benefits of using superheated steam

The use of superheated steam as a drying medium has many potential benefits to the consumer and industry and has been detailed by many authors (Beeby and Potter, 1985; Erdesz and Kudra, 1990; Franics and Di Bella, 1996; Lane and Stern, 1956; Shibata and Mujumdar, 1994; Tang and Cenkowski, 2000; van Deventer and Heijmans, 2001; Meunier and Munz, 1986; Pronyk, 2007; Tang, 2002; Wimmerstedt, 1995; Woods *et al.*, 1994):

- Use of superheated steam can lead to energy saving as high as 50 to 80% over use of hot air or flue gases. These savings can be achieved due to higher heat transfer coefficient and increased drying rates in the constant and falling periods if the steam temperature is above the inversion temperature. The constant rate drying period is also longer in SSD, thus providing high drying rates for longer periods of time. These higher drying rates will increase the efficiency of the processing operation, potentially leading to a reduction in equipment size or an increase in output. High thermal efficiency is usually achieved only if the exhaust steam is collected and used elsewhere in the processing operation.
- Use of SSD as the drying medium instead of hot air means that there is an oxygen free environment during drying. That means there are no oxidative or combustion reactions during drying (no fire or explosion hazards). The oxygen free environment also produces improved product quality (no scorching).
- Most superheated steam dryers are designed as closed systems where the exhaust may be collected and condensed. In this way toxic or expensive compounds are removed and collected before they reach the environment, thus reducing air pollution. In the same way, dust from the process can be collected.
- Processing in superheated steam allows concurrent blanching, pasteurization, sterilization, and deodorization of food products during drying.
- The high heat-transfer coefficient in SSD, especially in the operation under pressure, results in enhancing the drying rate, improving the production efficiency, and consequently reducing the equipment size and capital cost.
- Superheated steam has the property of stripping volatile or semi-volatile organic substances from drying products. The aroma of feed or food products dried with superheated steam could be improved due to the stripping lose of some acids in the products. In addition, some valuable volatile organic compounds generated from the materials to be dried could be recovered and separated by a condenser.
- The control of steam-drying process is easier than that of HAD. The drying rate and the final moisture content of the product can be controlled by simply monitoring the steam temperature and velocity in SSD, but a more complex control of humidity is necessary in HAD.

Limitations of using superheated steam

SSD, as a new technique, also has some limitations (Beeby and Potter, 1985; Bonazzi *et al.*, 1996; Elustondo *et al.*, 2001; Elustondo *et al.*, 2002; Erdesz and Kudra, 1990; Kumar and Mujumdar, 1990; Lane and Stern, 1956; Martinello *et al.*, 2003; Meunier and Munz, 1986; Pronyk, 2007; Shibata 1991; Taechapairoj *et al.*, 2003; Tang, 2002; Woods *et al.*, 1994):

- SSD results in a high product temperature which is equal to or above the boiling point of free water. This imposes a limitation on the application of SSD to temperature-sensitive products. To solve this problem, SSD under a vacuum can be used because the boiling point is reduced as the pressure is decreased.
- In SSD, difficulties may be encountered with the feeding of wet materials and the discharge of dried products without excessive steam leaking out or air leaking into the drying system. More complex drying systems are needed, especially for drying under pressure or vacuum.
- The initial moisture condenzation on the surface of the products to be dried may increase the drying time in some cases.
- It is difficult to achieve a low moisture content level in the dried products if the superheat of the drying steam is relatively low.

DRYING PRINCIPLES OF SUPERHEATED STEAM

Superheated steam is steam that has a temperature above the saturation or boiling point. As water is heated at any specific pressure and reaches its boiling point, it is referred to as saturated steam. Once heated beyond the boiling point, the steam becomes unsaturated or superheated. At this point, the steam can transfer heat to the product that is being dried raising the product's temperature to the boiling temperature and transferring heat to the product. In contrast to saturated steam, a drop in temperature does not cause condensation of the steam as long as the temperature is higher than the saturation temperature. Any moisture that is evaporated does not need to be exhausted, but instead becomes part of the drying medium (Pronyk, 2007; Tang, 2002).

Initial heating period

As with hot air drying (HAD), SSD has three separate phases. They are the initial heating period, the constant-rate period, and the falling-rate period. Compared with HAD, however, some special phenomena such as steam condensation, inversion-temperature point, and building-up of overpressure happen in SSD processes (Pronyk, 2007; Tang, 2002).

During the initial heating, the temperature of material to be dried changes from the initial value to the boiling point of free water at operating pressure *eg* 100°C at atmospheric pressure as heat is transferred from superheated steam to the material (Bonazzi *et al*., 1996). The heat, particularly if the degree of superheat (the difference between the temperature of superheated steam and the boiling point of free water) is not high, is transferred through the condenzation of steam on the cold surface of the material (Tang, 2002; Wimmerstedt and Hager, 1996). The moisture of the material then increases at the beginning of drying. This means that more drying needs to be accomplished (Tang, 2002).

The quantity of the condensed moisture depends on various factors such as the thermal diffusivity of the material to be dried, the initial moisture content of the material, and the superheat of the steam (Beeby and Potter, 1985). Trommelen and Crosby (1970) reported that drops of water initially at 30°C get an increase in mass of about 12.5% when exposed to the superheated steam of 150°C at atmospheric pressure (Tang, 2002).

The time for drying material which is predominantly liquid, such as solution droplets, will be little affected by the increase in moisture during the initial heating period. However, for materials initially containing low moisture, the increase of moisture may represent a major portion of moisture to be removed and may extend the time required for drying (Beeby and Potter, 1985; Tang, 2002).

Constant-rate period

The second period is known as the constant rate period where the internal resistance to moisture diffusion is less than the external resistance to water vapour removal from the products surface. In HAD the rate depends on the convective transfer of heat from the air to the product and diffusion of water from the product to the air through a boundary layer of moisture surrounding the product. However, in drying with superheated steam the water does not have this diffusive resistance to movement through the boundary layer and water moves by bulk flow only. As well, the heat transfer coefficient is greater for superheated steam and evaporation of water into superheated steam is greater than into dry air except when the temperature of superheated steam approaches the saturation temperature (Chu *et al*., 1953). At the same medium temperature the temperature of the product is higher in superheated steam than hot air. The product temperature will rise to the temperature of saturation at a given pressure for superheated steam, while in hot air the temperature will only raise to the corresponding wet bulb temperature. The constant rate period is also longer than for air drying under similar conditions (Pronyk, 2007).

The drying rate for superheated steam will be greater than for air if the temperature is above the inversion temperature. At the inversion temperature, the evaporation rates into pure superheated steam and completely dry air are equal (Fig. 3). Conversely, above the inversion temperature the rate of evaporation will be greater into superheated steam than dry air. Values between 160 and 260°C for the inversion temperature were summarized from several sources by Schwartze and Brocker (2002) and represent both experimental and theoretical values. If the superheated steam temperature is below the inversion temperature the process could still be economical if the drying rate is greater in the falling rate period (Pronyk, 2007).

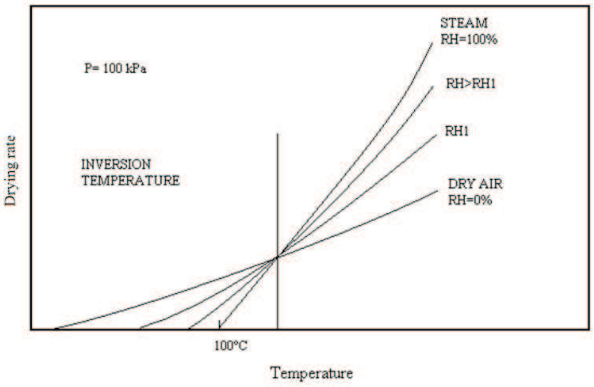


Fig. 3. Drying rate vs. temperature for air and steam (Kudra and Mujumdar, 2002).

Falling-rate period

After the outer surface begins to dry, the third period called the falling rate period begins. In the falling rate period the drying rate decreases and the product's temperature will rise to that of the superheated steam. In this period the internal resistance to moisture transport is greater than the external resistance. The drying rate is usually greater for superheated steam than for HAD because the product temperature is greater allowing for greater moisture diffusion in the product. As well, case-hardening (or 'skinning') may not occur and the product dried in superheated steam is more porous (Kudra and Mujumdar, 2002; Pronyk, 2007).

INDUSTRIAL APPLICATION OF SUPERHEATED STEAM DRYING

Due to the lack of suitable equipment, a broad industrial acceptance of SSD has not been reached. The application of this technique is limited to only a few industrial drying fields.

Drying of sugar-beet pulp

Sugar-beet pulp, the remains from sugar beets after sugar extraction, is mainly used as feed for animals. For long-time storage and convenient transportation, the sugar-beet pulp needs to be dried from a moisture content of 70-80% to a finial moisture content of about 10% (Jensen, 1992; Tang, 2002; Urbaniec and Malczewski, 1997; Wimmertedt and Hager, 1996). The pulp is conventionally dried in rotary-drum dryers by passing the pulp through the flue gases from a directly-fired furnace. Now superheated steam has been successfully used for drying sugar-beet pulp. A superheated steam dryer for sugar-beet pulp drying started operation in Sweden in 1983 (Svensson, 1985). A steam dryer with a 30m long belt was also developed for drying 25 t of sugar-beet pulp per hour at Villenoy, France (Miranda-Bernardo *et al*., 1990). At Stege, Denmark, in 1985, a pressurized fluid-bed steam dryer of the Niro type with the capacity of 9 t h^{-1} evaporation was installed in a sugar factory, and another Niro-type steam dryer was built at Nangis Sugar Factory in France (Brunce and Hulkkonen, 1998; Tang, 2002).

Drying of lumber

Drying of lumber is a very energy-intensive operation in wood processing, and can consume 40-70% of the total energy in the wood industry (Rosen, 1987; cited by Woods *et al*., 1994 Tang, 2002). The total energy for lumber drying in Canada was about 2% of total energy used in all Canadian industry during 1990 (Tang, 2002; Woods *et al*., 1994). Kollmann (1961) reported that a number of dryers operating with either superheated steam or a mixture of steam and air were employed for drying lumber in Germany (Tang, 2002). Drying with superheated steam in a vacuum has been developed for lumber processing. The new technique increases the drying rates by 3 to 7 times and provides high energy efficiency and excellent wood quality compared with conventional air drying with kiln dryers (Tang, 2002; Woods *et al*., 1994).

Drying of wood pulp and paper

At Rockanmmars Bruk in Sweden in 1979, a pneumatic-conveying dryer with superheated steam for pulp drying, with a capacity of 150 t of pulp per day, was built by MoDo Chemetics (Svensson, 1980, 1985). The pulp is mechanically dewatered to moisture content of about 55% and then dried to 10-15% moisture content. Compared with conventional flash dryers, the total energy cost is reduced by about 50%. The concept of drying paper with superheated steam was proposed by Mujumdar (1981, cited by Woods *et al*., 1994 and Tang, 2002). At McGill University in Canada, considerable research has been carried out regarding SSD of paper (Douglas, 1994; McCall and Douglas, 1994; Mujumdar, 1991), and in Finland (Malinen *et al*., 1994).

Drying of sludge

The TECOGEN Division of Thermo Power Corporation in USA developed a waste treatment system using an anaerobic digester with a superheated steam dryer (Franics and Di Bella, 1996). The system dries and sterilises sludge from the digester and produces a potentially saleable product. A fluidised-bed dryer for drying sludge with superheated steam was mounted at a landfill in Northern Germany in 1993 (Wimmerstedt and Hager, 1996; cited by Tang, 2002).

QUALITY FACTORS OF FOOD PRODUCTS IN SUPERHEATED STEAM

Processing in superheated steam may impart physical changes upon the product in addition to any drying that may take place. These changes may be unique to superheated steam and may not be achieved any other way. Products may be have odours removed, as with distillers spent grain where acetic acid can be stripped away by the superheated steam, thus giving the spent grain an aroma like baked goods instead of a sour smell (Tang and Cenkowski, 2001). When food products are processed in superheated steam they may become more porous due to increased heat transfer rates causing the moisture in a product to flash into steam, creating many pores (Kudra and Mujumdar, 2002; Yoshida and Hyodo, 1966). This may have an application in the snack food industry where frying in oil produces the same results.

Shrinkage

An aspect that is of great importance during drying of most biomaterials is product deformation. The degree of shrinkage and its variation with drying conditions as well as product moisture content influences the heat and mass transport within the product. There are a few numerical studies that investigated the effect of product deformation, involving modelling of coupled heat and mass transfer and stress, on drying and heat transfer (Hasatani and Itaya, 1996). Mihoubi *et al*. (2004) numerically studied and analysed the distribution of temperature, moisture, strain, and stress of a shrinkable product during drying. A validation of the model was achieved by the comparison of the numerical and experimental data. The experimental temperature and moisture profiles compared well with the model predictions. They also found that the distribution of displacement was not necessarily uniform within the material (the stress variation was larger at the surface than in the sample body) and might cause some bending and cracking within the material.

In the case of purely SSD, shrinkage of food products seemed to be lower when steam temperature increased due to less drying time. This trend has been observed for steam drying of potato chips (Caixeta *et al*., 2001), tortilla chips (Li *et al*., 1999; Moreira, 2001) and longan (Somjai *et al*., 2009). The reason for this is that a higher steam temperature produced samples with larger and more numerous pores, which may result in less shrinkage. However, the opposite trend was found for steam drying of cooked rice (Luangmalawat *et al*., 2008), chicken meat (Nathakaranakule *et al*., 2007) and shrimp (Prachayawarakorn *et al*., 2002). By comparing the purely SSD and SSD + HAD processes, it was found that products dried by SSD had the least degree of shrinkage due to the shorter period of SSD. This is in line with the study of Nathakaranakule *et al*. (2007) on chicken meat, and that by Somjai *et al*., (2009) on longan.

The volumetric shrinkage of the sample depended on the operating temperature and moisture content of the sample. The relationship between the volumetric shrinkage and moisture content of carrot undergoing low-pressure superheated steam drying (LPSSD), which was studied by Panyawong and Devahastin (2007), was used in the present simulation:

$$\frac{V}{V_i} = a\left(\frac{X}{X_i}\right)^2 + b\left(\frac{X}{X_i}\right) + c$$

where: a, b, and c are the empirical constants depending on the operating temperature, V_i and V are the volumes of carrot cube before and at any instant during drying (cm^3), respectively, and X_i and X are the moisture content of carrot cube before and at any instant during drying (d.b.), respectively. The values of the empirical constants for carrot undergoing LPSSD are listed in Table 1 (Kittiworrawatt and Devahastin, 2009).

Colour

Colour deterioration of fruits during thermal processing is due mostly to pigment degradation and browning reaction. Many fruits are rich in sugar, so that possible browning reaction, Millard reaction and/or caramelization could occur during the drying process (Chang *et al*., 1998).

Table 1. Empirical constants for shrinkage correlation of carrot at different temperatures (Kittiworrawatt and Devahastin 2009)

Drying temperature (°C)	a	b	c
60	-0.8288	1.8170	0.0366
70	-0.9026	1.9663	-0.0433
80	-0.9492	1.9938	-0.0421

Chua *et al*. (2001) studied time-varying drying (air temperature) in a heat pump dryer. It was observed that colour degradation of banana slices was reduced up to 40% and drying time was saved up to 180 min when the air temperature was stepped up from an initial value of 20°C to finish drying at 35°C. It was also found that stepping down the air temperature from 35 to 20°C reduced the colour degradation of banana slices by 23%.

Caixeta *et al*. (2002) studied the effects of impinging superheated steam temperature and convective heat transfer coefficient on the drying rates and some quality attributes of potato chips. Those investigators found that the samples dried at higher steam temperatures and high convective heat transfer coefficients suffered had higher porosity, darker colour, and lower vitamin-C content. However, HAD produced lower porosity, darker colour, and lower vitamin-C content potato chips. Iyota *et al*. (2001) determined the drying kinetics, surface conditions as well as colour changes of dried raw potato slices undergoing SSD and HAD. It was found that the samples dried by superheated steam were glossier and there were no remaining starch granules on the surface. On the other hand, starch gelatinization of the samples dried by hot air occurred more slowly than in the case of SSD. Non-gelatinised starch granules still remained on the surface of the product after the HAD process was completed. Moreover, the second layer of crust on the chips dried by hot air could be seen. The redness of the product dried in superheated steam was found to be higher than that of the product dried in hot air. Leeratanarak *et al*. (2006) dried potato slices using both LPSSD and HAD. The effects of hot-water blanching as well as drying temperature on the drying kinetics and various quality attributes of potato chips, viz. colour, texture (in terms of hardness) and browning pigment accumulation were investigated. It was found that LPSSD took shorter drying time than HAD when the drying temperatures were higher than 80°C. Longer blanching time and lower drying temperature resulted in better colour retention and led to chips of lower browning index.

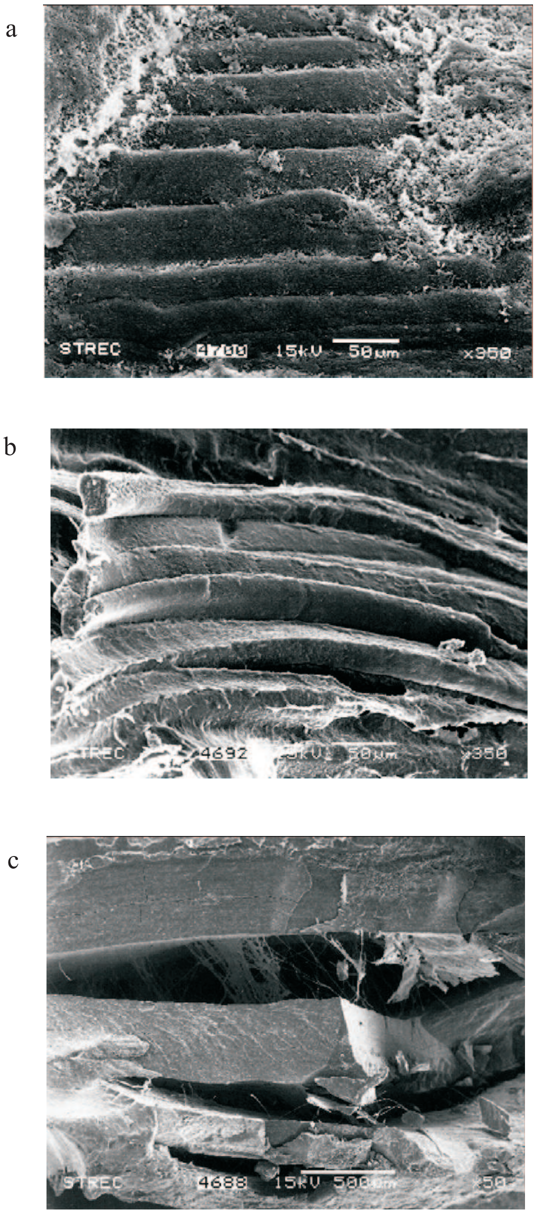
Devahastin *et al*. (2004) experimentally investigated drying of carrot cubes in both LPSSD and vacuum dryers. They found that, despite the longer required drying time in the operating ranges tested, carrot dried by LPSSD had superior quality (in terms of colour and rehydration behaviour) than that dried by vacuum drying. Leeratanarak *et al*. (2006) also indicated that LPSSD gave better quality dried potato chips than did HAD, both in terms of the physical and nutritional qualities.

Although drying with high-temperature superheated steam leads to increased drying rates and effective diffusion coefficients of the drying products (Li *et al*., 1999; Prachayawarakorn *et al*., 2002; Rordprapat *et al*., 2005; Uengkimbuan *et al*., 2005), the product quality, colour and texture as well as nutritional quality, is much damaged. Alternatively, two-stage drying can be an effective way to improve the quality of dried products. For example, combined superheated steam and HAD or heat pump drying (HPD) has been recommended to obtain quality improvement in various products including silk cocoon (Chen *et al*., 1992), shrimp (Namsanguan *et al*., 2004) and chicken meat (Nathakaranakule *et al*., 2007), compared to purely SSD.

Microstructure

Nathakaranakule *et al*. (2007) proposed two multi-stage drying techniques *ie* SSD in the first stage followed by HPD in the second stage (SSD + HPD), and SSD in the first stage followed by HAD in the second stage (SSD + HAD) for chicken meat. They analysed texture of the dried chicken by scanning electron microscope (JEOL, JSM-5600LV, JEOL Ltd., Japan) with an accelerating voltage of 10 kV. The scanning electron microscope (SEM) image of fresh chicken breast is shown in Fig. 4a. This image clearly shows the muscle fibres and connective tissues. When chicken was dried by SSD the muscle fibres were shortened and shrunk and the collagenous connective tissue was broken and completely hydrolysed into gelatine. In addition, voids were created as explained in the previous section (see Fig. 4b). Further heating at higher temperatures made the vapour pressure inside the samples to increase and expand to create larger voids, as is seen in Fig. 4b and c. On the other hand, chicken dried by both combined techniques exposed to the high-temperature environment of SSD shorter than in the case of purely SSD. Therefore, some broken collagenous connective tissues still remained as shown in Fig. 4d and 4e.

The microstructural changes of dried potato chips were observed using a scanning electron microscope (Leo 4551455, UK) at 100 × magnifications by Pimpaporn *et al*. (2007). The microstructure of dried potato chips was observed both on the surface and along the cross-section at the centre of the chips. The microstructure of dried potato chips was significantly affected by the drying temperature. At 90°C potato chips had more superior microstructure than those dried at lower drying temperatures. However, the effects of pretreatments on the microstructure were that only



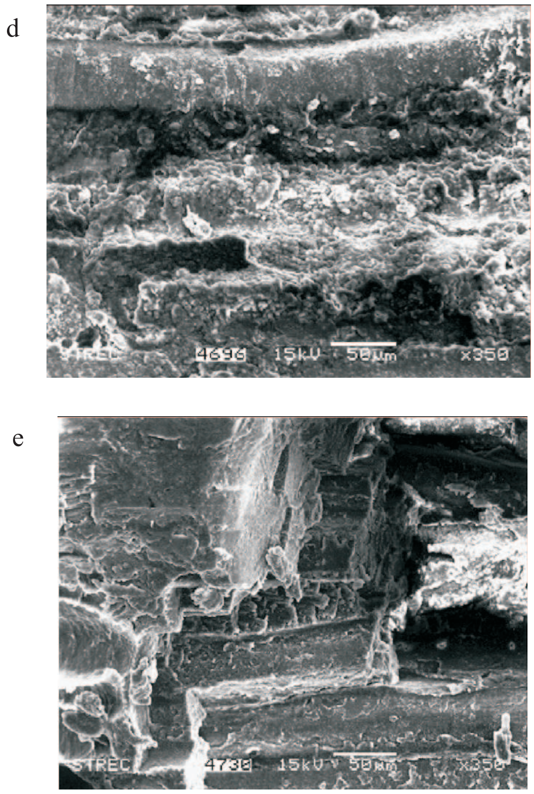


Fig. 4. Scanning electron micrographs of longitudinal section of chicken: a – fresh, b – dried by SSD at 120°C, c – dried by SSD at 160°C, d – dried by SSD + HAD (SSD 120°C, HAD 55°C and intermediate moisture content of 42.8% d.b.), e – dried by SSD + HPD (SSD 160°C, HPD 55°C and intermediate moisture content of 42.8% d.b.) (Nathakaranakule *et al*., 2007).

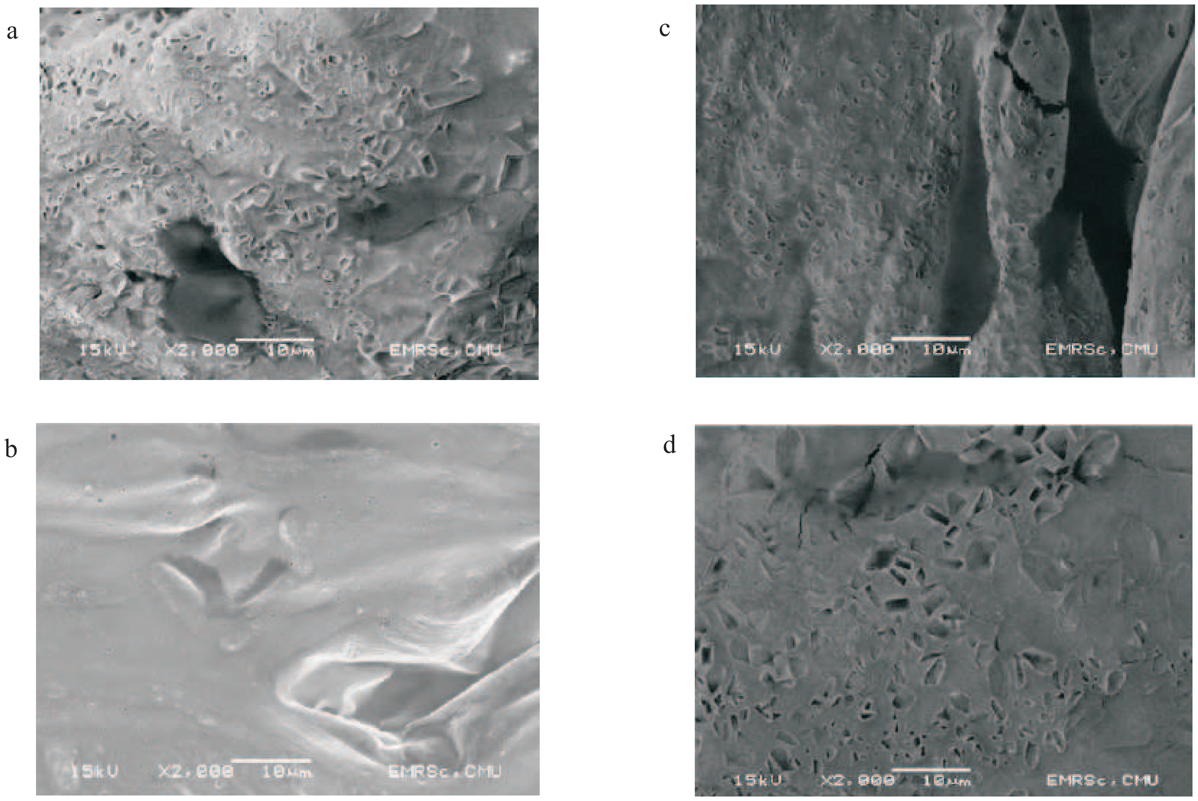


Fig. 5. Scanning electron micrographs of cross section of longan dried by SSD + HAD at different temperatures: a – SSD 120°C + HAD 60°C, b – SSD 180°C + HAD 60°C, c – SSD 120°C + HAD 70°C, d – SSD 180°C + HAD 70°C (Somjai *et al*., 2009).

combined blanching and freezing pretreatments led to the best integrity of microstructure (in terms of pore size, pore distribution and also less formation of rigid dense layer). The superior integrity of the microstructure might lead to the favourable texture of dried potato chips.

The microstructure of longon dried by SSD + HAD was analysed using a scanning electron microscope (JEOL Ltd., model JSM- 5910LV, Tokyo, Japan) with an accelerating voltage of 15 kV by Somjai *et al*. (2009). The samples were cut into 3 × 3 mm specimens which were plated on stubs and coated with a gold layer using a sputter-coater, and their cross sections were then photographed. SEM observations of SSD + HAD dried longan are illustrated in Fig. 5 which shows the nature of pores formed in the dried longan tissues subjected to different conditions of drying. SSD + HAD at low steam temperature formed structures containing many small voids and a few large cavities (Fig. 5a and c), resulting in considerable pore space inside the sample tissue. Higher steam temperatures gave less porosity in that although small pores were present larger macrocavities were rare. This is possibly caused by a lower degree of pore development occurring in the early stage of SSD as discussed by Nathakaranakule *et al*. (2007). Also, this might be due to increased chemical changes at higher temperature, especially a change in sugar content in the form of caramelization (John, 1994), which would result in a more homogeneous structure (as in Fig. 5b). Contrary to the effect of steam temperature, SSD + HAD at lower air temperature gave a product with less porosity than that at higher temperature. This is probably due to longer exposure to heat during the second-stage air drying, increasing the degree of thermal deformation. These results suggested that the morphological changes of longan dried by different temperatures of different media were obviously different. From SEM photographs, it was clear that the structural pattern of dried longan tissue was related to the degree of shrinkage; the lower the degree of shrinkage, the more void spaces inside the product.

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