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Effect of superheated steam drying on properties of foodstuffs and kinetic modeling

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ABSTRACT

Conventional hot air drying is an energy intensive technique which consumes around 15–25% of national industrial energy in most of the countries. It also often results in unacceptable product quality, nutrient degradation and non-uniform drying. Using air as a drying media leads to oxidation and combustion reaction and releases undesirable components creating environmental issues. Drying operation also needs continuous improvements to reduce energy consumption and preserve quality. Superheated steam drying (SSD) is an innovative drying technology, utilizing heated steam beyond its boiling point as a drying medium in a dryer to remove excess water from the material. Researchers on comparing conventional and SSD claimed that SSD supports product, environment, and energy saving benefits as well as it overcomes many constraints of hot air and other conventional drying techniques. This review will provide comprehensive detail about the effect of SSD on different properties (texture, microstructure, color, nutrient retention, shrinkage) of foodstuffs. Mathematical modeling and simulation of the SSD process as well as product characteristics undertaken by researchers are also compiled briefly in this article.

Industrial relevance: SSD offers many advantages over hot air drying which includes low net energy consumption, utilization of exhaust steam, no oxidative reactions and no hazardous gas, dust, dirt emission into environment. Kinetic modeling may prove to be useful for optimization and designing of the process.

Contents

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1. Introduction

Drying is an effective means of extending shelf life by reducing the moisture content of the material up to a level where biochemical reactions (microbial growth and enzymatic reactions) are reduced to minimum (Barbieri, Elustondo, & Urbicain, 2004). Under controlled temperature and humidity conditions, drying brings the moisture level to a safe limit and ensures good quality of products. It is well-known and low cost technique to preserve food products.

Drying, being energy intensive process needs continuous improvement to make it energy efficient. Industrial drying consumes around 20–25% of national energy in Germany and Denmark, whereas in Canada, USA, UK and France it is 10–15% (Satimehin, 2014). Most of conventional dryers, using hot air as the drying medium provokes detrimental effects on physicochemical properties of food stuffs, often results in unacceptable end qualities (nutrient degradation, harder texture, discoloration and non-uniform product quality), takes long drying time and gives low energy efficiency (Mujumdar & Law, 2010). The major cost in drying operation is attributed by operating cost rather than the capital cost of dryer. So drying system needs continuous research and developments to reduce the operating cost, energy as well as to minimize the nutritional losses and provide good quality dried food products. Various key areas for improvements as well as research and development challenges in conventional dryers have been reported by Mujumdar and Huang (2007). Recent advances in drying like superheated steam drying (SSD), heat pump-assisted drying and hybrid drying techniques are also discussed by Jangam (2011). Microwave, ultrasonic drying, and supercritical CO_2 drying are also very effective in retaining the nutrient quality of food commodities, but are very costly. So, the goal of researchers and industrialist is to minimize quality degradation, environmental pollution and to improve economics of operation. SSD is an innovative technology which is widely taken into consideration due to several benefits associated with it compared to conventional drying techniques.

Utilization of heated steam beyond its boiling point as a drying medium in a dryer to remove excess water from the material is a known SSD. The evaporated vapor becomes part of superheated steam (SS) which can be removed and readily condensed to provide heat for other applications and SS can be recycled (Ezhil, 2010). Many advantages that SSD offers over hot air drying (HAD) includes low net energy consumption, utilization of exhaust steam, no oxidative reaction and emission of hazardous gas, dust, and dirt into the environment. Under certain drying conditions (above inversion temperature) drying rates are higher than HAD (Jangam & Mujumdar, 2015). Steam can be produced using electricity; it can also be generated using solar heater and agricultural waste, which are easily available energy/fuel sources.

Generally conventional dryers (tray, tunnel, and drum) are not recommended for heat sensitive fruits and vegetables. To dry heat sensitive material, SSD can be carried out under low pressures, which only needs an additional vacuum pump to maintain low pressure and then drying can be done at low temperature effectively and efficiently (Mujumdar, 2000). It has been claimed by researchers that drying using SS leads to lowering of nutrient loss with least effect on quality (color, shrinkage, texture and rehydration) and faster drying rates. In SSD, case hardening is prevented thus produces dried product with better texture, also nutrient and volatile components are retained better than other conventional techniques (Pronyk, Cenkowski, & Muir, 2004).

In the recent years, numerous studies have reported the use of superheated steam as drying medium for several food commodities like potatoes (Tang & Cenkowski, 2000), apple (Elustondo, Elustondo, & Urbicain, 2001), shrimp (Prachayawarakorn, Soponronnarit, Wetchacama, & Jaisut, 2002), noodles (Markowski, Cenkowski, Hatcher, Dexter, & Edwards, 2003), tortilla chips (Pronyk et al., 2004), soyabean (Rordprapat, Nathakaranakule, Tia, & Soponronnarit, 2005), rice (Taechapairoj, Prachayawarakorn, & Soponronnarit, 2006), meat (Nathakaranakule, Kraiwanichkul, & Soponronnarit, 2007), banana (Nimmol, Devahastin, Swasdisevi, & Soponronnarit, 2007), fish (Borquez, Canales, & Quezada, 2008), carrot (Hiranvarachat, Suvarnakuta, & Devahastin, 2008), longan (Somjai, Achariyaviriya, Achariyaviriya, & Namsanguan, 2009), milk (Shrivastav & Kumbhar, 2010), mangosteen rind (Suvarnakuta, Chweerungrat, & Devahastin, 2011), cabbage (Phungamngoen, Chiewchan, & Devahastin, 2013), edible chitosan film (Thakhiew, Devahastin, & Soponronnarit, 2014), and coconut slices (Yun, Zzaman, & Yang, 2015) and some of the products are successfully dried at pilot scale. This review focuses on mechanism, benefits and limitations of SSD. It provides insight about the effect of SSD on properties of food material from various studies reported in literature in recent decades. In addition, modeling of SSD process for different food stuffs carried out by researchers is summarized at the end.

2. Principle of superheated steam drying

When water is heated at a specific pressure, it forms saturated steam at its boiling point. By further heating of saturated steam above boiling point at a corresponding pressure (100 °C at 1 atmospheric pressure), the saturated steam is converted into SS. In SSD, heat is transferred to the product using SS for raising its temperature to evaporation point and then evaporated water becomes part of drying medium (i.e. SS). Exhausted steam can be reused/recycled for further use which saves the cost of energy. Excess evaporated water or volatile component of food material can also be easily condensed and energy can be recovered or used elsewhere in other unit operations. Saturated steam is condensed as soon as there is a drop in temperature but no condensation occurs in superheated steam if temperature is maintained above saturation temperature at a specific pressure (Ezhil, 2010). A schematic diagram depicting process of SSD is shown in Fig. 1. It shows generation of steam, superheating of steam, drying using superheated steam in a closed circuit system and use of exhaust steam. Difference between SSD and air drying is in diffusion step. In air drying, diffusion of moisture occurs from inside the product to its surface and is important as well as rate limiting step. In SSD, evolution of moisture occurs within the material causing cells to expand as moisture flashes into steam which leads to a highly porous dried material. At the same temperature heat transfer properties in SSD are superior to air as in SSD air is not present, so there is no resistance to diffusion of the evaporated moisture in its own vapor. Moisture diffusivity is also high within product and mass transfer resistance between product surface and steam is low (Anto, Bv, Gc, & Hebbar, 2014). So, evaporation of vapor from surface of material is controlled by heat transfer in SSD (Ezhil, 2010).

The rate of evaporation of moisture present in a food material in steam is given by equation:

$$N = \frac{q}{\lambda} = \frac{h(T_{medium} - T_{surface})}{\lambda}.$$